Workshop on exotic hadronic atoms, deeply bound kaonic nuclear states and antihydrogen: present results, future challenges

ECT*, Strada delle Tabarelle 286, I-38050, Villazzano (Trento), Italy
June 19-24, 2006

edited by

C. Curceanu (Petrascu)\textsuperscript{1}, A. Rusetsky\textsuperscript{2,3}, E. Widmann\textsuperscript{4}

\textsuperscript{1} LNF - INFN, Via E. Fermi 40, 00044 Frascati, (Roma), Italy
\textsuperscript{2} Universität Bonn, Helmholtz-Institut für Strahlen- und Kernphysik (Theorie)
Nussallee 14-16, D-53115 Bonn, Germany
\textsuperscript{3} On leave of absence from: HEPI, Tbilisi State University
University st. 9, 380086 Tbilisi, Georgia
\textsuperscript{4} Stefan Meyer Institut für subatomare Physik, Boltzmanngasse 3, A-1090, Vienna, Austria

ABSTRACT

These are the miniproceedings of the workshop “Exotic hadronic atoms, deeply bound kaonic nuclear states and antihydrogen: present results, future challenges,” which was held at the European Centre for Theoretical Nuclear Physics and Related Studies (ECT*), Trento (Italy), June 19-24, 2006. The document includes a short presentation of the topics, the list of participants, and a short contribution from each speaker.
1 Introduction

The workshop “Exotic hadronic atoms, deeply bound kaonic nuclear states and antihydrogen: present results, future challenges” was held on June 19-24 at the European Centre for Theoretical Nuclear Physics and Related Topics (ECT*), Trento (Italy). The workshop has been largely inspired by latest theoretical and experimental progress, achieved in the investigation of the exotic hadronic bound systems, which offer a unique way for studies of fundamental interactions and symmetries in Nature. The topics of the workshop included:

- Hadronic atoms: status of the theory and of experimental results (including DEAR/SIDDHARTA at DAFNE, DIRAC at CERN, Pionic atoms at PSI)
- Meson-nucleon and meson-nucleus interactions in effective theories, unitarization models of Chiral Perturbation Theory.
- $K \rightarrow 3\pi$ decay: theory and experimental results (including NA48 at CERN)
- Deeply bound kaonic-nuclear states: status of the theory and experimental results (including E471 and E549/570 at KEK, FINUDA at DAFNE, FOPI at GSI)
- Antihydrogen physics: production mechanisms, precision spectroscopy for testing CPT and QED, gravitation of antimatter
- Next generation experiments at DAFNE2, J-PARC, FAIR

Around 50 physicists took part in the workshop, which was held in a unique atmosphere of intense discussions and learning. In total 45 talks were presented. At the end of the workshop, an informal discussion on deeply bound $\bar{K}$-nuclear states took place (convener: W. Weise).

Acknowledgments.

We wish to thank all participants for traveling to Trento and for making an exciting and very lively meeting. We want to thank our secretary Ines Campo for the excellent performance, and the whole staff of the ECT* for their help.

The Workshop was financially supported by ECT* and by the FP6 EC contract RII3-CT-2004-506078 “Study of strongly interacting matter” (“I3 HadronPhysics”).

For the full program and the complete list of speakers see: http://www.itkp.uni-bonn.de/~rusetsky/TRENTO06/trento06.html

Frascati/Bonn/Vienna, October 13, 2006

Catalina Curceanu (petrascu@lnf.infn.it)
Akaki Rusetsky (rusetsky@itkp.uni-bonn.de)
Eberhard Widmann (eberhard.widmann@oeaw.ac.at)
## List of Participants

|   | Name                  | Affiliation | Email Address                      |
|---|-----------------------|-------------|------------------------------------|
| 1 | Petros Aslanyan       | (Yerevan)   | aslanyan@sunhe.jinr.ru            |
| 2 | Yoshinori Akaishi     | (RIKEN)     | yoshinori.akaishi@kek.jp          |
| 3 | Vadim Baru            | (ITEP)      | baru@itep.ru                       |
| 4 | George Beer           | (TRIUMF, Uvic) | gbeer@uvic.ca                      |
| 5 | Bugra Borasoy         | (Bonn)      | borasoy@itkp.uni-bonn.de          |
| 6 | Paul Bühler           | (SMI Vienna) | paul.buehler@oeaw.ac.at           |
| 7 | Gianmaria Collazuol   | (Pisa)      | gianmaria.collazuol@pi.infn.it    |
| 8 | Catalina Curceanu     | (LNF-INFN)  | catalina@lnf.infn.it              |
| 9 | Evgeny Epelbaum       | (FZ Jülich) | epelbaum@itkp.uni-bonn.de         |
| 10| Torleif Ericson       | (CERN)      | torleif.ericson@cern.ch           |
| 11| Eli Friedman          | (Jerusalem) | elifried@vms.huji.ac.il           |
| 12| Avraham Gal           | (Jerusalem) | AVRAGAL@vms.HUJI.AC.IL            |
| 13| Juerg Gasser          | (Bern)      | gasser@itp.unibe.ch               |
| 14| Detlev Gotta          | (FZ Jülich) | d.gotta@fz-juelich.de             |
| 15| Carlo Guaraldo        | (LNF-INFN)  | carlo.guaraldo@lnf.infn.it        |
| 16| Ryugo Hayano          | (Tokyo)     | ryugo.hayano@cern.ch              |
| 17| Norbert Herrmann      | (Heidelberg)| herrmann@physi.uni-heidelberg.de |
| 18| Gino Isidori          | (LNF-INFN)  | gino.isidori@lnf.infn.it          |
| 19| Andrey Ivanov         | (Vienna)    | ivanov@kph.tuwien.ac.at           |
| 20| Masahiko Iwasaki      | (RIKEN)     | masa@riken.jp                     |
| 21| Bertalan Juhasz       | (SMI Vienna) | Bertalan.Juhasz@cern.ch           |
| 22| Kenta Itahashi        | (RIKEN)     | itahashi@riken.jp                |
| 23| Paul Kienle           | (SMI Vienna) | Paul.Kienle@ph.tum.de            |
| 24| Tadafumi Kishimoto    | (Osaka)     | kisimoto@phys.sci.osaka-u.ac.jp   |
| 25| Alexander Kudryavtsev  | (ITEP)      | kudryavt@itep.ru                  |
| 26| Naofumi Kuroda        | (RIKEN)     | rlehner@lns.mit.edu               |
| 27| Ralf Lehner           | (MIT)       | LemmerR@physics.wits.ac.za        |
| 28| Johann Marton         | (SMI, Vienna)| johann.marton@oeaw.ac.at          |
| 29| Nikolaos Movramatos   | (London)    | nikolaos.mavramatos@kcl.ac.uk     |
| 30| Natalia Troitskaya    | (St. Petersburg)| natroitskaya@yandex.ru       |
| 31| Robin Nißler          | (Bonn)      | rniessler@itkp.uni-bonn.de        |
| 32| Hiroaki Ohnishi       | (RIKEN)     | h-ohnishi@riken.jp               |
| 33| Eulogio Oset          | (Valencia)  | oset@ific.uv.es                   |
| 34| Jose A. Oller         | (Murcia)    | oller@um.es                      |
| 35| Haruhiko Outa         | (RIKEN)     | outa@riken.jp                    |
| 36| Joaquim Prades        | (Granada)   | prades@ugr.es                    |
| 37| Akaki Rusetsky        | (Bonn)      | rusetsky@itkp.uni-bonn.de         |
| 38| Udit Raha             | (Bonn)      | udit@itkp.uni-bonn.de             |
| 39| Leopold Simons        | (PSI)       | leopold.simons@psi.ch             |
| 40| Ludwig Tauscher       | (Basel)     | dirk.trautmann@unibas.ch          |
| 41| Volodymyr Magas       | (Barcelona) | vladimir@ecm.ub.es                |
44. Wolfram Weise (TUM Munchen)  wolfram.weise@physik.tu-muenchen.de
45. Eberhard Widmann (SMI Vienna)  eberhard.widmann@oeaw.ac.at
46. Slawomir Wycech (Warsaw)  Slawomir.Wycech@fuw.edu.pl
47. Toshimitsu Yamazaki (Tokyo)  yamazaki@nucl.phys.s.u-tokyo.ac.jp
48. Valeriy Yazkov (Moscow State)  yazkov@nusun.jinr.ru
49. Johann Zmeskal (SMI, Vienna)  Johann.Zmeskal@oeaw.ac.at
# Contributions

## Exotic Atoms

| Author(s) | Title | Page |
|-----------|-------|------|
| L. M. Simons | *Pionic Hydrogen* | 8 |
| D. Gotta | *Pionic Deuterium* | 9 |
| E. Epelbaum | *Chiral forces and few-nucleon systems* | 10 |
| A. Rusetsky et al | *The theory of pionic deuterium: status and perspectives* | 11 |
| V. Baru et al | *ChPT for $NN \rightarrow NN\pi$ and absorption correction to $a_{\pi d}$* | 12 |
| K. Itahashi et al | *Future programs for the precision spectroscopy of pionic atoms in the nuclear reactions* | 13 |
| B. Borasoy | *Low-energy $\bar{K}N$ interactions* | 14 |
| J. A. Oller | *About the Strangeness $-1$ $S$-wave Meson-Baryon Scattering* | 15 |
| R. Nißler | *Chiral unitary approach to $K^-p$ scattering* | 16 |
| J. Marton | *Kaonic Hydrogen Experiments* | 17 |
| V. Yazkov | *Measurement of the $\pi^+\pi^-$ atom lifetime at DIRAC* | 18 |
| U. Raha et al | *$\bar{K}N$ Scattering Lengths From Kaonic Deuterium* | 19 |
| D. Trautmann et al | *How accurate are the pionium breakup calculations?* | 20 |
| A. Kudryavtsev | *Analytic theory for hadronic atoms beyond the Deser approximation* | 22 |
| T.E.O. Ericson et al | *Corrections to scattering lengths from hadronic atoms* | 23 |
| E. Friedman | *Kaonic atoms as a starting point for antikaon nuclear physics* | 24 |
**Antiprotonic atoms**

R.S. Hayano  
* Determination of the Antiproton-to-Electron Mass Ratio by Precision Laser Spectroscopy of $\bar{p}\text{He}^+$  

D. Gotta  
* Light Antiprotonic Atoms  

N.E. Mavromatos  
* Looking for “smoking gun” signatures of CPT Violation  

R. Lehnert  
* Lorentz and CPT tests with antimatter  

R.S. Hayano  
* Antihydrogen  

B. Juhasz et al  
* Measurement of the ground-state hyperfine structure of antihydrogen  

N. Kuroda et al  
* MUSASHI – An ultra-slow antiproton beam source – Ultra-slow antiproton beam source and antiprotonic atom formation  

**K-clusters**

S. Wycech  
* On the structure of KNN, KNKN states  

A. Gal  
* Dynamical calculations of $K^-$ nuclear bound states  

E. Oset et al  
* Chiral dynamics of $K$-nucleus interaction: critical review of deeply bound states  

Y. Akaishi et al  
* Deeply bound kaonic nuclear states in reply to recent criticisms  

A. Ivanov et al  
* Phenomenological quantum field theoretic model of Kaonic Nuclear Clusters $K^-pp$, $K^-pnn$ and so on  

V. Magas et al  
* Simulation of the $K$- nuclear absorption at FINUDA  

P. Kienle  
* Probing the Structure of Nuclei Bound by Antikaons
W. Weise
Conditions for antikaon-nuclear bound states ........................................ 39

T. Yamazaki et al
Present status of the experimental investigation of deeply bound kaonic states ...... 40

T. Kishimoto
Study of kaonic nuclei by in-flight \((K^-, N)\) reactions ................................. 41

N. Herrmann
Search for deeply bound kaonic states with FOPI at GSI ............................ 42

P. Bühler et al
Search for \(K^- pp\) clusters in \(p+d\)-reaction with FOPI ............................. 43

P.Zh. Aslanyan
\(\Lambda p\) spectrum analysis at 10 GeV/c in \(p+C\) interactions ......................... 44

T. Yamazaki et al
Enhanced formation of \(K^- pp\) clusters by short-range \(pp\) collisions .............. 45

H. Ohnishi
A search for deeply-bound kaonic nuclear states by in-flight \(^3\)He\((K^-, n)\) reaction at \(J\)-PARC ................................................................. 46

J. Zmeskal
AMADEUS AT DAΦNE ................................................................. 47

W. Weise (convener)
Discussion panel on deeply bound \(K\)-nuclear states .................................. 48

\(K \rightarrow 3\pi\) DECAYS

J. Prades et al
FSI in \(K \rightarrow 3\pi\) and Cabibbo’s Proposal to Measure \(a_0 - a_2\) ....................... 50

G. Collazuol
Pion scattering lengths from the \(NA48/2\) experiment at CERN ....................... 51

G. Isidori et al
On the cusp effects in \(K \rightarrow 3\pi\) decays .............................................. 52

J. Gasser et al
Non relativistic \(QFT\) and \(K \rightarrow 3\pi\) decays ........................................... 53
Pionic Hydrogen

L. M. Simons

Paul Scherrer Institut, CH-5232 PSI/Villigen, Switzerland

for the PIONIC HYDROGEN collaboration

The new pionic hydrogen experiment at PSI [1] aims at an improvement in the determination of the strong interaction ground state shift and width of the pionic hydrogen atom using high precision X-ray crystal spectroscopy. The final goal is the extraction of isospin separated scattering lengths with accuracies at the percent level. Compared to previous efforts the energy resolution and statistics have been improved and the background is much reduced. The spectrometer response function has been determined precisely using a novel method [2].

The inherent difficulties of the exotic atom’s method result from the fact that the pionic hydrogen atom must be formed at higher gas pressures. For the extraction of a strong interaction shift an extrapolation method to vacuum conditions proved to be successful and the measured line shift

\[
\epsilon_{1s} = +7.120 \pm 0.008 \text{ (stat.)} \pm 0.006 \text{ (sys.)} \text{ eV}
\]  

(1)
could be attributed exclusively to the strong interaction [3]. The measured line shape of a pionic hydrogen K transition does not permit to extract the strong interaction width \( \Gamma_{1s} \) directly as it is Doppler broadened by various de-excitation steps caused by by \( n \rightarrow n' \) Coulomb transitions. Based on the precise knowledge of the spectrometer’s resolution function it was tried to identify various contributions to the line shape from Coulomb de-excitation.

With this procedure the analysis of the three transitions \( \pi H(2p - 1s) \), \( \pi H(3p - 1s) \) and \( \pi H(4p - 1s) \) at different pressures could be combined to yield a preliminary result for the strong interaction width to be

\[
\Gamma_{1s} = 823 \pm 19 \text{ meV.}
\]  

(2)

The efforts to improve the accuracy of the scattering lengths as well face the problem that the linear combination \( a^+ + a^- \) to be determined from \( \epsilon_{1s} \) suffers from the poor knowledge of \( \delta \). The correction \( \delta_{\Gamma} \) for \( \Gamma_{1s} \) seems to be much better under control [5]. This allows to quote a preliminary value for the isovector scattering length to be

\[
a^- = (86.44 ^{+0.10}_{-1.02}) \cdot 10^{-3} \text{ [m}^{-1}\pi].
\]  

(3)

References

[1] PSI experiment R-98.01, [http://pihydrogen.web.psi.ch](http://pihydrogen.web.psi.ch).
[2] D. F. Anagnostopoulos et al., Nucl. Instr. Meth. A545 (2005) 217.
[3] M. Hennebach, PhD thesis, Universität zu Köln, 2003.
[4] J. Gasser et al., Eur. Phys. J. C 26 (2003) 13; T E. O Ericson, this workshop.
[5] P. Zemp, Ph. D. thesis, (University of bern, 2004), P. Zemp and J. Gasser, in prep.
Pionic Deuterium

D. Gotta

Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany

*for the PIONIC HYDROGEN collaboration*

Precise measurements of shift $\epsilon_{1s}$ and width $\Gamma_{1s}$ of the pionic hydrogen ground state have been performed [1] in order to extract the isoscalar and isovector scattering lengths $a^+$ and $a^-$ within the framework HB$\chi$PT calculations [2]. Whereas $\Gamma_{1s} \propto (a_{\pi^- p} \rightarrow a_{\pi^0 n})^2 \propto (a^-)^2$ yields directly $a^-$, the shift is due to elastic scattering with $\epsilon_{1s} \propto a_{\pi^- p} \rightarrow a_{\pi^0 n} \propto a^+ + a^-$. The determination of $a^+ \ll a^-$ from this linear combination suffers in particular from the large uncertainty of the low-energy constant $f_1$.

