Probing Strong Interaction with SIDDHARTA-2

Johann ZMESKAL1,2*, Alessandro SCORDO2, Aidin AMIRKHANI3, Claude AMSLER1, Ata BANIAHMAD4, Massimiliano BAZZI2, Giovanni BELLOTTI6, Carolina BERUCCI1, Damir BOSNAR5, Mario A. BRAGADIREANU6, Michael CARGNELL1, Catalina CURCEANU2, Raffaele Del GRANDE2, Laura FABBRIETTI7, Carlo FIORINI1, Francesco GHIO2, Carlo GUARALDO2, Mihai ILIESCU2, Masahiko IWASAKI8, Paolo LEVI SANDRF, Johann MARTON1,2, Marco MILUCCI2, Pawel MOSKAL9, Dorel PIETREANU2,6, Kristian PISCICCHIA,2,10, Alessandro SCORDO2, Michal SILARSKI9, Diana SIRGHI2,6, Florin SIRGHI2,6, Magdalena SKURZOK9, Antonio SPALLONE2, Marlene TUCHLER1, Oton VAZQUEZ DOCE2,7 and Eberhard WIDMANN1

1Stefan Meyer Institute for Subatomic Physics, Austrian Academy of Sciences, Vienna, Austria
2INFN, Laboratori Nazionali di Frascati, Frascati (Roma), Italy
3Politecnico Milano and INFN Sezione di Milano, Milano, Italy
4University of Rome Tor Vergata, Physics Department, Rome, Italy
5Department of Physics, Faculty of Science, University of Zagreb, Zagreb, Croatia
6Horia Hulubei National Inst. of Physics and Nuclear Engineering, Bucharest, Romania
7Excellence Cluster Universe, Technische Universitaet Muenchen, Garching, Germany
8RIKEN Nishina Center, RIKEN, Wako, 351-0198, Japan
9M. Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
10Museo Storico della Fisica e Centro Studi e Ricerche “Enrico Fermi”, Roma, Italy

*E-mail: johann.zmeskal@oeaw.ac.at
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The antikaon-nucleon interaction close to threshold provides crucial information on the interplay between spontaneous and explicit chiral symmetry breaking in low-energy QCD involving strangeness. The unique feature of DAQNE, namely the production of low-energy kaons, has led to a series of successfully conducted experiments with light kaonic atoms like SIDDHARTA, where the most precise value for the antikaon-proton scattering length was determined. Kaonic deuterium X-ray spectroscopy is still missing and with SIDDHARTA-2 the ground state $1s$-level shift and width should be measured with a precision of 30 eV and 75 eV, respectively.

KEYWORDS: low-energy QCD with strangeness, chiral symmetry, kaonic atoms, X-ray spectroscopy
1. Introduction

Confinement implies that QCD in the low-energy limit is realized as a theory of hadronic degrees of freedom rather than on the quark-gluon level. Spontaneous chiral symmetry breaking implies further that the appropriate framework is Chiral Effective Field Theory (ChEFT) [1-5], a systematic approach describing the interactions of the pseudo-scalar Nambu-Goldstone bosons amongst each other and with baryons. In the hierarchy of quark masses in QCD the strange quark is very special, their masses of ~100 MeV/c² is well separated on the mass scale from light $u$ and $d$ quarks (with current quark masses of only a few MeV/c²) as well as from heavy $c$, $b$ and $t$ quarks (with masses in the GeV/c² range). The strengths of the attractive s-wave antikaon-nucleon interaction at threshold can be expressed by the kaon mass and the pseudo-scalar decay constant. The appearance of the pseudo-scalar decay constant (~100 MeV/c²) is characteristic of spontaneously broken chiral symmetry in low-energy QCD, while the kaon mass reflects explicit breaking of chiral symmetry by the non-vanishing (strange) quark mass. Measurements of the antikaon–nucleon interaction close to threshold provides crucial information on the interplay between spontaneous and explicit chiral symmetry breaking in low-energy QCD.

Therefore, kaonic atoms offer an ideal framework to study strong interaction physics. Of particular interest are studies of kaonic systems formed with hydrogen isotopes, which will give access to the basic low-energy parameters like the antikaon-nucleon scattering lengths. Kaonic atoms allow to perform experiments at vanishing relative energies between the antikaon and the nucleon, because their atomic binding energies are in the keV range, far below the lowest energies of extracted beams for scattering experiments.