In $\pi D$ to leading order, $\epsilon_{1s} \propto a^+$. Consequently, higher orders (multiple scattering, deuteron structure, absorption, etc.) contribute significantly, but as shown by theoretical calculations are well under control [3]. Hence, a precise measurement of $\epsilon_{1s}$ in $\pi D$ being an independent access to $a^+$ imposes constraints on $a^+$ and $a^-$ as obtained from $\pi H$. Even more, limits can be derived for $f_1$. It is worth mentioning that due to the leading order cancellations, isospin-breaking effects amount to $\approx 40\%$ for $\epsilon_{1s}$ in $\pi D$ [4], which is an outstanding occurrence in pion–nuclear interaction involving charged pions.

For $\pi D$, $\Gamma_{1s}$ is directly related to threshold pion production in the reaction $pp \rightarrow \pi^+ d$ by detailed balance and charge independence. The threshold parameter $\alpha$ representing s-wave pion production is proportional to the imaginary part of the $\pi d$ scattering length being $\propto \Gamma_{1s}$. Calculations of $\alpha$ within HB$\chi$PT are continuously improved and require experimental data at least at the expected final level of accuracy [7].

The forthcoming experiment, using the $\pi D(3p-1s)$ transition, aims at an improvement for $\epsilon_{1s}$ and $\Gamma_{1s}$ from $3\% \rightarrow 0.5\%$ and $12\% \rightarrow 4\%$, respectively [5,6]. Possible molecular effects will be identified by studying the pressure dependence like in the $\pi H$ experiment.

References

[1] L. S. Simons, this workshop; D. F. Anagnostopoulos et al., EXA05, Vienna, 2005, p.107.
[2] J. Gasser et al., Eur. Phys. J. C 26 (2003) 13; P. Zemp, Ph. D. thesis, (University of Bern, 2004); P. Zemp and J. Gasser, in prep.
[3] T. E. O. Ericson, B. Loiseau, A. W. Thomas, Phys. Rev. C 66 (2002) 014005; Beane et al., Nucl. Phys. A 720 (2003) 399.
[4] U.-G. Meissner, U. Raha, A. Rusetsky, [arXiv:nucl-th/0512035](http://arxiv.org/abs/nucl-th/0512035). A. Rusetsky, this workshop.
[5] D. Chatellard et al., Nucl. Phys. A 625 (1997) 855; P. Hauser et al., Phys. Rev. C 58 (1998) R1869.
[6] PIONIC HYDROGEN collaboration, PSI experiment R-06.03.
[7] V. Lensky et al., Eur. Phys. J. A 27 (2006) 37.
Chiral forces and few-nucleon systems

E. Epelbaum$^{1,2}$

$^1$Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany
$^2$HISKP (Theorie), Universität Bonn, Nußallee 14-16, 53115 Bonn, Germany

Chiral effective field theory provides a systematic and controlled framework to study the dynamics of few-nucleon systems [1]. It relies on the low-momentum expansion and allows to derive nuclear forces and current operators from the most general effective Lagrangian for pions, nucleons and external sources in harmony with (approximate) chiral symmetry of QCD.

The structure of the nuclear force at few lowest orders in the chiral expansion were discussed and selected applications to few–nucleon systems were presented, see [2] for a recent review article. The most advanced studies in the two–nucleon sector at next–to–next–to–next–to–leading order (N$^3$LO) in the chiral expansion demonstrate the ability of the chiral forces to provide an accurate description of the data in the low–energy region [3,4]. For three– and more nucleon systems calculations have so far been performed up to next–to–next–to–leading order (NNLO). At this order one has to take into account for the first time the chiral three–nucleon force (3NF) [5,6]. Most of the calculated elastic and breakup nucleon–deuteron (Nd) scattering observables are in a reasonable agreement with the data up to $E_{\text{lab}} \sim 65$ MeV. In few cases such as the vector analyzing power in elastic Nd scattering and the Nd breakup cross section in certain configurations [7] large discrepancies with the data are observed.

It is important to extend the calculations for three and more nucleons to N$^3$LO in order to test the convergence of the chiral expansion and to be able to increase the energy range. This will require the inclusion of the leading corrections to the 3NF which have yet to be worked out. Work along these lines is underway. For four– and more–nucleon systems, the leading four–nucleon force (4NF) will also need to be taken into account. The parameter–free expressions for the 4NF at N$^3$LO have recently been derived [8].

References

[1] S. Weinberg, Nucl. Phys. B363 (1991) 3.
[2] E. Epelbaum, Prog. Part. Nucl. Phys. 57 654, nucl-th/0509032.
[3] D.R. Entem and R. Machleidt, Phys. Rev. C68 (2003) 041001, nucl-th/0304018.
[4] E. Epelbaum, W. Glöckle and U.G. Meißner, Nucl. Phys. A747 (2005) 362, nucl-th/0405048.
[5] U. van Kolck, Phys. Rev. C49 (1994) 2932.
[6] E. Epelbaum et al., Phys. Rev. C66 (2002) 064001, nucl-th/0208023.
[7] J. Ley et al., Phys. Rev. C73 (2006) 064001.
[8] E. Epelbaum, Phys. Lett. B, in press, nucl-th/0511025.
The theory of pionic deuterium: status and perspectives

Ulf-G. Meißner\textsuperscript{1,2}, Udit Raha\textsuperscript{1} and Akaki Rusetsky\textsuperscript{1,3}

\textsuperscript{1}HISKP (Theorie), Universität Bonn, Nußallee 14-16, 53115 Bonn, Germany
\textsuperscript{2}Forschungszentrum Jülich, Institut für Kernphysik (Theorie), D-52425 Jülich, Germany
\textsuperscript{3}On leave of absence from: High Energy Physics Institute, Tbilisi State University, 0186 Tbilisi, Georgia

In this talk I give a comprehensive survey of theoretical calculations of the pion-deuteron scattering length in chiral effective field theories – both in the isospin-conserving and in the isospin-breaking sectors. Namely, it is demonstrated that the estimated systematic uncertainties in the isospin-conserving part of the pion-deuteron scattering length can not be responsible for the huge discrepancy, which emerges in the recent analysis of the pionic hydrogen and pionic deuterium data from Pionic Hydrogen collaboration at PSI. If has been further demonstrated that isospin-breaking corrections to the pion-deuteron scattering length can be very large, because of the vanishing of the isospin-symmetric contribution to this scattering length at leading order in chiral perturbation theory. What is most interesting, these corrections can explain the bulk of the above-mentioned discrepancy. We also give the first estimate of the size of the electromagnetic low-energy constant $f_1$.

Further, we propose to include the correlations, which are due to the presence of the same low-energy constants in different bound-state observables, in the simultaneous analysis of the pionic hydrogen and pionic deuterium data. In this manner, one may substantially reduce the systematic error, arising from these low-energy constants and determine the $S$-wave $\pi N$ scattering lengths at a much better accuracy. To this end, however, one needs to evaluate the isospin-breaking corrections at least at order $p^3$ both in the pionic hydrogen and pionic deuterium.

The main results of the talk are contained in Refs. [1,2].

References

[1] U.-G. Meißner, U. Raha and A. Rusetsky, \texttt{arXiv:nucl-th/0512035}.

[2] U.-G. Meißner, U. Raha and A. Rusetsky, Eur. Phys. J. C \textbf{41} (2005) 213 \texttt{arXiv:nucl-th/0501073}, Erratum \textit{ibid} C \textbf{45} (2006) 545.
ChPT for $NN \rightarrow NN\pi$ and absorption correction to $a_{\pi d}$

V. Baru$^1$, C. Hanhart$^2$, J. Haidenbauer$^2$, A. Kudryavtsev$^1$, V. Lensky$^{1,2}$ and U.-G. Meißner$^{2,3}$

$^1$ Institute of Theoretical and Experimental Physics, 117259, B. Cheremushkinskaya 25, Moscow, Russia

$^2$ Institut für Kernphysik, Forschungszentrum Jülich GmbH, D–52425 Jülich, Germany

$^3$ Helmholtz-Institut für Strahlen- und Kernphysik (Theorie), Universität Bonn, Nußallee 14-16, D–53115 Bonn, Germany

We present the parameter free calculation for the reaction $NN \rightarrow NN\pi$ up to NLO in ChPT [1] utilizing the counting scheme that acknowledges the large center-of-mass momentum $p \sim \sqrt{m_\pi M_N}$ between initial nucleons (see review [2] and Refs. therein). It turns out that in this counting scheme some loops start to contribute already at NLO. Moreover the contribution of these loops to the amplitude of the reaction $pp \rightarrow d\pi^+$ at NLO grows linearly with respect to the final NN relative momentum. This behavior leads to a large sensitivity to the final NN wave function when the convolution integral with the transition operator is evaluated. However the central finding of our recent paper [1] is that there are additional irreducible terms that contribute at the same order and cancel exactly the linear growth to restore the consistency of the formalism. These terms stem from the so called box diagrams that allow the two-nucleon intermediate cuts and therefore are formally reducible (see Fig. 1a in Ref [1]). However the part of the Weinberg-Tomozawa $\pi N \rightarrow \pi N$ vertex cancels one of the nucleon propagators. This produces additional irreducible terms that bring the sum of all loops at NLO to vanish. Moreover the rest of the box diagrams after a proper separation of the irreducible terms is a purely reducible contribution with one important modification as compared to the standard treatment, namely that the $\pi N \rightarrow \pi N$ vertex is to be on shell ($2m_\pi$ instead of standard $3/2m_\pi$). This enhancement by a factor of $4/3$ for the amplitude is sufficient to bring the cross section for $pp \rightarrow d\pi^+$ close to the experiment.

Once the reaction $pp \rightarrow d\pi^+$ is understood within ChPT one can apply the formalism and the counting rules for the calculation of the dispersive and absorptive corrections to the $\pi d$ scattering length. We have recently done this work [3]. Specifically we have calculated both the hadronic $\pi d \rightarrow NN \rightarrow \pi d$ and the photonic $\pi d \rightarrow \gamma NN \rightarrow \pi d$ processes. We have shown that as soon as all diagrams at leading order are included their net effect on the real part of $a_{\pi d}$ is negligible. Also we get that both the ratio and the sum of the hadronic and photonic absorptive corrections to the imaginary part of $a_{\pi d}$ are in agreement with the data.

References

[1] V. Lensky et al., Eur. Phys. J. A 27, 37 (2006) [arXiv:nucl-th/0511054].

[2] C. Hanhart, Phys. Rep. 397 (2004) 155 [arXiv:hep-ph/0311341].

[3] V. Baru et al., in preparation
Future programs for the precision spectroscopy of pionic atoms in the nuclear reactions

K. Itahashi¹, R.S. Hayano², M. Iwasaki¹, P. Kienle³, H. Outa¹, and K. Suzuki³

¹ Advanced Meson Science Laboratory, RIKEN, 2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan
² Department of Physics, University of Tokyo, 7-3-1 Hongo, Tokyo 113-0033, Japan
³ Physik-Department, Technische Universität München, D-85748 Garching, Germany

A recent technical break-through of pionic atom spectroscopy has been yielding precious information on the pion—nucleus strong interaction [1], and stimulates theoretical investigations on the origin of hadron mass in the viewpoint of the restoration of the Chiral symmetry in nuclei [2].

Experimentally, the precision spectroscopy of deeply bound pionic atoms is one of the most important achievements, and we have employed recoil-free \((d, ^3\text{He})\) nuclear reactions to form the pionic atoms and performed precision spectroscopy. The precision of the measured binding energies and widths for the pionic 1s tin (Sn 115∼123) isotopes go down to \(\sim 20\) keV and 80 keV, respectively.

Presently, the method is well established and this field of spectroscopy is approaching the next steps: we have two directions. One is to perform systematic measurement covering wide range of pionic atoms with highest possible resolution. Another is to explore possibility of making spectroscopy on the pionic atoms with unstable nuclei, which still requires basic instrumental studies.

What we need to focus in the near future is the former, the systematics study of pionic atoms with wide range of nuclei. This requires many indispensable properties in the experimental facility. For instance, the accelerator is expected to provide 250 MeV/nucleon deuteron beam with higher intensity than \(1 \times 10^{12}/\text{sec}\). This is because ... the formation cross section of the pionic atom in the nuclear reaction is not larger than several tens of micro barn per steradian. Since target thickness is one of the largest factor to determine the experimental resolution, there is no way to choose thick target...

After examining the possibility of performing the systematic study on the accelerator facilities in the world, we came to conclude that the newly-built facility in RIKEN, RI beam factory (RIBF), is most suited for this purpose. The facility has an accelerator complex to provide very high quality deuteron and heavy ion beams with sufficiently high intensity and high duty factor. The projectile fragment separator, BigRIPS will provide an excellent performance as a spectrometer with its flexible optical settings. The first beam is scheduled in the year 2007. We will just start the practical preparation for the experiment now. Any contributions are welcomed.

References

[1] K. Suzuki et al. Phys. Rev. Lett. 92 (2004) 072302 and references therein.

[2] W. Weise et al. Prog. Theor. Phys. Suppl. 149 (2003) 1.
Low-energy $\bar{K}N$ interactions

B. Borasoy

Universität Bonn, Nußallee 14-16, 53115 Bonn, Germany

The low-energy $\bar{K}N$ system is of special interest as a testing ground for chiral SU(3) symmetry in QCD and, in particular, for the role of explicit symmetry breaking induced by the relatively large mass of the strange quark. Most significantly, the existence of the $\Lambda(1405)$ resonance just 25 MeV below the $K^-p$ threshold makes chiral perturbation theory inapplicable in this channel. Non-perturbative coupled-channel techniques based on driving terms of the chiral SU(3) effective Lagrangian have proved useful and successful in dealing with this problem, by generating the $\Lambda(1405)$ dynamically as an $I = 0 \bar{K}N$ quasibound state and as a resonance in the $\pi\Sigma$ channel. High-precision $K^-p$ threshold data set important constraints for such theoretical approaches.

In several studies [1,2,3,4] we have investigated the $K^-p$ system within different variants of chiral unitary approaches. Based on a very large variety of different fits to data we can provide an error range for the strong $K^-p$ scattering length which is related to the strong interaction shift and width in kaonic hydrogen. We obtain an energy shift and width in kaonic hydrogen which is in agreement with the KEK experiment, but disagrees with DEAR. Our analyses point on questions of consistency of the recent DEAR measurement with previous $K^-p$ scattering data. The conservative error range for $a_{K^-p}$ derived from chiral unitary approaches is in clear disagreement with the one deduced from the DEAR experiment.

The upcoming measurement at SIDDHARTA@DAΦNE aiming for a precision at the level of a few electron volts in the shift and width of kaonic hydrogen will further clarify the situation. Our investigations are also of considerable interest in the discussion of possible deeply bound $K^-$-nuclear states.

References

[1] B. Borasoy, R. Nißler and W. Weise, Phys. Rev. Lett. 94 (2005) 213401 \texttt{arXiv:hep-ph/0410305}.

[2] B. Borasoy, R. Nißler and W. Weise, Eur. Phys. J. A 25 (2005) 79 \texttt{arXiv:hep-ph/0505239}.

[3] B. Borasoy, R. Nißler and W. Weise, Phys. Rev. Lett. 96 (2006) 199201 \texttt{arXiv:hep-ph/0512279}.

[4] B. Borasoy, U.-G. Meißner and R. Nißler, \texttt{arXiv:hep-ph/0606108}.
About the Strangeness $-1$ S-wave Meson-Baryon Scattering

José A. Oller

Departamento de Física, Universidad de Murcia, E-30071 Murcia, Spain

We consider meson-baryon interactions in S-wave with strangeness $-1$. This is a non-perturbative sector populated by plenty of resonances interacting in several two-body coupled channels. We study this sector combining a large set of experimental data. The recent experiments from the Crystal Ball Collaboration are remarkably accurate demanding a sound theoretical description to account for all the data. We employ unitary chiral perturbation theory to accomplish this aim \cite{1,2}. The approach is employed up to and including $\mathcal{O}(p^2)$ baryon CHPT amplitudes which are then used as interaction kernels in a general expression that resums the right hand or unitarity cut, making use of unitarity plus analyticity. We find two types of solutions that agree well with scattering data. However, while one of these solutions, the so called solutions A, agree well with the accurate measurement by the DEAR Collaboration of the width and shift of the energy of the fundamental state of kaonic hydrogen this is not the case with other solutions, the so called solutions B. The spectroscopy of our solutions is studied in detail in ref.\cite{2}, discussing the rise from the pole content of the two $\Lambda(1405)$ resonances, $\Lambda(1670)$, $\Lambda(1800)$, $\Sigma(1440)$, $\Sigma(1620)$ and $\Sigma(1750)$ for the solutions of type A. Notice that all these resonances are the ones appearing in the PDG from $\pi\Sigma$ threshold up to 1.8 GeV, with the quantum numbers we are considering. However, B type solution is only able to generate the two $\Lambda(1405)$, $\Lambda(1670)$ and $\Sigma(1440)$ resonances. We also argue about the fact that there are two $I=1$ poles before and above the $\bar{K}N$ threshold that finally give rise to bumps in the physical amplitudes with an effective width of around 20-25 MeV, although the imaginary part of their poles positions are smaller than the half of this width. Since they appear consecutively before and above threshold this is why the resulting width is significantly larger. We also show that the $\Sigma^+\pi^-$ and $\Sigma^-\pi^+$ event distributions measured in ref.\cite{3} show different shapes, with a $\Lambda(1405)$ peak clearly displaced from one another, that can be naturally explained if one allows for $I=1$ resonances around the $\bar{K}N$ threshold. We also consider other parametrizations with a constant term for the $I=1$ amplitude for $\pm100$ MeV around the $\bar{K}N$ threshold and the reproduction of these data is much worse. This is considered as an evidence for the presence of the $I=1$ poles at these energies. Since the solutions of type A offers a very good agreement with scattering, kaonic hydrogen and spectroscopy present data, including DEAR measurement, we prefer them over the solutions of type B, which do not agree with DEAR and do not give rise to so many resonances.

References

[1] J. A. Oller, J. Prades and M. Verbeni, Phys. Rev. Lett. 95, 172502 (2005); Phys. Rev. Lett. 96 (2006) 199202.

[2] J. A. Oller, Eur. Phys. J. A28 (2006) 63.

[3] R.J. Hemmingway, Nucl. Phys. B253 (1985) 742.
Chiral unitary approach to $K^-p$ scattering

R. Nißler

HISKP (Theorie), Universität Bonn, Nussallee 14-16, 53115 Bonn, Germany

Chiral unitary approaches combine Chiral Perturbation Theory, the low-energy effective field theory of QCD, with non-perturbative methods based on unitarity of the $S$-matrix and have been very successful in describing meson-meson and meson-baryon processes at low energies—in particular in the vicinity of resonances. However, in most such calculations found in the literature an examination of theoretical errors has not been undertaken. Based on previous work [1,2,3] we provide a thorough investigation of theoretical uncertainties within the framework of chiral unitary approaches for $K^-p$ scattering [4].

One main source of theoretical errors is related to different choices of input from the chiral Lagrangian, e.g., some authors prefer to work with the leading order chiral Lagrangian while others also take next-to-leading order terms into account. In order to estimate the pertinent uncertainty, we compare the results obtained with three different interaction kernels derived from the leading- and next-to-leading order Lagrangian.

The unknown parameters of the approach are constrained by performing a least-squares fit to $\bar{K}N$ scattering data. Making use of Monte-Carlo methods we have performed an extremely large number of fits and estimated the statistical errors which result from the fitting procedure. We can thus provide $1\sigma$ confidence regions for our theoretical results.

Furthermore, we have critically investigated the pole structure of the fits, in particular the isospin zero poles in the energy region of the $\Lambda(1405)$ resonance. We have also illustrated that the general pole structure of a fit can serve as a criterion to consider the fit as unphysical. In this respect, the upcoming $\Lambda(1405)$ electroproduction experiment at the ELSA accelerator in Bonn may help to further clarify the pole structure of the $K^-p$ scattering amplitude below threshold.

References

[1] B. Borasoy, R. Nißler and W. Weise, Phys. Rev. Lett. 94 (2005) 213401 arXiv:hep-ph/0410305.

[2] B. Borasoy, R. Nißler and W. Weise, Eur. Phys. J. A 25 (2005) 79 arXiv:hep-ph/0505239.

[3] B. Borasoy, R. Nißler and W. Weise, Phys. Rev. Lett. 96 (2006) 199201 arXiv:hep-ph/0512279.

[4] B. Borasoy, U.-G. Meißner and R. Nißler, arXiv:hep-ph/0606108.
Kaonic Hydrogen Experiments

J. Marton for the DEAR/SIDDHARTA Collaborations

Stefan Meyer Institut für subatomare Physik, Österreichische Akademie der Wissenschaften, Boltzmangasse 3, A-1090, Wien, Österreich

Research on kaonic atoms using X-ray spectroscopy is conducted by the DEAR/SIDDHARTA Collaborations at LNF-INFN, Frascati, Italy. The kaonic hydrogen atom represents the simplest hadronic atom with strangeness. The strong interaction kaon-proton leads to the energy shift $\epsilon_{1s}$ and width $\Gamma_{1s}$ of the $1s$ state. After the KEK experiment [1] identified the repulsive-type character of the $K^{-}p$ interaction, the DEAR experiment verified this finding but found smaller values for $\epsilon_{1s}$ and $\Gamma_{1s}$ with higher precision [2]. These results stimulated new theoretical work [3]. The future of such type of measurements is related to the development of new large area X-ray silicon drift detectors (SDDs), conducted by the SIDDHARTA Collaboration. SDDs will provide the application of the time correlation between the emitted charged kaon pair in DAFNE (where the measurement will be performed) and the kaonic hydrogen X-ray detection. In comparison with DEAR, the signal-to-background ratio will be improved by 2-3 orders of magnitude. A precision for kaonic hydrogen $\epsilon_{1s}$ and $\Gamma_{1s}$ at the percent level is anticipated (see fig.1). Moreover, for the first time the X-ray spectrum of kaonic deuterium will be measured.

Figure 1: Experimental values for the kaonic hydrogen strong interaction shift and width. The anticipated precision using SDDs is seen as small rectangular area.

References

[1] M. Iwasaki et al., Phys. Rev. Lett. 78 (1997) 3067; T.M. Ito et al., Phys. Rev. C58 (1998) 2366.
[2] G. Beer et al., Phys. Rev. Lett. 94 (2005) 212302.
[3] B. Borasoy, R. Nißler and W. Weise, Phys. Rev. Lett. 94 (2005) 213401; J.A. Oller, J. Prades and M. Verbeni, Phys. Rev. Lett. 95 (2005) 172502; A.N. Ivanov et al., Eur. Phys. J. A21 (2004) 11; U.-G. Meißner, U. Raha, and A. Rusetsky, Eur. Phys. J. C 35 (2004) 349, hep-ph/0402261.

Work supported by EU within I3-HadronPhysics and TARI-INFN, Contract No. RI3-CT-2004-506078.
Measurement of the $\pi^+\pi^-$ atom lifetime at DIRAC

V. Yazkov\(^1\) on behalf of DIRAC Collaboration

\(^1\)Skobeltsyn Institute of Nuclear Physics of Moscow State University, 1 - 2, Leninskie Gory, GSP-2, Moscow, 119992, Russia

Pionium or $A_{2\pi}$ is a hydrogen-like atom consisting of $\pi^+$ and $\pi^-$ mesons. The goal of the DIRAC experiment at CERN (PS212) is to measure the pionium lifetime with 10% precision. Such a measurement would yield a precision of 5% on the value of the $S$-wave $\pi\pi$ scattering lengths combination $|a_0 - a_2|$ which is predicted to be $a_0 - a_2 = 0.265 \pm 0.004$. Corresponded $A_{2\pi}$ lifetime is $\tau = (2.9 \pm 0.1) \times 10^{-15}$ s \(^2\).

The $A_{2\pi}$ are produced by Coulomb interaction in the final state of $\pi^+\pi^-$ pairs generated in proton–target interactions \(^3\). Some of them are broken up due to their interaction with matter of a target producing “atomic pairs”, characterized by small pair c.m. relative momenta $Q < 3$ MeV/c. Other atoms annihilate into $\pi^0\pi^0$. The amount of broken up atoms $n_A$ depends on the lifetime which defines the decay rate.

Also $\pi^+\pi^-$ pairs are generated in free state. Essential fraction of such pairs (“Coulomb pairs”) are affected by Coulomb interaction. Number of generated atoms ($N_A$) is proportional to a number of “Coulomb pairs” ($N_A = K \cdot N_C$). The coefficient $K$ is precisely calculable. The dependence of breakup probability $P_{br}(\tau) = n_A/N_A = n_A/(K \cdot N_C)$ on the lifetime $\tau$ is determined by the solution of differential transport equations \(^4\).

The DIRAC experiment uses a magnetic double-arm spectrometer at the CERN 24 GeV/c extracted proton beam T8 \(^5\). The data used for this work were taken in 2001 with Ni target ($\sim 42\%$ of data). The number of “atomic pairs” $n_A = 6530 \pm 294$ is obtained as an excess of experimental distribution above the approximated distribution of “free pairs” only in the region $Q < 4$ MeV/c. It provides break up probability $P_{br} = 0.452 \pm 0.023^{\text{stat}} +0.009_{-0.032}^{\text{syst}} = 0.452^{+0.025}_{-0.039}$.

Taking into account the dependence of breakup probability on lifetime \(^4\) a first result on the pionium lifetime is \(^6\):

$$\tau_{1S} = \left[2.91^{+0.19}_{-0.38}\right]^{+0.045}_{-0.033} \times 10^{-15} \text{ s} = \left[2.91^{+0.49}_{-0.62}\right] \times 10^{-15} \text{ s}.$$ (1)

This lifetime corresponds to $|a_0 - a_2| = 0.264^{+0.033}_{-0.020} m_\pi^{-1}$.

References

[1] G. Colangelo, J. Gasser and H. Leutwyler, Nucl. Phys. B603 (2001) 125.
[2] J. Gasser, V. E. Lyubovitskij, A. Rusetsky and A. Gall, Phys. Rev. D 64 (2001) 016008.
[3] L. Nemenov, Sov. J. Nucl. Phys. 41, 629 (1985).
[4] L. Afanasyev and A. Tarasov, Phys. At. Nucl. 59, 2130 (1996).
[5] B. Adeva et al., Nucl.Instr.Meth. A515 (2003) 467.
[6] B. Adeva et al., Physics Letters B 619 (2005) 50
\textbf{KN Scattering Lengths From Kaonic Deuteron}

Ulf-G. Mei\ss{}ner\textsuperscript{1,2}, Udit Raha\textsuperscript{1} and Akaki Rusetsky\textsuperscript{1,3}

\textsuperscript{1}HISKP (Theorie), Universität Bonn, Nussallee 14-16, 53115 Bonn, Germany
\textsuperscript{2}Forschungszentrum Jülich, Institut für Kernphysik (Theorie), D-52425 Jülich, Germany
\textsuperscript{3}On leave of absence from: High Energy Physics Institute, Tbilisi State University, 0186 Tbilisi, Georgia

My talk deals with the extraction of the $S$-wave $\bar{K}N$ scattering lengths from a combined analysis of experimental data on kaonic hydrogen and kaonic deuterium which is important in the context of the recently proposed SIDDHARTA collaboration experiment at Frascati. While still awaiting the first results from the SIDDHARTA collaboration, we present a systematic study of the near-threshold kaon-deuteron scattering within the framework of low-energy effective field theory, using the existing DEAR or KEK data for kaonic hydrogen and “synthetic” experimental data for kaonic deuterium. In our analysis, we consider the partial re-summation of the multiple scattering series for the $K^-d$ scattering in the Fixed Center Approximation Limit. In this limit, we show that the isospin breaking effects in the $Kd$ system are small, in-spite of the large unitary cusp corrections in the the $\bar{K}N$ system. What is more interesting is that with the present DEAR central values of the width and energy shift of the kaonic hydrogen ground-state, very stringent constraints have to be imposed on the input $Kd$ scattering length in order to ensure that the physical solutions for the $\bar{K}N$ scattering lengths $a_0$, $a_1$ exist. In case of the KEK data such constraints turn out to be much milder.

The main results of the talk are contained in Refs. [1].

\textbf{References}

[1] Kaon-nucleon scattering lengths from kaonic deuterium experiments
U.-G. Mei\ss{}ner, U. Raha and A. Rusetsky
[arXiv: nucl-th/0603029].
(accepted for publication in EPJC)
How accurate are the pionium breakup calculations?

D. Trautmann\textsuperscript{1}, T. Heim\textsuperscript{1}, K. Hencken\textsuperscript{1}, and G. Baur\textsuperscript{2}

\textsuperscript{1}Institut für Physik, Universität Basel, Klingelbergstr. 82, 4056 Basel, Switzerland
\textsuperscript{2}Institut für Kernphysik, Forschungszentrum Jülich, 52425 Jülich, Germany

Our group provides very precise calculations of electromagnetic excitation and ionization cross sections for pionium as required for the analysis of the experiment DIRAC. In order to achieve the required accuracy of 1\% for the electromagnetic cross sections we have to employ sophisticated atomic scattering models taking into account even minor effects of the interaction of pionium atoms with the target material.

Our calculations incorporate a fully quantum mechanical treatment of the electromagnetic transitions in pionium\textsuperscript{1}: target-elastic (coherent) as well as incoherent (target-inelastic) scattering processes within the framework of Dirac-Hartree-Fock theory\textsuperscript{2}; the explicit determination of magnetic and relativistic terms in the pionium–atom interaction\textsuperscript{3}. Our calculated momentum distributions for the pions from breakup of pionium\textsuperscript{4} help to reduce the background in the analysis of the experimental data. Higher order contributions and multi-photon exchange have been calculated in the Glauber approximation\textsuperscript{5}. Proceeding from the elementary interaction between pionium and a single target atom, we have studied the propagation of the pionium atom as it moves through the target material with a Monte Carlo approach\textsuperscript{6}. The distribution of different states, as well as the probability of ionization vs. excitation are of crucial importance for the analysis of DIRAC. Since a description in terms of transition probabilities (rather than propagating the amplitudes) is not fully justified, we have studied the influence of degenerate states within an ‘optimal mixture’ approach\textsuperscript{7}. The difference within the Monte Carlo simulation was found to be of the order of 0.5\%.

While our calculations are consistently accurate within our own model to better than 1\%, we have to allow for the possibility that the target atomic structure functions (form factors and scattering functions) may present a more serious limitation of the overall accuracy than previously estimated. Comparisons of cross section calculations with various atomic form factor models, including other state-of-the-art calculations\textsuperscript{8,9} reveal a seemingly systematic shift in the results obtained. A direct comparison of these calculations is, however, hampered by several circumstances. For one, the tables of factors found in the literature have been prepared with the purpose of ‘conventional’ atomic scattering in mind. Therefore, these tables concentrate on maximum accuracy and reliability in a range of momentum transfer that is comparatively small for our setting with pionium instead of normal atomic scattering. The dominating momentum scale relevant for pionium scattering is typically 136 times larger than that for conventional atomic scattering. At these high momentum transfers, the existing tables have a less dense grid of points. Our own calculations of the form factors, on the other hand, put maximum emphasis on this region of greatest importance for us. In addition, we note that complex atomic scattering processes are routinely calculable only with a limited accuracy, as discussed e.g. in\textsuperscript{10}. 

References

[1] Z. Halabuka, T. Heim, K. Hencken, D. Trautmann and R. Viollier, Nucl.Phys. B554 (1999) 86.

[2] T. Heim, K. Hencken, D. Trautmann and G. Baur, J. Phys. B33 (2000) 3583.

[3] T. Heim, K. Hencken, D. Trautmann and G. Baur, J. Phys. B34 (2001) 3763.

[4] T. Heim, K. Hencken, M. Schumann, D. Trautmann and G. Baur, Proc. of HadAtom02 (2002) hep-ph/0301266

[5] M. Schumann, T. Heim, K. Hencken, D. Trautmann and G. Baur, J. Phys. B 35 (2002) 2683.