2. Formation of kaonic hydrogen atoms

When a negatively charged kaon enters a target it is slowed down to a kinetic energy of a few tens of eV by ionizations and excitations of the target molecules. Finally, it will be captured into an outer atomic orbit by replacing an electron and thus forming a kaonic atom. Kaonic atoms allow to perform experiments at vanishing relative energies between the antikaon and the nucleon, because their atomic binding energies are in the keV range, far below the lowest energies of extracted beams for scattering experiments.

![Fig. 1. Cascade processes for kaonic hydrogen down to the 1s ground state, which is shifted due to strong interaction and broadened due to nuclear absorption of the kaon by the proton.](image)

When a negatively charged kaon enters a target it is slowed down to a kinetic energy of a few tens of eV by ionizations and excitations of the target molecules. Finally, it will be captured into an outer atomic orbit by replacing an electron and thus forming a kaonic atom. The initial principal quantum number $n$ of the kaonic atom is given by the reduced mass $\mu$ and the electron mass $m_e$ with the principal quantum number $n_e$ of the outermost electron shell:

$$n \approx \sqrt{\frac{\mu}{m_e}} \cdot n_e$$
For kaonic hydrogen the kaon starts from an outer shell with a main quantum number, \( n \sim 25 \) to cascade down to the \( 1s \) ground state (Fig.1). During cascade processes, especially for kaonic hydrogen atoms, the Stark effect is strongly density dependent and will become important. Stark-mixing occurs when the exotic atom passes through the Coulomb field of another target atom. The electric field mixes the \( l \)-states with the same principal quantum number. For kaonic atoms, this means that the kaon-nuclear absorption may occur even from higher \( n \)-orbits in \( s \)-states. Stark mixing is therefore mainly responsible of a drastic reduction of the X-ray yield with increasing target density.

3. The antikaon-nucleon scattering length

The study of the strong interaction effects with strangeness was the major motivation for performing experiments with kaonic atoms. The electromagnetic interaction with the nucleus is very well known, the energy levels can be calculated by solving the Klein-Gordon equation and then applying finite size and vacuum corrections, achieving a value for the \( 2p-1s \) transition of \( \Delta E_{2p-1s}^{\text{QED}} = 6479.6 \text{ eV} \) [6].

By measuring the transition X-ray energies \( \Delta E_{2p-1s}^{\text{meas.}} \) to the \( 1s \) ground state of kaonic hydrogen atoms \((K^-p)\) the deviation \( \varepsilon_{1s} \) from the purely electromagnetic value can be determined with high precision:

\[
\varepsilon_{1s} = \Delta E_{2p-1s}^{\text{meas.}} - \Delta E_{2p-1s}^{\text{QED}}
\]

The values \( \varepsilon_{1s} \) and the energy broadening \( \Gamma_{1s} \) can be related to the \( K^-p \) complex scattering length \( a_{K^-p} \) by the so-called Deser-Trueman formula [7,8]. However, it turns out that isospin-breaking corrections in the case of kaonic hydrogen are important and much larger than e.g. for pionic hydrogen. The improved Deser formula [9,10], derived from non-relativistic effective field theory (EFT) includes isospin breaking corrections and writes as follows:

\[
\varepsilon_{1s} - \frac{1}{2} \Gamma_{1s} = 2 \alpha^2 \mu^2 a_{K^-p} (1 - \alpha \ln \alpha - 1) a_{K^-p}
\]

with the fine structure constant \( \alpha \) and the reduced mass \( \mu \).

The \( s \)-wave complex scattering length \( a_{K^-p} \) and \( a_{K^-d} \) are related to the \( KN \) isoscalar and isovector scattering lengths \( a_0 \) and \( a_1 \), through:

\[
a_{K^-p} = \frac{1}{2} (a_0 + a_1), \quad a_{K^-n} = a_1 \quad (4)
\]

\[
a_{K^-d} = (a_{K^-p} + a_{K^-n}) \sim \frac{1}{2} (a_0 + 3a_1) \quad (5)
\]

Therefore, to obtain the isospin dependent scattering lengths one has to determine the kaonic deuterium scattering length, which will provide information on a different combination of \( a_0 \) and \( a_1 \) (4, 5).