[6] C. Santamarina, M. Schumann, L. G. Afanasyev and T. Heim, J. Phys. B 36 (2003) 4273.

[7] K. Hencken et al., Proc. of HadAtom03 (2003) hep-ph/0401204

[8] Hubbell et al. J. Phys. Chem. Ref. Data 4 (1975) 471.

[9] Hubbell et al. J. Phys. Chem. Ref. Data 8 (1979) 69.

[10] Chantler, J. Phys. Chem. Ref. Data 29 (2000) 597.
Analytic theory for hadronic atoms beyond the Deser approximation

A. Kudryavtsev
ITEP, Bolshaya Cheremushkinskaya 25, 117258, Moscow, Russia

The size of lightest hadronic atoms is determined by the Bohr radius $a_B$. This size is much larger than the range of strong interaction $r_0$, $r_0 \ll a_B$. The spectrum of atom is given by the set $\{E_{nl}\}$, where $E_{nl} = E_{nl}^{\text{Coul}} + \Delta E_{nl}^{\text{st}}$, $E_{nl}^{\text{Coul}} = -E^C/2n^2$ with $E^C = me^4/\hbar^2$. Here $\Delta E_{nl}^{\text{st}}$ is the hadronic shift. Usually $\Delta E_{nl}^{\text{st}}$ is very small and the Deser approximate equation is valid:

$$\frac{\Delta E_{nl}^{\text{st}}}{E^C} = \frac{2a^s}{a_Bn^3} \quad (l = 0) \quad (1)$$

This equation works well in the case of the small values of the scattering length $a^s \ll a_B$. However in the case of the strong attractive potential the scattering length $a^s$ may become large. In this case the phenomenon of rearrangement of atomic spectrum takes place [1]. The equation which describes the spectrum for arbitrary values of scattering length was obtained in ref. [2]. In the units $\hbar = e = m = 1$ it could be written as

$$2[\psi(1 - 1/\lambda) + \lambda/2 + \ln \lambda] = \frac{1}{a^{cs}} + \frac{1}{2} r^{cs} \lambda^2 \quad (2)$$

Here $\psi(z) = \Gamma'(z)/\Gamma(z)$ and $E = -\lambda^2/2$.

Solving this algebraic equation one may express the energies of atomic levels and the energy of a loosely bound nuclear level in terms of the Coulomb-modified scattering length $a^{cs}$ and the effective range $r^{cs}$. In the limit of small values for $a^{cs}$ the equation (2) reproduces the Deser equation (1) plus small corrections. The leading correction to the Deser’s formula corresponds to the substitution $a^s \Rightarrow a^{cs}$ in the equation (1). The relation between $a^{cs}$ and $a^s$ contains large logarithm ($\sim \ln(a_B/r_0)$). It is discussed in the Handbook ”Collision Theory” by M.Goldberger and K.Watson, see also refs. (23).

References

[1] A. Kudryavtsev, V. Markushin, and I. Shapiro ZhETP 74 (1978) 432.

[2] V. Popov et al., Sov.Physics JETP 53 (1981) 650.

[3] V. Mur, A. Kudryavtsev and V. Popov. Sov. J. Nucl. Phys. 37 (1983) 844.
Corrections to scattering lengths from hadronic atoms

T. E. O. Ericson¹, A. N. Ivanov², B. Loiseau³ and S. Wycech⁴

¹ Theory Division, CERN, CH-1211 Geneva 23, Switzerland
² Atomic Institute of the Austrian Universities, A-1040 Wien, Austria
³ LPNHE, Univ. P. & M. Curie, 4 Pl. Jussieu, F-75252 Paris, France
⁴ Soltan Institute for Nuclear Studies, PL-00681 Warszawa, Poland

The high precision reached in the determination of the strong interaction energy shift and width in the \(\pi^-p\) atom (0.2%) raises the question to which extent the Deser-Trueman relation \(\epsilon_{1s} \propto a_{l=0}\) gives an accurate determination of the hadronic scattering length as well as question of the nature of the corrections [1,2]. This relation is exact to order \(\alpha^2\) in terms of the ”Coulomb scattering length”. Our previous results are now generalized and extended. We show that on general grounds for any hadronic atom there are 2 classes of corrections to order \(\alpha^2\) in the scattering length: the coherent ones with the system remaining in its ground state and intrinsic corrections associated with the virtual excitation of the system. The coherent contributions describe the effect of the external Coulomb field (“Z\(\alpha\)” with extended charges, i.e., the kinematical effect of the depth of the Coulomb potential near the origin as well as the correct initial and final wave function near the origin. The virtual excitations, on the other hand, gives rise to genuine isospin breaking and they contribute also in the absence of Coulomb scattering. In the single hadronic channel channel case the coherent corrections are in the limit of zero-range interactions:

1. The wave function change at the origin for an extended charge \(-ma\langle r\rangle_{em} a_0\).
2. The change of scattering energy from the threshold value to kinetic energy corresponding to the Coulomb potential at the origin for the extended charges such that the threshold expansion gives non-relativistically.
3. A cusp correction which is very insensitive to the detailed charge distribution; it corresponds to a final state wave function consistent with the physical scattering length.

We show that the zero-range approximation is accurate for s-waves with small additional corrections for the finite interaction range, while the corresponding result for higher waves depends on the detailed interplay of the interaction and charge range.

For the \(\pi^-p\) atom, however, the largest e.m. correction is due to the dispersive effect of \(\pi^-p \rightarrow \gamma X\) processes, dominated by \(X = N, \Delta\) with an important contribution from the latter. A comparison to the results of effective ChPT [3] gives both an interpretation of the physics of the chiral constants and their approximate value. The results have obvious implications for isospin violation in \(\pi N\) scattering at threshold.

References

[1] T. E. O. Ericson, B. Loiseau and S. Wycech Phys. Lett. B 594 (2004) 76
[2] T. E. O. Ericson and A. Ivanov Phys. Lett. B 634 (2006) 39
[3] J. Gasser, et al., Eur. Phys. J. C26 (2002) 13.
**Kaonic atoms as a starting point for antikaon nuclear physics**

E. Friedman

The Racah Institute of physics, the Hebrew University, Jerusalem, Israel

Recent experimental evidence on candidates for $\bar{K}$-nuclear deeply bound states in the range of binding energy $B_{\bar{K}} \sim 100 - 200$ MeV again highlighted the open question of how attractive the $\bar{K}$-nucleus interaction is below the $\bar{K}N$ threshold, a topic which was discussed over a decade ago [1]. The best source of information on the antikaon-nucleus potential at threshold are strong interaction effects in kaonic atoms. These, however, are sensitive to the surface region of the nucleus and the continuation of the potential into the nuclear interior is an open question: whereas chirally-motivated potentials [2] lead to ‘shallow’ real potentials of about 55 MeV deep, various phenomenological approaches lead to 180 MeV deep potentials and to **significantly better** fits to data. The systematics of the kaon-nucleus potential is discussed, particularly in connection with the very recent calculations of $\bar{K}$ nuclear bound states within a dynamical model [3]. Figure 1 shows the phenomenological antikaon-nucleon interaction density-dependence when moving from the interior towards 50% and 10% of the central density (marked with vertical dotted lines).

![Figure 1: Density-dependence of the antikaon-nucleon interaction.](image)

This work was supported in part by the Israel Science Foundation grant 757/05.

**References**

[1] C.J. Batty, E. Friedman, A. Gal, Phys. Rep. **287** (1997) 385 and references therein.

[2] A. Cieplý, E. Friedman, A. Gal, J. Mareš, Nucl. Phys. A **696** (2001) 173.

[3] J. Mareš, E. Friedman and A. Gal, Nucl. Phys. A **770**, (2006) 84.
Determination of the Antiproton-to-Electron Mass Ratio by Precision Laser Spectroscopy of $\bar{\text{p}}\text{He}^+$

R.S. Hayano (CERN ASACUSA collaboration)

Department of Physics, University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan

A femtosecond optical frequency comb and continuous-wave pulse-amplified laser were used to measure twelve transition frequencies of antiprotonic helium (metastable three-body system consisting of an antiproton, an electron and a helium nucleus)\cite{1} to fractional precisions of $(9 - 16) \times 10^{-9}\cite{2}$. One of these is between two states having microsecond-scale lifetimes hitherto unaccessible to our precision laser spectroscopy method. Comparisons with three-body QED calculations yielded an antiproton-to-electron mass ratio of $M_{\bar{p}}/m_e = 1836.152674(5)$. This also corresponds to a new limit of 2 parts per billion on any possible difference between the antiproton and proton masses and charges.

![Figure 1](image-url)

**Figure 1:** (a) Frequency of $\bar{\text{p}}^4\text{He}^+$ transition $(37, 35) \rightarrow (38, 34)$ measured in this and previous\cite{3,4} experiments, (b) proton-to-electron\cite{5,6} and antiproton-to-electron mass ratios.

**References**

1. T. Yamazaki et al., Phys. Rep. 366 (2002) 183.
2. M. Hori et al., Phys. Rev. Lett. 96 (2006) 243401.
3. M. Hori et al., Phys. Rev. Lett. 91 (2003) 123401.
4. M. Hori et al., Phys. Rev. Lett. 87 (2001) 093401.
5. P.J. Mohr and B.N. Taylor, Rev. Mod. Phys. 72 (2000) 351.
6. P.J. Mohr and B.N. Taylor, Rev. Mod. Phys. 77 (2005) 1.
Light Antiprotonic Atoms

D. Gotta

Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany

The measurement of the characteristic X–radiation emitted from antiprotonic atoms constitutes an antinucleon–nucleus scattering experiment at relative energy zero. The strong interaction manifests in an energy shift and broadening of the low–lying atomic states, which are directly related to the complex antiproton–nucleus scattering length being sensitive to the medium- and long range part of the antinucleon–nucleus interaction. The hydrogen isotopes allow access to the elementary systems $\bar{p}p$ and $\bar{p}n$. Light nuclei serve as a testing ground to build up a consistent picture of the interaction with nuclei [1].

In $\bar{p}H$ the resolution of hyperfine states, which is equivalent to a double polarisation experiment at threshold, became already possible during the LEAR era [2,3]. However, the low precision – mainly due to statistics – hinders a sensitive test of the various theoretical approaches. The experimental information on the antiproton-deuteron s–wave interaction urgently needs confirmation from a new measurement [4] and the accuracy of the measurements of the helium isotopes is modest [5].

For precision studies high statistics is essential. In order to achieve sufficiently large X–ray yields antiprotonic hydrogen and helium must be formed in dilute gases to reduce the influence of non-radiative de–excitation processes owing to collisions. Therefore, gas targets with thin entrance and exit windows must be used. Antiproton beams of 100–300 keV are well suited as planned for the low–energy antiproton facility FLAIR at GSI [6]. Combining an antiproton plasma inside a trap with a gas jet might be considered in context with the improving performance of such devices.

The low–lying X-ray transitions of hydrogen and helium isotopes are in the energy range 2–15 keV. For hydrogen, the hadronic effects are of the order of 1 keV and 10–500 meV for the s–wave and p–wave interaction, respectively. Consequently, the measurement requires two different approaches: a direct measurement with semiconductor detectors, e.g., fast CCDs and ultimate resolution by using a Bragg crystal spectrometer. Whereas CCDs allow an efficient reduction of the annihilation induced background by the analysis of the hit pattern, a Bragg spectrometer is self collimating due to the small angular acceptance.

References

[1] D. Gotta, Prog. Part. Nucl. Phys. 52 (2004) 133, and ref. therein.
[2] M. Augsburger et al., Nucl. Phys. A 658 (1999) 149.
[3] D. Gotta et al., Nucl. Phys. A 660 (1999) 283.
[4] M. Augsburger et al., Phys. Lett. B 461 (1999) 417.
[5] M. Schneider et al., Z. Phys. A 338 (1991) 217.
[6] http://www.oeaw.ac.at/smi/flair/
Looking for “smoking gun” signatures of CPT Violation

Nick E. Mavromatos,
King’s College London, Department of Physics, Strand, London WC2R 2LS, U.K.

Due to the weakness of the gravitational interaction, one may think that prospects of testing quantum aspects of gravity in the foreseeable future are futile. In this talk I argue that this may not be the case. First, I will present arguments, coming from several theoretical approaches to quantum gravity, according to which experimental falsification of models within the current or immediate future facilities may have realistic prospects of success. One of the most profound aspects of, at least some, models of quantum gravity is CPT violation (CPTV) “in vacuo”: the latter could either occur through spontaneous Lorentz violation or through quantum decoherence of matter propagating in a “foamy space-time” vacuum of quantum gravity [1]. In the latter case CPT is intrinsically violated due to the ill-defined nature of the CPT operator. In the talk I review first some tests associated with quantum fluctuations of the space-time metric in some models of quantum gravity, which lead to the so-called light cone fluctuations [2], or, equivalently, to violations of Lorentz symmetry in individual measurements but possibly not on average. Then I proceed to discuss some, arguably unique, possible signatures of decoherence-induced CPTV in entangled particle states [3], such as neutral mesons in meson factories. The effects of quantum gravity CPTV in that case (termed ω-effect) amount to a modification of the pertinent Einstein-Podolsky-Rosen (EPR) correlations among the neutral mesons produced on each side of the detector. They are associated with (direction dependent) interaction terms in the part of the meson Hamiltonian expressing entanglement with the foam. These result in modifications of the mass eigenstates by the medium of quantum gravity. The effects can be (in principle) disentangled experimentally from other possible non-unitary effects of the foam generated through the evolution of the system in the quantum-gravity medium. I also present theoretical models of the generation of the ω-effect, which indicate an order of magnitude not far from the experimental sensitivity expected to be attained at future upgrades of φ-factories such as DAΦNE.

References

[1] For a concise review see: N. E. Mavromatos, Lect. Notes Phys. 669 (2005) 245. and references therein.

[2] L. H. Ford, Phys. Rev. D 51 (1995) 1692. H. w. Yu and L. H. Ford, Phys. Lett. B 496 (2000) 107;[arXiv:gr-qc/0004063] J. R. Ellis, N. E. Mavromatos and D. V. Nanopoulos, Gen. Rel. Grav. 32 (2000) 127.

[3] J. Bernabéu, N. E. Mavromatos and J. Papavassiliou, Phys. Rev. Lett. 92 (2004) 131601. N. E. Mavromatos, J. Papavassiliou and A. Waldron-Lauda, Nucl. Phys. B 744, 180 (2006). J. Bernabéu, N. E. Mavromatos and Sarben Sarkar,[arXiv:hep-ph/0606137]
Lorentz and CPT tests with antimatter

Ralf Lehnert

Center for Theoretical Physics
Massachusetts Institute of Technology, Cambridge, MA 02139, U.S.A.

One of the most engaging scientific endeavors is the search for physics underlying the Standard Model (SM) and general relativity (GR). Substantial theoretical efforts have been devoted to this undertaking. Experimental work, on the other hand, is extraordinarily challenging in this context due to the expected Planck suppression of the associated observational signatures. However, minute Lorentz/CPT violations have recently been identified as promising quantum-gravity signals: they are amenable to ultrahigh-precision tests, and they are predicted by various candidate underlying theories including strings, spacetime foam, loop gravity, non-commutative geometry, varying couplings, and braneworld scenarios.

Low-energy signatures of Lorentz/CPT violation are described by an effective field theory called the Standard-Model Extension (SME). This framework incorporates the entire body of established physics (i.e., the SM and GR). It also includes all Lorentz-/CPT-violating corrections compatible with key principles of physics. To date, the SME has provided the basis for numerous studies of Lorentz/CPT breaking involving protons, neutrons, electrons, muons, and photons. Discovery potential exists in neutrino physics.

A particularly promising class of Planck-scale CPT tests are matter–antimatter comparisons. Note that if conventional unitary quantum mechanics remains valid, CPT violation implies Lorentz breakdown. The SME exemplifies this rigorous result and therefore predicts sidereal variations as a general observable feature of CPT breaking. (For a model without conventional unitary quantum mechanics, see N. Mavromatos' talk.)

At present, various experimental efforts (ALPHA, ASACUSA, ATRAP) are underway to trap cold antihydrogen; the goal is to perform hydrogen–antihydrogen spectroscopy (see R. Hayano’s and B. Juhasz’ talks). The 2-photon 1S–2S transition has received considerable attention because an eventual resolution of one part in $10^{18}$ seems feasible. Each S state contains four levels; prior to excitation, the $\vec{B}$ field in the trap confines the two 1S low–field seekers $|c\rangle_1$ and $|d\rangle_1$. Two 2-photon 1S–2S transitions are allowed: one between the pure-spin levels $|d\rangle_{1,2}$ and one between the mixed-spin states $|c\rangle_{1,2}$. The leading-order SME predictions show that Lorentz/CPT violation only perturbs the $c$ transition, while the $d$ transition is left unaffected. Another SME study suggests an alternative $\text{H}^+\overline{\text{P}}$ comparison employing the 1S Zeeman transition: with a 1 mHz resolution, the competitive bound $|b^p_3| < 10^{-18}$ eV on the Lorentz-/CPT-breaking proton parameter $b^p_3$ could be achieved.

Other matter–antimatter Lorentz/CPT tests involve proton–antiproton comparisons with Penning traps. The SME predicts that the anomaly-frequency shifts are different for protons and antiprotons. An instantaneous comparison with a 2 Hz resolution would yield a $10^{-15}$ eV sensitivity to $b^p_5$. Another popular CPT test employs meson interferometry. Such measurements are performed at the KTeV, OPAL, FOCUS, DELPHI, BELLE, and BaBar experiments. Sensitivities of up to $10^{-12}$ eV to the SME quark parameters $\Delta a^\mu$ have been achieved.
Antihydrogen

R.S. Hayano

Department of Physics, University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan

Since motivations to look for CPT-violating effects have been thoroughly discussed by the previous two speakers\[1,2\], I will first discuss why we are interested in antihydrogen. High-precision spectroscopy of antihydrogen is one of the promising ways to test the CPT symmetry, since methods now exist to measure the $1s - 2s$ splitting\[3\] as well as the ground-state hyperfine splitting (GSHFS) of ordinary hydrogen to very high precision (to be discussed by the next speaker\[4\]).

“Cold” antihydrogen atoms were successfully produced at CERN’s antiproton decelerator (AD) by ATHENA\[5\] and ATRAP\[6\] collaborations; both groups used the “nested Penning trap” method, in which synchrotron-radiation-cooled positrons were mixed with electron-cooled antiprotons. ATHENA’s reported $\bar{H}$ production rate was about 300 Hz, when $10^4$ antiprotons were mixed with a positron plasma whose density was $\sim 10^8\text{cm}^{-3}\[7\].

However, this does not mean that antihydrogen atoms can be readily studied by high-precision laser spectroscopic methods. The prerequisites are i) atoms are in the ground state, and ii) atoms are cold (slow) enough so that they stay long enough in the laser beam. Although ordinary hydrogen atoms can be cooled with a cold finger\[3\], the method is clearly not applicable to antihydrogen atoms. Both ATRAP and ALPHA (successor to ATHENA) groups therefore plan to trap $\bar{H}$ atoms in a minimum-B magnetic trap, whose typical depth is about 1 K.

At present, there is no positive identification of $\bar{H}$ atoms in the $1s$ state; the fact that ATRAP used a field-ionization method to detect $\bar{H}$ atoms indicates that their detected $\bar{H}$s are highly excited\[6\]. Moreover the atoms seem to have much higher energies than the ambient trap temperature\[8\]. Thus, although antihydrogen-atom spectroscopy is a promising tool to probe ‘Planck-scale’ physics\[1,2\], there are still many hurdles to be cleared.

References

[1] N. Mavromatos, in these proceedings.

[2] R. Lehnert, in these proceedings.

[3] See, for example, M. Fischer et al., Lect. Notes Phys. 648 (2004) 209.

[4] B. Juhász, in these proceedings.

[5] M. Amoretti et al., Nature 419 (2002) 456.

[6] G. Gabrielse et al., Phys. Rev. Lett. 89 (2002) 213401.

[7] M. Amoretti et al., Phys. Lett. B 578 (2004) 23.

[8] G. Gabrielse et al. Phys. Rev. Lett. 89 (2002) 233401; N. Madsen et al., Phys. Rev. Lett. 94 (2005) 033403.
Measurement of the ground-state hyperfine structure of antihydrogen

B. Juhász\textsuperscript{1}, and E. Widmann\textsuperscript{1}

\textsuperscript{1}Stefan Meyer Institut für subatomare Physik, Boltzmanngasse 3, A-1090 Vienna, Austria

The hydrogen atom is one of the most extensively studied atomic systems, and its ground state hyperfine splitting (GS-HFS) of $\nu_{\text{HFS}} = 1.42$ GHz has been measured with an extremely high precision of $\delta \nu_{\text{HFS}}/\nu_{\text{HFS}} \sim 10^{-12}$. Therefore the antimatter counterpart of hydrogen, the antihydrogen atom, consisting of an antiproton and a positron, is an ideal laboratory for studying the CPT symmetry.

As a test of the CPT invariance, measuring $\nu_{\text{HFS}}$ of antihydrogen can surpass in accuracy a measurement of the 1S–2S transition frequency proposed by other groups. In fact, it has several advantages over a 1S–2S measurement. Firstly, it does not require the (neutral) antihydrogen atoms to be trapped. Secondly, the only existing consistent extension of the standard model, which is based on a microscopic theory of CPT and Lorentz violation \cite{1}, predicts that $\nu_{\text{HFS}}$ should be more sensitive to CPT violations. In addition, the parameters introduced by Kostelecky et al. have the dimension of energy (or frequency). Therefore, by measuring a relatively small quantity on an energy scale (like the 1.42 GHz GS-HFS splitting), a smaller relative accuracy is needed to reach the same absolute precision for a CPT test. This makes a determination of $\nu_{\text{HFS}}$ with a relative accuracy of $10^{-4}$ competitive to the measured relative mass difference of $K^0$ and $\bar{K}^0$ of $10^{-18}$, which is often quoted as the most precise CPT test so far.

The ASACUSA collaboration at CERN’s Antiproton Decelerator (AD) has recently submitted a proposal \cite{2} to measure $\nu_{\text{HFS}}$ of antihydrogen in an atomic beam apparatus similar to the ones which were used in the early days of hydrogen HFS spectroscopy. The apparatus consists of two sextupole magnets for the selection and analysis of the spin of the antihydrogen atoms, and a microwave cavity to flip the spin. This method has the advantage that antihydrogen atoms of temperatures up to 150 K, “evaporating” from a formation region, can be used. Numerical simulations show that such an experiment is feasible if $\sim 100$ antihydrogen atoms per second can be produced in the ground state, and that an accuracy of better than $10^{-6}$ can be reached within reasonable measuring times.

References

[1] R. Bluhm, V. A. Kostelecký, and N. Russell, Phys. Rev. Lett. \textbf{82} (1999) 2254.

[2] Proposal CERN-SPSC 2005-002, SPSC P-307 Add. 1, ASACUSA collaboration, 2005.
MUSASHI – An ultra-slow antiproton beam source –
Ultra-slow antiproton beam source and antiprotonic atom formation

N. Kuroda1, H.A. Torii2, M. Shibata1, H. Imao1, Y. Nagata2, Y. Enomoto2, Y. Kanai1,
A. Mohri1, K. Komaki2, and Y. Yamazaki1,2

1Atomic Physics Laboratory, RIKEN, 2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan
2Institute of Physics, University of Tokyo, 3-8-1 Komaba, Meguro-ku,
Tokyo 153-8902, Japan

The preparation of large numbers of antiprotons at low energy plays an important role to
synthesize antihydrogen (\(\bar{\text{p}}\text{e}^+\)) and antiprotonic atoms (\(\bar{\text{p}}\text{A}^+\)). Such exotic atoms can only
be efficiently synthesized at a few tens of eV or less. We, MUSASHI sub-group of ASACUSA
collaboration, developed an ultra-slow antiproton beam source, MUSASHI, Monoenergetic
Ultra-Slow Antiproton beam Source for High-Precision Investigation, with a sequential combi-
nation of the CERN Antiproton Decelerator (AD) and the radio-frequency quadrupole
decelerator (RFQD). With 10–1000 eV energy beam from MUSASHI, we will study initial
process of antiprotonic atom formation [1] and will make polarized antihydrogen atoms with
cusp trap [2] for antihydrogen hyperfine structure measurement [3].

The apparatus, MUSASHI, consists of two parts. One is an antiproton trapping section,
so called multiring electrode trap (MRT) housed in a 4 K bore tube of a 2.5 T superconduct-

ing solenoid in which antiprotons are captured and cooled to sub-eV energy after collisions
between simultaneously confined electrons. We succeeded in confining \(1.2 \times 10^6\) antiprotons
per AD shot [4], with \(3 \times 10^8\) electrons. The other part is an ultra-slow antiproton beam
transport line [5]. This beam line has a differential pumping capability for pressure difference
between \(10^{-12}\) Torr in the MRT and \(10^{-6}\) Torr in the target gas chamber for antiprotonic
atom formation. Extracted \(3 \times 10^5\) antiprotons with 250 eV energy as an ultra-slow beam
were transported to the beam line end.

In the year 2006, we will start our planned experiment, \(\bar{\text{p}}\text{A}^+\) formation cross section
measurement with MUSASHI and a supersonic gas jet target. At the same time, we installed
a new superconducting solenoid cooled by three refrigerators free of any liquid helium for
stable operation and increasing trapping and extraction efficiency.

References

[1] Y. Yamazaki, Nucl. Instrum. Methods B 154 (1999) 174.

[2] A. Mohri and Y. Yamazaki, Europhys. Lett. 63 (2003) 207.

[3] E. Widmann et al, The Hydrogen Atom: Precision Physics of Simple Atomic Systems,
edited by S.G. Kahrshenboim et al, Springer Verlag (2001) 528.

[4] N. Kuroda et al, Phys. Rev. Lett. 94 (2005) 023401.

[5] K. Yoshiki Franzen et al, Rev. Sci. Instrum. 74 (2003) 3305.
On the structure of KNN, KNNN states

S. Wycech

Soltan Institute for Nuclear Studies, Warsaw, Poland

A semi-quantitative understanding of the KEK [1,2] and FINUDA [3] findings is attempted. Leaving aside the interpretation of the peaks attributed to Kpp and KNNN systems, two essential theoretical questions arise:

• what is the binding mechanism,
• can the widths be narrow.

The K-N scattering amplitudes relevant to the bound K-few-nucleon systems involve subthreshold energies determined by $E_B$ - the kaon and nucleon bindings and $E_{\text{recoil}}$ - the recoil of the KN pair with respect to the residual system

$$f_{KN} = f_{KN}(-E_B - E_{\text{recoil}})$$

(1)

If the binding is as strong as 100 MeV, the momenta involved in the wave functions reach 400 MeV/c and the average recoil energy amounts to $\approx 100$ MeV. The energies of interest $-E_B - E_{\text{recoil}}$ are located well below the $\Lambda(1405)$ and $\Sigma(1385)$ states. The amplitudes there are strongly attractive and give rise to very strong binding [4]. The energies are far away from the physical region tested in the KN scattering and there arise uncertainties in the KN scattering amplitudes. For instance, if $\Lambda(1405)$ is a KN bound state, the amplitude far below the resonance is given not only by the KN binding but largely by the Born term which indicates strong dependence on the uncertain interaction range. Similar dependence occurs with the $\Sigma(1385)$ resonance.

The K-few-nucleon binding energies are calculated via the variational procedure with a meson trial wave function generated with fixed nucleons. This allows to find a contraction potential in the NN and NNN systems due to the presence of K meson. It amounts to $\approx 250$ for pp and $\approx 400$ MeV for NNN at less than 0.5 fm ranges. The real binding is determined by the repulsive core in the NN interactions. With the Argonne NN potential one obtains Kpp state bound by about 50 MeV and KNNN states bound by about 150 MeV. In the first system the effect of $\Sigma(1385)$ is small but in the KNNN states it adds large contribution to the binding.

The width of about 60 MeV is obtained in the Kpp case as the result of mesonic decays only. We argue qualitatively that the widths in KNNN systems may be smaller if these are bound by a 150 MeV or more. That comes as the result of the recoil energy taken by the spectators in the dominant non-mesonic decay mode.

References

[1] T. Suzuki et al. Phys.Lett. B597(2004)263 :
[2] M. Iwasaki, Proceedings of EXA05, Austr.Acad.Sc.Press p.93
[3] M. Agnello et al., Phys.Rev.Lett. 94(2005)212303
[4] S. Wycech and A. M. Green, ArXiv : nucl-th/0501019
Dynamical calculations of $K^-$ nuclear bound states

Avraham Gal

Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel

Evidence for and against strongly attractive $K$-nuclear interaction, capable of binding $\bar{K}s$ by over 100 MeV where the main decay channel $\bar{K}N \to \pi\Sigma$ is kinematically closed, is reviewed. A key issue is the residual width anticipated from $\bar{K}NN \to YN$ absorption modes for $\bar{K}$ deeply bound states. This and other relevant issues in $\bar{K}$-nuclear dynamics are studied, using a relativistic mean-field model Lagrangian which couples the $\bar{K}$ to the scalar and vector meson fields mediating the nuclear interactions [1]. The reduced phase space available for $\bar{K}$ absorption from these bound states is taken into account by adding a $-is\rho$ imaginary term, with an energy-dependent strength $s$ normalized at threshold to fits to the $K^-$ atomic data (the subject of $K^-$ atoms is covered by E. Friedman in these Proceedings). $\bar{K}$-nuclear bound states are generated self consistently over a wide range of energies by varying the $\bar{K}$-meson couplings. Substantial polarization of the core nucleus is found in this dynamical model for light nuclei, and the binding energies and widths differ appreciably from those calculated for a static nucleus. These calculations provide a lower limit of $\Gamma_{\bar{K}} = 50\pm10$ MeV on the width of nuclear bound states for $\bar{K}$ binding energy in the range $B_{\bar{K}} \sim 100 - 200$ MeV, as shown in Fig. 1. Comments are made on the experimental signals proposed for $\bar{K}$-nuclear deeply bound candidate states.

![Graph](image)

Figure 1: Dynamically calculated widths of 1s states as function of the $K^-$ nuclear binding energy for nonlinear RMF models. The dotted line is for a static nuclear-matter calculation with $\rho_0 = 0.16$ fm$^{-3}$.

References

[1] J. Mareš, E. Friedman, A. Gal, Phys. Lett. B 606 (2005) 295; Nucl. Phys. A 770 (2006) 84.
Chiral dynamics of $\bar{K}$-nucleus interaction: critical review of deeply bound states

E. Oset$^1$, V. K. Magas$^2$, A. Ramos$^2$ and H. Toki$^3$

$^1$Departamento de Física Teórica and IFIC, Universidad de Valencia
$^2$Departament d’Estructura i Constituents de la Materia, Universitat de Barcelona
$^3$Research Center for Nuclear Physics, RCNP, Osaka University

In this talk I reported on the chiral dynamics of meson baryon interaction and present models for the $\bar{K}N$ interaction. Results were reported on the selfconsistent evaluation of the $\bar{K}$ selfenergy in a nuclear medium, leading to a potential which is in good agreement with $K^-$ atoms. This potential was shown to be much smaller than the one claimed in the work of Akaishi and Yamazaki (AY), and the differences were traced to several rough approximations in the work of AY, like assuming that the $\Lambda(1405)$ is a bound state of $\bar{K}N$, when in chiral dynamics is a subtle consequence of coupled channel dynamics of $\bar{K}N$ and $\pi\Sigma$, assuming a Fermi sea of infinite nuclear matter for $^3He$, not including selfconsistency in the calculations and compressing the matter to ten times nuclear matter density.

Since the potential obtained by Ramos-Oset (RO), corroborated by other five independent microscopical studies, leads to deeply bound states with widths of about 100 MeV, the experimental claims made at KEK and FINUDA of narrow deeply bound states look incompatible with the chiral predictions. Then we looked for alternative explanations of the peaks seen at KEK and FINUDA and we could interpret them in terms of $K^-$ absorption by pairs of nucleons going to $\Sigma N$ and $\Lambda N$ with no further interaction with the daughter nucleus in the case of KEK and with final state interaction in the case of FINUDA. The works are reported in [1,2].

In the discussion I clarified that the criticism of AY to those works was unfounded. Akaishi confused the cut off used in chiral theories to regularize the loop of a meson and a baryon with the range of the potential. These two concepts have nothing to do with each other. It was also clarified that the calculation of RO contains the double selfconsistency of using the binding of the kaons in the intermediate loops and evaluating the selfenergy for kaons with the same mass that the calculation provides. AY fail to put the selfenergy in the loops which is fatal in the presence of a resonance, as it is the case here. Yamazaki claimed that the peak of FINUDA coming from $K^-pp$ absorption did not exist and I showed that this was not the case, it was obvious in the published paper and there was a whole paragraph devoted to explain the nature of this peak. I also clarified that from the $K^-$ $^4He$ absorption into $\Sigma^-pd$, where the deuteron has about 200 MeV/c from Fermi motion, a peak of strength 1.6 percent measured by Katz (the amount claimed in the KEK experiment) with a width of about 10 MeV was unavoidable, contrary to what was claimed by Yamazaki.

References

[1] E. Oset and H. Toki, arXiv:nucl-th/0509048
[2] V. K. Magas, E. Oset, A. Ramos and H. Toki, arXiv:nucl-th/0601013
Deeply bound kaonic nuclear states in reply to recent criticisms

Yoshinori Akaishi and Toshimitsu Yamazaki

1College of Science and Technology, Nihon University, Funabashi, Chiba 274-8501, Japan, and Nishina Center for Accelerator-Based Science, RIKEN, Wako, Saitama 351-0198, Japan

2Department of Physics, University of Tokyo, 7-3-1 Hongo, Tokyo 113-0033, Japan, and Nishina Center for Accelerator-Based Science, RIKEN, Wako, Saitama 351-0198, Japan

The possible existence of few-body kaonic nuclear states was theoretically predicted by the present authors [1]. Recently, this prediction has been critically reviewed by Oset and Toki (OT) [2]. Our reply to some of their criticisms is summarized as follows:

1) The phenomenological $\bar{K}N$ interaction used in our prediction is much more attractive than that of Oset-Ramos(OR)'s chiral unitary model [3], nevertheless it is in a reasonable agreement with other chiral unitary ones [4] as judged from forward scattering amplitudes. OR’s interaction gives unrealistic oscillating behavior of the $\Lambda(1405)$ wave function in coordinate space due to their sharp-cutoff regularization in momentum space.

2) The double-pole nature of $\Lambda(1405)$ was theoretically discussed by Jido et al., and its experimental evidence was claimed by Magas, Oset and Ramos (MOR) [5]. When the residue of a resonance pole is deeply complex, the resonance shape and position are largely changed by an interference between resonance and background terms. MOR’s broader peak is explained as a remnant of the ”narrower resonance pole” due to the interference. Thus, MOR’s conclusion is not sound. The ”broader one” of the double poles remains at a relatively narrow width of 132 MeV due to unphysical potential barriers coming from the sharp-cutoff regularization. The ”broader resonance pole” effect on $\Lambda(1405)$ is probably a kind of artifact.

3) We have formulated a microscopic derivation of the $\bar{K}$ optical potential. The optical potential must be distinguished between the cases of a $\bar{K}$ in nuclear bound states and of a $\bar{K}$ in scattering states, which is deep for the former and is shallow for the latter. The optical potential, as is defined to reproduce not phase shift but energy shift for a $\bar{K}$ in a decaying bound state, becomes deep more than 100 MeV attraction. OT insists to use a self-consistent ”shallow optical potential” even for a $\bar{K}$ in nuclear bound states. This opinion, however, has no many-body theoretical foundation.

References

[1] Y. Akaishi and T. Yamazaki, Phys. Rev. C 65 (2002) 044005. T. Yamazaki and Y. Akaishi, Phys. Lett. B535 (2002) 70.

[2] E. Oset and H. Toki, Phys. Rev. C 74 (2006) 015207.

[3] E. Oset and A. Ramos, Nucl. Phys. A 635 (1998) 99.

[4] N. Kaiser, P.B. Siegel and W. Weise, Nucl. Phys. A 594 (1995) 325. A.Cieply, E. Friedman, A. Gal and J. Mares, Nucl. Phys. A 696 (2001) 173

[5] V.K. Magas, E. Oset and A. Ramos, Phys. Rev. Lett. 95 (2005) 052301.
Phenomenological quantum field theoretic model of Kaonic Nuclear Clusters $K^-pp$, $K^-pnn$ and so on

A. N. Ivanov$^{1,2}$, P. Kienle$^1$, J. Marton$^1$, and E. Widmann$^1$

$^1$Stefan Meyer Institut für subatomare Physik, Österreichische Akademie der Wissenschaften, Österreich

$^2$Atominstitut der Österreichischen Universität, Technische Universität Wien, Österreich

We propose an oscillator model for the description of the wave functions of the Kaonic Nuclear Clusters (KNC) $K^-pp$ and $K^-pnn$ observed experimentally [1]. Assuming that all stiffnesses of linear restoring forces are equal we fix the frequencies of oscillations in terms of the width and binding energy of the resonance $\Lambda(1405)$ treating it as a bound $K^-p$ state [2]. The binding energy $\epsilon_{K^-X}$ and width $\Gamma_{K^-X}$ of the KNC $(K^-X)$, where $X = p$, $pp$ and $pnn$, are defined by

$$-\epsilon_{K^-X} + i \frac{\Gamma_{K^-X}}{2} = \int d\tau \Phi^*_K M(K^-X \to K^-X) \Phi_K,$$

where $d\tau$ is an element of the phase volume of the system $K^-X$, $\Phi_K$ is the wave function of the KNC $K^-X$ and $M(K^-X \to K^-X)$ is the amplitude of $K^-X$ scattering. We calculate the amplitudes of $K^-X$ scattering in the tree–approximation to leading order in chiral and large $N_C$ expansion within ChPT with non–linear realisation of chiral $SU(3) \times SU(3)$ symmetry and large $N_C$ expansion. The main contributions to the binding energies come from the Weinberg–Tomozawa terms. The width of the KNC $(K^-pp)$ is caused by non–pionic decays only. The main contribution to the width of the KNC $(K^-pnn)$ comes from the $K^-pnn \to \Sigma^-pn$ decay.

For the binding energies, widths and nuclear matter densities of the KNC $(K^-pp)$ and $(K^-pnn)$ we obtain the following results

$$\begin{align*}
\epsilon_{K^-pp} &= -118 \text{ MeV}, \quad \Gamma_{K^-pp} = 58 \text{ MeV}, \quad \rho_{K^-pp}(0) = 0.26 \text{ fm}^{-3}, \\
\epsilon_{K^-pnn} &= -197 \text{ MeV}, \quad \Gamma_{K^-pnn} = 16 \text{ MeV}, \quad \rho_{K^-pnn}(0) = 0.53 \text{ fm}^{-3}.
\end{align*}$$

The obtained results agree well with the experimental data [1]: $\epsilon_{K^-pp} = -115^{+6}_{-5} \text{ MeV}$, $\Gamma_{K^-pp} = 67^{+14}_{-11} \text{ MeV}$ and $\epsilon_{K^-pnn} = -194.0^{+1.5}_{-4.4} \text{ MeV}$, $\Gamma_{K^-pnn} < 21 \text{ MeV}$. They are also in qualitative agreement with those predicted by Akaishi and Yamazaki [2,4].

References

[1] M. Agnello et al., Phys. Rev. Lett. 94 (2005), 212303; T. Suzuki et al., Phys. Lett. B 597 (2004) 263.

[2] Y. Akaishi and T. Yamazaki, Phys. Rev. C 65, 044005 (2002); T. Yamazaki and Y. Akaishi, Phys. Lett. B 535 (2002) 70.

[3] A. N. Ivanov et al., nuclear-th/0512037

[4] A. Andronic et al., Nucl. Phys. A 765 (2006) 211.
Simulation of the $K^-$ nuclear absorption at FINUDA

V.K. Magas$^1$, E. Oset$^2$, A. Ramos$^1$, H. Toki$^3$

1 Departament d’Estructura i Constituents de la Matèria, Universitat de Barcelona, Diagonal 647, 08028 Barcelona, Spain
2 Departamento de Física Teórica and IFIC Centro Mixto Universidad de Valencia-CSIC, Institutos de Investigación de Paterna Apdo. correos 22085, 46071, Valencia, Spain
3 Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan

We performed a theoretical simulation of the $K^-$ absorption process in different nuclei and show that the peak in the $\Lambda p$ spectrum that was interpreted as a deep $K^-pp$ bound state \cite{FINUDA} corresponds mostly to the process $K^-pp \rightarrow \Lambda p$ followed by final state interactions of the produced particles with the daughter nucleus \cite{Magas}.

To reach the former conclusion, computer simulations are made allowing the stopped kaons in the nucleus to be absorbed by a pair of nucleons of a local Fermi sea. The nucleon and the $\Lambda$ emitted in the $K^-pp \rightarrow \Lambda p$ and $K^-pn \rightarrow \Lambda n$ absorption processes are allowed to re-scatter with other nucleons in the nucleus leading to nuclear breakup and producing a $\Lambda p$ invariant mass spectrum with a distinct peak corresponding to one collision. This peak, which is analogous to the quasi-elastic peak of any inclusive reaction like $(e,e')$, $(p,p')$ etc, reproduces the experimental peak \cite{Magas}. Another peak, broader and at smaller energies coming from baryon secondary collisions, also appears both in our simulation and in the experimental data \cite{FINUDA} at the same place and hence, an explanation for the whole experimental spectrum is found, which does not require to invoke the creation of the $K^-pp$ bound state. The agreement between our simulations and the experimental data is very good, giving a $\chi^2$ per data point of 1.25 \cite{Magas}.

We have presented results for $^6Li$, $^7Li$, $^{12}C$, $^{27}Al$ and $^{51}V$ \cite{Magas}, all of them measured by the FINUDA experiment, although the spectrum was only shown for the combined data of the three lighter nuclei. The width of the distribution increases slightly with the nuclear mass while the peak stays in the same location, in accordance with our interpretation of it as coming from the quasi-elastic processes. Disentangling the spectrum for each of the nuclear targets used in the FINUDA experiment would be of particular relevance because a possible interpretation of the data as evidence of bound $K^-$ nuclear states would unavoidably produce the peak at a different energy for each nucleus.

References

\cite{FINUDA} M. Agnello et al. [FINUDA Collaboration], Phys. Rev. Lett. 94 (2005) 212303.
\cite{Magas} V. K. Magas, E. Oset, A. Ramos and H. Toki, [arXiv:nucl-th/0601013]
Probing the Structure of Nuclei Bound by Antikaons

Paul Kienle\textsuperscript{1,2}
\textsuperscript{1}Stefan Meyer Institute, ÖAW, Wien
\textsuperscript{2}Technische Universität München

Following a short review of the present status of the search for deeply bound kaonic states in light nuclei, an outlook is given on what to do in the future to establish this new field of strangeness dynamics in nuclear clusters. It is pointed out that for this purpose detectors covering a large solid angle, preferably $4\pi$, are needed for the simultaneous study of the formation and decay of the systems in an exclusive reaction experiment. A first step towards this goal is the use of FOPI at the GSI Darmstadt for the study of strangeness containing nuclear states and hyperon resonances in proton and heavy ion induced reactions.

Recently we proposed for exclusive reaction studies in the framework of the AMADEUS project at Daphne in Frascati a modified KLOE detector to search for kaonic nuclear clusters using stopped $K^-$ induced $p$ and $n$ knock out reactions on cryogenic gas targets, such as $^3\text{He}$ and $^4\text{He}$ to start with. The KLOE detector allows identifying all charged particles including light nuclei and measuring their momenta and energies with the wanted accuracy, and has in addition the capability of measuring the energies of neutrons and $\gamma$-rays, This allows performing missing mass spectroscopy in the reaction channels as well as invariant measurement of the decays.

With exclusive experiments it will be possible for the first time to measure the mass, the total width and the partial widths of all decay channels. In three body decays one can measure Dalitz plots and determine from the phase space occupation the size, density distribution and the angular momentum of the decaying cluster.

Finally a new method is proposed for implanting 2 $K^-$ in a nucleus using antiproton annihilation at rest or in flight to search for systems containing double strangeness, which are expected to show very high binding energies and large densities for which various phase transitions are predicted.
Conditions for antikaon-nuclear bound states

W. Weise
Physik-Department, Technische Universität München, D-85747 Garching, Germany

This presentation summarizes ongoing work examining the conditions under which $\bar{K}$-nuclear clusters or bound states might exist. Our starting point is chiral SU(3) dynamics based on the three-flavour meson-baryon effective chiral Lagrangian. When combined with coupled-channel methods, this approach successfully describes s-wave $\bar{K}N$ scattering, the formation of the $\Lambda(1405)$ resonance and the couplings to $\pi\Sigma$ or $\pi\Lambda$ channels below $\bar{K}N$ threshold. The resulting $K^-p$ amplitude, extrapolated to subthreshold energies well below the $\Lambda(1405)$, suggests strong attraction of the $K^-$ in a nuclear environment. The following questions need to be addressed:

a) Are such binding effects sufficiently strong to compete with $\bar{K}N \rightarrow \pi Y$ decay widths and $\bar{K}NN \rightarrow YN$ absorptive broadening ($Y = \Lambda, \Sigma$)?

b) Can $K^-NN$ or $K^-NNN$ clusters be highly compressed (as previously suggested by Akaishi and Yamazaki) in view of the strong short range NN repulsion?

We are investigating these questions using the AMD variational approach (Akaishi, Dote et al.) for few-body systems, with a realistic Argonne V18 nucleon-nucleon potential and $\bar{K}N$ interactions derived from chiral SU(3) dynamics. P-wave $K^-N$ interactions involving the $\Sigma(1385)$ resonance turn out to be important. For heavier nuclei, we solve the Klein-Gordon equation with $\bar{K}$-nuclear self-energies based on realistic energy dependent input amplitudes.

Our intermediate results are summarized as follows:

1. $K^-pp$ clusters: quasi-molecular binding occurs despite the strong short-range NN repulsion. However, the binding energy is extremely sensitive to the poorly known range of the $\bar{K}N$ interaction. We note that the leading s-wave Weinberg-Tomozawa term alone is not strong enough to produce binding which emerges only with inclusion of $K^-p \leftrightarrow \pi\Sigma$ coupled-channels. The subthreshold $\bar{K}N$ p-wave interaction supports binding significantly once the energy drops below the $\Sigma(1385)$ resonance. $K^-pp$ binding energies in the range around 100 MeV, together with widths larger than 60 MeV, are not excluded.

2. $K^-ppn$ and $K^-pnn$ systems: weakly bound states appear to be possible, but their existence depends again sensitively on the range of the $\bar{K}N$ interaction. A previous interpretation (Akaishi and Yamazaki) of the observed KEK events in terms of narrow, deeply bound $K^-ppn$ and $K^-pnn$ states can so far not be confirmed within this extended framework. In particular, such states, if existent, are expected to have widths larger than 80 MeV.

3. $K^-$ nuclear bound states: in nuclei from $^{16}$O through $^{208}$Pb the $K^-$ can be bound at normal nuclear density by about 50-80 MeV, with widths of similar order. We find results in qualitative agreement with calculations by Mares, Friedman and Gal (reported at this workshop).

References

[1] A. Dote, R. Härtle and W. Weise, in progress

[2] B. Borasoy, R. Nißler and W. Weise, Phys. Rev. Lett. 94 (2005) 213401, Eur.Phys.J. A25 (2005) 79, Phys. Rev. Lett. 96 (2006) 199201; B. Borasoy and R. Nißler, this workshop.
Present status of the experimental investigation of deeply bound kaonic states

Toshimitsu Yamazaki$^1$ and Yoshinori Akaishi$^2$

$^1$Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan, and Nishina Center for Accelerator-Based Science, RIKEN, Wako, Saitama 351-0198, Japan

$^2$College of Science and Technology, Nihon University, Funabashi, Chiba 274-8501, Japan, and Nishina Center for Accelerator-Based Science, RIKEN, Wako, Saitama 351-0198, Japan

We discuss the following problems with particular attention among others.

1) The $K^-$ capture at rest occurs in the nuclear surface region (not at a remote peripheral) by nucleons of substantial momenta, and thus, the emission spectra of proton and $\Lambda$ are broad, contrary to a recent claim of Oset and Toki [1]. Only one exceptional case is $K^-$ capture by $^6\text{Li}$ due to the very small internal momentum of $d$ in $^6\text{Li}$ ($\sim$ 50 MeV/c). This explains the recently observed 500 MeV/c peak by FINUDA [2] as originating from a quasi-$d$ capture, $K^- + "d" \rightarrow p + \Sigma^-$, but such a monoenergetic proton peak is not expected from $^4\text{He}$ nor from any other nucleus because the internal momentum of $d$ is large ($\sim$ 200 MeV/c).

2) The invariant mass and the angular correlation of $\Lambda - p$ pairs emitted from $K^-$ capture by light nuclei as observed by FINUDA [3] can be explained only by invoking a nuclear bound state $K^-pp$ [4,5] with a binding energy of $B_K = 115$ MeV, but not by a suggested mechanism (via final state interactions) of Magas et al. [6]. An improved experimental data in a wider range of the invariant mass is waited for.

References

[1] E. Oset and H. Toki, arXiv:nucl-th/0509048

[2] M. Agnello et al., arXiv:nucl-ex/0606021

[3] M. Agnello et al., Phys. Rev. Lett. 94 (2005) 212303.

[4] Y. Akaishi and T. Yamazaki, Phys. Rev. C 65 (2002) 044005.

[5] T. Yamazaki and Y. Akaishi, Phys. Lett. B 535 (2002) 70.

[6] V.K. Magas, E. Oset, A. Ramos and H. Toki, arXiv:nucl-th/0601013
Study of kaonic nuclei by in-flight ($K^-$, $N$) reactions

Tadafumi Kishimoto

Department of Physics, Osaka University

Study of kaonic nuclei becomes one of the central issues recently since it could answer the question whether kaon condensation takes place in the core of neutron stars. We studied $\bar{K}$-nucleus system by the ($K^-$, $N$) reaction on $^{12}$C and $^{16}$O. This reaction could be the best probe to study $\bar{K}$-nuclear systems since reaction mechanism is well understood. The experiment was carried out at the K2-beam line of 12GeV Proton Synchrotron at KEK. $K^-$ beam of 1 GeV/c was employed for the study. The observed missing mass spectra were compared with theoretically calculated spectra. The comparison shows that the kaon nucleus potential is as deep as 200 MeV. We also observed large isospin dependence which is consistent with I=0 dominance of KN attractive interaction. I described our experimental conditions and current status of our analysis.
The possibility that due to the strongly attractive kaon nucleon potential deeply bound states might be formed [1] has triggered a number of experimental efforts and results [2] that are controversially interpreted [3]. More complete information is needed from experiment. Based on the speculation that the densities reached in heavy-ion reaction might be favorable for the formation of such states [4], a search program was initiated with the FOPI apparatus at GSI [5].

Exotic multi-baryon resonances might have a sizable decay branching ratio into the two body channel Λ - hyperons and protons (or deuterons) that can be easily reconstructed by a large solid angle charged particle detector like FOPI that allows to calculate the invariant mass of the particle pair. The experimental difficulty arises from the fact that due to the very short lifetime of the resonance it will decay in the target and it’s decay product are indistinguishable from directly emitted hadrons. With event samples of large statistics correlated pairs can be identified by subtracting the background of uncorrelated ones. Data samples of $120 \cdot 10^6$ events from the reaction Ni+Ni and $370 \cdot 10^6$ Al + Al events at an incident energy of 1.9 AGeV are available for the search.

The background of uncorrelated pairs needs to be constructed very carefully in order to remove correlations in the data sample that originate from non-resonance effects like the presence of a reaction plane and tracking efficiencies of the detector. In order to demonstrate the feasibility of reconstructing short lived resonances, Λ + π correlations are analyzed. The $Σ^*(1385)$ hyperon can be clearly identified with a significance of about 10 and a reconstructed width of $Γ = 50 \pm 10$ MeV that is in agreement with the PDG value. The relative production yield with respect to the Λ - baryon is $5 \cdot 10^{-2}$ at a signal - to - background ratio of $3 \cdot 10^{-2}$. No stable signal like this could be identified so far in the correlations of Λ - baryons with protons and deuterons.

References

[1] Y. Akaishi and T. Yamazaki, Phys. Rev. C 65 (2002) 044005, T. Yamazaki and Y. Akaishi, Phys. Lett. B 535 (2002) 70.

[2] T. Suzuki et al., Phys. Lett. B 597 (2004) 263, M. Agnello et al. (FINUDA), Phys. Rev. Lett. 94 (2005) 212303.

[3] E. Oset, H. Toki, arXiv:nucl-th/0509048, subm. to Phys. Rev. C, V.K. Magas et al., arXiv:nucl-th/0601013, M. Agnello et al. (FINUDA), arXiv:nucl-th/0606021

[4] T. Yamazaki, A. Doté and Y. Akaishi, Phys. Lett. B587 (2004) 167.

[5] J. Ritmann et al., (FOPI collaboration), Nucl. Phys. B44 (1995) 708
Search for K$^-_{pp}$ clusters in p+d-reaction with FOPI

P. Bühler$^1$, M. Cargnelli$^1$, L. Fabbietti$^2$, P. Kienle$^{1,2}$, N. Herrmann$^3$, K. Suzuki$^2$, T. Yamazaki$^4$, J. Zmeskal$^1$ & FOPI collaboration

$^1$Stefan Meyer Institut, Vienna, Austria, $^2$Technical University München, Germany, $^3$University Heidelberg, Germany, $^4$RIKEN & University of Tokyo, Japan

In November 2005 an experiment was carried out with the FOPI detector at GSI with the aim to produce and verify the existence of the K$^-_{pp}$, the simplest system of "$\bar{K}$ nuclear clusters”, in collisions of 3.5 GeV protons with a liquid deuterium target. With the reaction $p+N \rightarrow p+\Lambda^*+K \rightarrow K^-_{pp}+K \rightarrow \Lambda+p+K \rightarrow p+\pi^-+p+K$, proposed by Yamazaki & Akaishi the existence of a K$^-_{pp}$ cluster manifests as a peak in the invariant mass spectrum of the decay products of the K$^-_{pp}$ ($\approx 2.28$ GeV/c$^2$) and also in the missing mass spectrum of the reaction products. In combination these two mass spectra allow to unambiguously test the existence of these clusters. With the data gathered during this first run - limited statistics and data quality - it was however not possible to compute the missing mass spectra and only the invariant mass analysis was performed. Figure 1(a) shows the invariant mass spectrum of $\Lambda_p$ measured in the central drift chamber (CDC). In the upper panel the black line represents same-event combinations and the red line is the background estimated with an event-mixing method. The lower panel shows the difference and is consistent with no signal. With the available statistics only about 20 K$^-_{pp}$ clusters are estimated to be formed, which is not detectable in the relatively large background. With the same technique also $\Lambda+\pi^-$ correlations can be studied (figure 1(b)). In this case an enhancement is observed around the nominal mass of the $\Sigma$ resonance at 1385 GeV/c$^2$. The exact peak position and width depend on the background treatment and need further systematic analysis. Bumps at masses of 1480 and 1580 GeV/c$^2$ may be indications of other $\Sigma$ resonances. A proposal for additional beamtime is in preparation. Experimental improvements are discussed which shall allow to suppress the combinatorial background. A more thorough investigation of the $\Sigma$-resonances with a higher-statistics run is envisaged as well.

Figure 1: Invariant mass of $\Lambda+p$ (left) and $\Lambda+\pi^-$. Upper panels show signal (black line) and combinatorial background (red line) and lower panels show background subtracted signal.

43
\textbf{Λp spectrum analysis at 10 GeV/c in p+C interactions}

P.Zh. Aslanyan\textsuperscript{1,2}

\textsuperscript{1}Joint Institute for Nuclear Research, Dubna, Russia
\textsuperscript{2}Yerevan State of University, Yerevan, Armenia

On the theoretical side, many calculations of the Λp correlations have been performed using bag models\textsuperscript{1}, a phenomenological "Kaonic Nuclear Cluster models" \textsuperscript{2} and et. al. New particles or states of matter containing 1,2-or more strange quarks have inspired a lot of experiments at BNL(AGS), CERN, FNAL, GSI, SEBAF, KEK, JINR and et al..

The effective mass spectra of strange multiquark metastable states with Λ hyperon systems from proton exposure in pC → ΛX reaction at 10 GeV/c in 700000 stereo photographs (or neutron exposure at 7 GeV/c) on LHE JINR PBC were observed significant enhancement in invariant mass spectra\textsuperscript{3-5}:(Λ p), (Λpπ), (ΛΛ), (Λ, p, p) and (Λππ). There were succeeded in finding narrow resonance-like peaks by using different bin sizes and conditions of the analysis for (Λp) spectra in ranges of :\textsuperscript{(2085-2120),(2145-2180),(2195-2230),(2260-2300)} and (2360-2400) MeV/c\textsuperscript{2}. A few events, detected on the photographs of the propane bubble chamber exposed to a 10 GeV/c proton beam, were interpreted as weak decays of H dibaryons \textsuperscript{6-9}. There are two groups of events interpreted as S=-2 stable dibaryons: 1) the first group is formed of the neutral, S=-2 stable dibaryons, the masses of which are below (Λ, Λ) threshold; 2) the second group is formed of neutral and positively charged S=-2 heavy stable dibaryons. The weak decay mode of dibaryon hypothesis were observed by decay channels of Σ\textsuperscript{-}p, Λπ\textsuperscript{0}p, Λπ\textsuperscript{-}p, Σ\textsuperscript{+}pπ\textsuperscript{-} and K\textsuperscript{-}pp.

\section*{References}

[1] R.L. Jaffe, Phys. Rev. D 15 (1977) 267, 281; R.L. Jaffe, Phys. Rev. Lett. 38(1977)195.

[2] Y. Akaishi and T. Yamazaki,Phys. Rev.C 65, 044005 (2002); T. Yamazaki and Y. Akaishi, Phys.Lett. B 535,70 (2002).

[3] P.Z. Aslanyan et al., Proc. XVI ISHEPP,10-15 June, Dubna,Russia,2002.

[4] P.Z. Aslanyan et al., International Conference: I.Ya.Pomeranchuk and Physics at the Turn of Centuries, Moscow, 24-28 January 2003,\texttt{hep-ex/0406034}.

[5] P.Z. Aslanyan et al., Proc. Int. Conference on LEAP05, May 16-22, Bonn - Julich, Germany, 2005; AIP,v.796,ISBN 0-7354-0284-1,Melville, NY, \texttt{hep-ex/0504026} 2005.

[6] Aslanian P.Zh. et al. Nuclear Physics B 75B(1999)63-65.

[7] P.Z.Aslanian et al.,JINR Rapid Commun.,No.1(87)-98,1998.

[8] P.Z. Aslanyan et al.,Int.Conference, Bologna’2000, 29 May - 3 June, Italy ISBN981-02-4733-8, 2001.

[9] P.Z. Aslanyan et al., JINR Commun. E1-2001-265,2002.
Enhanced formation of $K^-pp$ clusters by short-range $pp$ collisions

Toshimitsu Yamazaki$^1$ and Yoshinori Akaishi$^2$

$^1$Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan, and Nishina Center for Accelerator-Based Science, RIKEN, Wako, Saitama 351-0198, Japan

$^2$College of Science and Technology, Nihon University, Funabashi, Chiba 274-8501, Japan, and Nishina Center for Accelerator-Based Science, RIKEN, Wako, Saitama 351-0198, Japan

The most basic kaonic nuclear cluster, $K^-pp$, was predicted [1,2], and an experimental indication has been observed by FINUDA [3]. Its formation by nucleon and heavy ion collisions is searched for by FOPI [4] at GSI. We have found theoretically that the elementary process, $p + p \rightarrow K^+ + \Lambda(1405) + p$, which occurs in a short impact parameter and with a large momentum transfer ($Q \sim 1.6$ GeV/c), leads to unusually large self-trapping of $\Lambda(1405)(\equiv \Lambda^*)$ by the projectile proton, when a $K^-pp$ system exists as a dense bound state. The seed, called “$\Lambda^*p$ doorway”, is expected to play an important role in the $(p, K^{+0})$ type reactions and heavy-ion collisions to produce various $\bar{K}$ nuclear clusters.

Figure 1: (Left) Predicted structure of $K^-p$ and $K^-pp$. (Right) Spectral shapes for different binding energies of $K^-pp$ in $pp \rightarrow K^+ + K^-pp$ reaction at $T_p = 3$ GeV.

References

[1] Y. Akaishi and T. Yamazaki, Phys. Rev. C 65 (2002) 044005.
[2] T. Yamazaki and Y. Akaishi, Phys. Lett. B 535 (2002) 70.
[3] M. Agnello et al., Phys. Rev. Lett. 94 (2005) 212303.
[4] FOPI experiment at GSI (2005).
A search for deeply-bound kaonic nuclear states by in-flight $^3$He$(K^-,n)$ reaction at J-PARC

H. Ohnishi for J-PARC E-15 experiment

RIKEN, Nishina Center for Accelerator Based Science, 351-0198, Saitama, Japan

We propose to perform an experimental search for deeply bound kaonic states using $^3$He target by the in-flight kaon reaction, both the invariant mass and missing mass spectroscopy with design resolution of 37 MeV/$c^2$ (FWHM) and 20 MeV/$c^2$ (FWHM), respectively.

Since, the interaction between $K^-$ and proton is confirmed to be strongly attractive[1], one can assume that $\Lambda(1405)$ would be a bound state between $K^-$ and proton. This assumption is naturally extended by Akaishi and Yamazaki[2] to the light nucleus, such as $^3$He, $^4$He and $^8$Be, to investigate whether $K^-$ forms bound state with light nuclei or not. Their coupled channel calculation predicted $K^-$ bound states to have narrow widths and large binding energies.

The KEK-PS E471[3] experiment was motivated with the possible formation of deeply bound kaonic nucleus $K^-ppn$ with isospin zero, which is expected to be detected most easily. The result is much different from the prediction in mass (twice bigger in terms of binding energy) and in isospin (T=1 instead of 0). To understand the difference between the data and the theory, study on simple system would be most efficient.

The second simplest kaonic nuclear system is $\bar{K}$ bound with two nucleons, such as a $\bar{K}^-pp$ state. Theoretically, binding energy and width is calculated to be 48 MeV and 61 MeV[4], respectively. Experimentally, this reaction allows to perform missing mass study using primary neutron, and invariant mass spectroscopy via the decay chain $K^-pp \to \Lambda p \to \pi^-pp$, simultaneously. Detailed study of this simple system would be a doorway towards investigation of the kaon bound states in heavy nucleus and/or a multi-kaon bound system in a nucleus.

References

[1] M. Iwasaki et al., Phys. Rev. Lett. 78 (1997) 3067.

[2] Y. Akaishi and T. Yamazaki, Phys. Rev. C65 (2002) 044005.

[3] T. Suzuki et. al. Phys. Lett. B597(2004) 263.

[4] Yamazaki and Akaishi, Phys. Lett. B535(2002)70
AMADEUS AT DAΦNE

Johann Zmeskal on behalf of the AMADEUS Collaboration,

Stefan Meyer Institut für subatomare Physik, Österreichische Akademie der Wissenschaften, Boltzmgasse 3, A-1090, Wien, Österreich

A new series of experiments are planned at Laboratori Nazionali di Frascati to search for the existence of antikaon-mediated bound nuclear states [1] with an upgrade of the DAΦNE machine [2]. This search deals with one of the most important, yet unsolved, problems in hadron physics: how the hadron masses and hadron interactions change in the nuclear medium and what might be the structure of cold dense hadronic matter. Deeply bound antikaon nuclear states (\( \bar{K} -n \)-nuclear clusters), if they exist, will offer the ideal conditions for investigating the way in which the spontaneous and explicit chiral symmetry breaking pattern of low-energy QCD changes in the nuclear environment [3].

The design strategy for the search of antikaon-mediated bound nuclear systems is to go fully exclusive – that means not only to detect the formation channel by missing mass spectroscopy, but also the decay channel using invariant mass analysis. Therefore, an unambiguous picture of a formed kaonic cluster could be extracted.

To do so, it is necessary to build a detector which allows the determination of all involved charged and neutral particles. Fortunately, already a great part of the detector exists at DAΦNE, namely the KLOE detector with a large Central Drift Chamber (CDC) for charge particle tracking, surrounded by an Electromagnetic Calorimeter (EMC) optimized for gamma detection and also providing neutron detection. The inner region around the beam pipe has to be adapted for the AMADEUS setup with a cryogenic target and an inner tracker system.

The scientific program of AMADEUS consists of precision spectroscopy studies, starting with light nuclei \(^3\)He and \(^4\)He to form the most basic antikaon nuclear clusters: “strange dibaryon” (\( ppK^- \)) and “tribaryon” (\( ppmK^- \), \( pnnK^- \)) states. Measurements of medium heavy nuclear targets are planned as well. A detailed structure information can be extracted from a Dalitz analysis of three-body decays of kaonic nuclei as was pointed out recently by Kienle, Akaishi and Yamazaki [4]. This is one of the most interesting feature to be performed with the AMADEUS setup. Finally, these data will clearly proof or disproof the existence of antikaon-mediated bound nuclear systems, a question strongly discussed in theory.

References

[1] AMADEUS LOI, http://www.lnf.infn.it/esperimenti/siddharta/

[2] A. Gallo, Proceedings EXA05, Austrian Academy of Science Press, Vienna 2005, p. 423.

[3] W. Weise, Proceedings EXA05, Austrian Academy of Science Press, Vienna 2005, p. 35; see as well the talks presented at this Workshop.

[4] P. Kienle, Y. Akaishi and T. Yamazaki, Phys. Lett. B 632 (2006) 187.
Discussion panel on deeply bound $\bar{K}$-nuclear states

W. Weise (Convener)

Physik-Department, Technische Universität München, D-85747 Garching, Germany

The panel session closing this workshop focused on the quest for deeply bound states of antikaon-nuclear systems which, if existent, would open up an entirely new dimension in the physics of hadrons and nuclei. The discussion proceeded along a line of questions "Where do we stand?" and "What next?"

Part I: Experiment

The present experimental situation is not yet conclusive. Missing mass spectra from $(K^-, p)$ and $(K^-, n)$ with stopped kaons on $^4$He at KEK show signals tentatively interpreted as $K^-pnn$ and $K^-ppn$ bound state candidates at binding energies $B(K^-pnn) \approx 194$ MeV and $B(K^-ppn) \approx 169$ MeV. Their small widths ($\Gamma < 20$ MeV) are, however, not understood. The FINUDA experiment observes structures in $\Lambda p$ invariant mass spectra, following stopped $K^-$ absorption on Li and C nuclei, which can hypothetically be interpreted as $K^-pp$ clusters with $B(K^-pp) \approx 115$ MeV and $\Gamma \approx 70$ MeV. This interpretation competes with a conventional analysis in terms of final state interactions. Searches are also performed with FOPI at GSI for similar structures in spectra produced by ion induced collisions with nuclei.

Necessary next steps:
- The KEK data require confirmation with higher statistics.
- Variation of kinematical cuts in the FINUDA experiment and systematics over several nuclei should clarify the role of final state interactions.
- A detailed re-analysis of data taken with the KLOE drift chamber is performed in search for $K^-ppn$ and $K^-pnn$ clusters.
- In the future the AMADEUS experiment at LNF is expected to provide a much improved, high-statistics data base with special emphasis on exclusive measurements of all final states.

Part II: Theory

The theoretical studies have so far been restricted to simple potential models implemented in few-body variational calculations and mean-field approaches. Improvements are required at several levels:
- Realistic finite-range subthreshold $\bar{K}N$ interactions with their full energy dependence must be incorporated in the few-body computational framework. Accurate threshold constraints from kaonic hydrogen measurements (SIDDHARTA) will be important, beyond the precision that has already been reached with the DEAR experiment.
- Realistic nucleon-nucleon interactions must be used with particular attention paid to short-range dynamics.
- A detailed theoretical treatment of $\bar{K}NN \rightarrow YN$ absorption channels is essential in order to understand the widths of possible $K^-$-nuclear strongly bound states. A high-precision determination of real and imaginary parts of the $K^-$-deuteron scattering length (again a case for SIDDHARTA) will be important in determining the corresponding $\bar{K}NN$ to $YN$ coupling.
- In constructing a Hamiltonian for such systems, systematic guidance by an appropriate effective field theory is mandatory.

**Part III: The Dense Matter connection**

The existence of antikaon-nuclear bound systems may have an impact on long-standing questions related to kaon condensation in dense matter. Connections with the equations of state for nuclear matter (deduced from high-energy heavy-ion collisions) and neutron star matter (from progressively more accurate astrophysical observations) should be examined in this context.
FSI in $K \to 3\pi$ and Cabibbo’s Proposal to Measure $a_0 - a_2$

Elvira Gámiz, Joaquim Prades, and Ignazio Scimemi

1Department of Physics and Astronomy, The University of Glasgow, Glasgow G12 8QQ, United Kingdom
2 CAFPE and Departamento de Física Teórica y del Cosmos, Universidad de Granada, Campus de Fuente Nueva, E-18002 Granada, Spain
3 Departament de Física Teòrica, IFIC, CSIC-Universitat de València, Apt. de Correus 22085, E-46071 València, Spain

In this work, we study the recent Cabibbo’s proposal to measure the $\pi\pi$ scattering lengths combination $a_0 - a_2$ from the cusp effect in the $\pi^0\pi^0$ energy spectrum around threshold both for $K^+ \to \pi^0\pi^0\pi^+$ and $K_L \to \pi^0\pi^0\pi^0$, and give the relevant formulas to describe it including NLO in $\pi\pi$ scattering effects near threshold. We use fitted CHPT formulas at NLO to describe the real part of the regular contribution to the $K \to 3\pi$ amplitudes near threshold while the imaginary and the non-regular parts are obtained just using unitarity and analyticity.

Previous NLO results can be found in and first experimental results have been also presented. At present, the theoretical uncertainties dominate and it is interesting both to check them and study how to reduce them further. Recently, a non-relativistic effective field theory in scattering lengths has been presented.

For explicit formulas and our results see [1]. Here, we just enumerate our main conclusions. 1) If we make the same approximations done in [3], we agree analytically with the results there. 2) The presence and effects of the singularity at pseudo-threshold are discussed. 3) We estimate the theory uncertainty due to NNLO scattering effects to be around 5% and it is thus necessary to go to NNLO in $\pi\pi$ re-scattering effects to reduce/check this uncertainty. 4) Several approximations done in [3] are identified and quantified. Though they are individually negligible, they tend to go in the same direction and add up to around 2%. These approximations should be of course eliminated if one wants to reach the per cent level of uncertainty. 5) At NLO, our final theoretical uncertainty is around 5%, if various small—from 1% to 2%—theoretical uncertainties are added quadratically. If these small theoretical uncertainties are added linearly, one gets a theoretical uncertainty around 7%.

References

[1] E. Gámiz, J. Prades and I. Scimemi, hep-ph/0602023.
[2] N. Cabibbo, Phys. Rev. Lett. 93 (2004) 121801.
[3] N. Cabibbo and G. Isidori, J. High Energy Phys. 03 (2005) 021.
[4] J.R. Batley et. al. [NA48/2 Collaboration], Phys. Lett. B 633 (2006) 173; S. Giudici [NA48/2 Collaboration], hep-ex/0505032.
[5] G. Colangelo, J. Gasser, B. Kubis, and A. Rusetsky, hep-ph/0604084.
Pion scattering lengths from the NA48/2 experiment at CERN

G. Collazuol, on behalf of the NA48/2 collaboration

Scuola Normale Superiore and INFN Sezione di Pisa, Italy

The NA48 experiment at CERN collected more than $3.1 \times 10^9$ $K^\pm \rightarrow \pi^\pm \pi^\mp \pi^\mp$ decays and more than $110 \times 10^6$ $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ decays for searching CP violating asymmetries in charged kaon decays. No asymmetries were found up to now at a level of $10^{-4}$ but an unexpected effect involving strong interactions was found while studying the kinematics of those decays. A study of a partial sample of $23 \times 10^7$ $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ decays was reported at this workshop, whose results show an anomaly (cusp) in the distribution of the $\pi^0 \pi^0$ invariant mass ($m_{\pi\pi}$) in the region around $m_{\pi\pi} = 2m_\pi$, where $m_\pi$ is the charged pion mass. This cusp, never observed in the past, is interpreted as an effect due mainly to the final state charge exchange scattering process $\pi^+ \pi^- \rightarrow \pi^0 \pi^0$ in the $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ decay.

This provides a new method for a precise determination of the difference $a_0 - a_2$ between the scattering lengths in the isospin $I = 0$ and $I = 2$ states. A best fit to a rescattering model corrected for isospin symmetry breaking gives $(a_0 - a_2)m_\pi = 0.268 \pm 0.010_{\text{stat}} \pm 0.004_{\text{syst}}$ with additional external error of 0.013 from branching ratio and theoretical uncertainties. The measured value is in agreement with chiral perturbation theory and with other measurements exploiting different methods. For the first time the parameter $a_2 = -0.041 \pm 0.022_{\text{stat}} \pm 0.014_{\text{syst}}$ was directly measured. If the correlation between $a_0$ and $a_2$ predicted by chiral symmetry is taken into account, this result becomes $(a_0 - a_2)m_\pi = 0.264 \pm 0.006_{\text{stat}} \pm 0.004_{\text{syst}} \pm 0.013_{\text{ext}}$. Pionium bound state is also found as an additional sharp peak on top of the cusp. By analyzing the full data sample we expect an increase in statistics by a factor of 5. An experimental error below 1.5% seems not to be out of reach. At the moment the external uncertainty related to the theoretical method is 5% and the data quality calls for additional theoretical effort in order to extract precise values of the $\pi\pi$ scattering parameters (higher orders and electromagnetic corrections). A fit according to different amplitudes representation is also in progress.

The cusp effect was confirmed by the NA48 collaboration, by finding a similar anomaly in the study of the $\pi^0 \pi^0$ invariant mass in the $K_L \rightarrow 3\pi^0$ decays, collected in the year 2000 with a statistics exceeding $100 \times 10^6$.

References

[1] R. Batley et.al, Phys. Lett. B634 (2006) 474.
[2] R. Batley et.al, Phys. Lett. B638 (2006) 22.
[3] R. Batley et.al, Phys. Lett. B633 (2006) 173.
[4] N. Cabibbo, Phys. Rev. Lett. 93 (2004) 121801.
[5] N. Cabibbo, G. Isidori, JHEP 503 (2005) 21.
[6] G. Colangelo, J. Gasser, B. Kubis and A. Rusetsky hep-ph 0604084.
On the cusp effects in $K \to 3\pi$ decays

N. Cabibbo, a G. Isidori b

a Dip. Fisica and INFN, Univ. Roma “La Sapienza”, P.le A. Moro 2, I-00185 Rome, Italy
b INFN - Laboratori Nazionali di Frascati, C.P. 13-1-00044, Frascati, Italy

As pointed out in Ref. [1], the rescattering of the final state pions produces a prominent cusp in the $M_{\pi^0\pi^0}$ spectrum of the $K^+ \to \pi^+\pi^0\pi^0$ decay. This effect can be used to obtain a precise determination of the $\pi-\pi$ scattering lengths ($a_I$) and, particularly, of the $a_0 - a_2$ combination. In order to fully exploit the high-statistics and high-quality data collected by NA48 on the $K^+ \to \pi^+\pi^0\pi^0$ decay [2], an accurate theoretical description of this effect in terms of the $a_I$ is necessary. A first step in this direction has been presented in Ref. [3].

The method of Ref. [3] is based on a systematic expansion in powers of the $\pi-\pi$ scattering lengths. The approach is less ambitious than the ordinary loop expansion performed in effective field theories, such as CHPT: the scope is not a dynamical calculation of the entire decay amplitudes, but a systematical evaluation of the singular terms due to rescattering effects only. As far as the description of the cusp effect is concerned, this approach is more efficient and substantially simpler than ordinary CHPT. Using this method, the coeff. of the square-root singularities occurring at $M_{\pi^0\pi^0} = 2M_{\pi^+}$ have been computed at $O(a_I^2)$ accuracy.

A technical assumption has been employed to simplify the calculation of complicated two-loop topologies of the type in Fig. 1: one-loop subdiagrams have been approximated by suitable polynomial expressions [3]. As recently shown in Ref. [4], this procedure does not reproduce the correct analytic properties of the amplitudes; however, it turns out to be an excellent numerical approximation.

The theoretical error in the extraction of $a_0 - a_2$ from $K^+ \to \pi^+\pi^0\pi^0$ based on the method of Ref. [3] has been estimated to be $\approx 5\%$. The conservative nature of this estimate seems to be confirmed by the recent analysis of Ref. [5]. A somewhat larger uncertainty is expected in the $K_L \to 3\pi^0$ case, due to the accidental smallness of the leading $O(a_I)$ term. To go beyond this level of precision, a complete evaluation of radiative corrections is needed. The non-relativistic QFT formulation of Ref. [4] offers a systematic tool to evaluate these effects.

References

[1] N. Cabibbo, Phys. Rev. Lett. 93 (2004) 121801 [hep-ph/0405001].
[2] J. R. Batley et al. [NA48/2 Coll.], Phys. Lett. B 633 (2006) 173 [hep-ex/0511056].
[3] N. Cabibbo and G. Isidori, JHEP 0503 (2005) 021 [hep-ph/0502130].
[4] G. Colangelo, J. Gasser, B. Kubis and A. Rusetsky, Phys. Lett. B 638 (2006) 187 [hep-ph/0604084].
[5] E. Gamiz, J. Prades and I. Scimemi, hep-ph/0602023.
Non relativistic QFT and $K \to 3\pi$ decays

G. Colangelo$^1$, J. Gasser$^1$, B. Kubis$^2$, A. Rusetsky$^{2,3}$

$^1$Institute for Theoretical Physics, University of Bern, Sidlerstr. 5, CH-3012 Bern, Switzerland
$^2$Helmholtz-Institut für Strahlen- und Kernphysik, Universität Bonn, Nussallee 14-16, D-53115 Bonn, Germany
$^3$On leave of absence from: High Energy Physics Institute, Tbilisi State University, University St. 9, 380086 Tbilisi, Georgia.

Recently, it has been pointed out by Cabibbo and Isidori [1,2,3] that isospin violating effects generate a pronounced cusp in $K \to 3\pi$ decays whose experimental investigation may allow one to determine the combination $a_0 - a_2$ of $\pi\pi$ scattering lengths with high precision. A first analysis of data based on this proposal has appeared [4]. In order for this program to be carried through successfully, one needs to determine the structure of the cusp with a precision that matches the experimental accuracy. In view of the large amount of data available [4], this is a considerable task. A first step in this direction has been done in Ref. [2]. For a confirmation of the uncertainties quoted in [2], see [5,6]. In Ref. [7], a non-relativistic QFT framework is constructed, which automatically satisfies unitarity and analyticity constraints and, in addition, allows one to include electromagnetic contributions in a standard manner. In this framework – in contrast to relativistic field theory – an expansion in powers of scattering lengths emerges automatically from the loop expansion. Moreover, it is a scheme that provides a proper power counting.

The results in [7] are displayed without a detailed derivation, which will be provided in a forthcoming publication [8]. A short comparison with the framework used in Ref. [2] is provided by Isidori in his contribution to this workshop [3].

References

[1] N. Cabibbo, Phys. Rev. Lett. 93 (2004) 121801 [arXiv:hep-ph/0405001].
[2] N. Cabibbo and G. Isidori, JHEP 0503 (2005) 021 [arXiv:hep-ph/0502130].
[3] G. Isidori, contribution to this workshop.
[4] J. R. Batley et al. [NA48/2 Collaboration], Phys. Lett. B 633 (2006) 173 [arXiv:hep-ex/0511056].
[5] E. Gamiz, J. Prades and I. Scimemi, [arXiv:hep-ph/0602023].
[6] J. Prades, contribution to this workshop.
[7] G. Colangelo, J. Gasser, B. Kubis and A. Rusetsky, Phys. Lett. B 638 (2006) 187 [arXiv:hep-ph/0604084].
[8] J. Gasser, B. Kubis and A. Rusetsky, in preparation.