4. SIDDHARTA setup and results

The SIDDHARTA (Silicon Drift Detector for Hadronic Atoms Research with Timing Applications) experiment determined the kaonic hydrogen shift \( \varepsilon_{1s} \) and width \( \Gamma_{1s} \) of the \( 1s \) ground state of kaonic hydrogen, with the highest precision up to now [11]. The SIDDHARTA experiment was performed at the DAΦNE electron-positron collider at the Laboratori Nazionali di Frascati of INFN (Italy). DAΦNE produces \( \phi \)-mesons almost
at rest, which decay into $K^+$ and $K^-$ emitted back-to-back, with a branching ratio of about 49%. These monochromatic low-energy kaons ($\sim 16$ MeV) are stopped efficiently in a gaseous target forming kaonic hydrogen atoms.

To detect the back-to-back correlated $K^+$ and $K^-$ from $\phi$ decay, with one of the kaons moving in direction of the target cell, two plastic scintillation counters were mounted above and below the $e^+e^-$ interaction point. The coincidence signal of the two scintillators defines the kaon trigger, which is a good indication that a kaon will stop in the target cell.

This trigger condition was used to build a triple-coincidence including a measured X-ray event in the Silicon Drift Detectors (SDDs) to suppress uncorrelated background events by almost 3-orders of magnitude. The SDDs [12] were developed within a European research project (EU-FP6 framework program: Hadron-Physics) devoted to this experiment. Each of the 144 SDDs used in the apparatus has an area of 1 cm$^2$ and a thickness of 450 $\mu$m. The SDDs, operated at a temperature of $\sim 170$ K have an energy resolution of 185 eV (FWHM) at 8 keV and a timing resolution below 1 $\mu$sec, in contrast to the CCD detectors used in DEAR [13] which had no timing capability.

Data were accumulated with integrated luminosity of $\sim 340$ pb$^{-1}$ for the kaonic hydrogen measurement over six months in 2009, with the background subtracted spectrum shown in Fig. 2. The SIDDHARTA results [12] for shift $\epsilon_{1s}$ and width $\Gamma_{1s}$ of the kaonic hydrogen $1s$-level are:

\[ \epsilon_{1s} = -283\pm36{\text{stat}}\pm6{\text{sys}} \text{ eV} \]  
\[ \Gamma_{1s} = 541\pm89{\text{stat}}\pm22{\text{sys}} \text{ eV} \]

5. Kaonic deuterium with SIDDHARTA-2

Although the importance of kaonic deuterium X-ray spectroscopy has been well recognized for more than 30 years (Dalitz et al. [14]), no experimental results have yet been obtained due to the difficulty of the X-ray measurement. The experimental challenges of SIDDHARTA-2 are the very small kaonic deuterium X-ray yield as well as the larger width of the $1s$ ground state compared to kaonic hydrogen and, in addition, the
difficulty to perform X-ray spectroscopy in the high bremsstrahlung environment of the DAΦNE collider. Therefore, it is crucial to improve the X-ray detection efficiency, as well as to control the signal-to-background ratio for a successful observation of the kaonic deuterium X-rays. Dedicated Monte Carlo simulations as well as R&D work on the detector side lead to the finally developed SIDDHARTA-2 apparatus (Fig. 3), with the three main improvements, essential for a successful kaonic deuterium X-ray experiment:

- A lightweight cryogenic target with a sidewall thickness < 150 μm, made of 2 layers of 50 μm Kapton glued together with an epoxy adhesive, allowing for an X-ray transmission of approximately 90% for 8 keV X rays. The working temperature of the target cell is 30 K with a maximum working pressure of 0.3 MPa.
- Recently developed robust SDDs with an active area as large as 246 cm² and a drastic improved active to total area ratio, with excellent timing capability (< 500 ns) and energy resolution (~ 170 eV).
- A charged particle veto detector system consisting of two veto systems: Veto-1, an outer veto detector as active shielding and Veto-2, an inner veto detector for the suppression of charged particles. Additionally, for both veto systems an excellent time resolution about 500 ns (FWHM) is required to distinguish between kaons stopped in the gaseous target cell or kaons stopped in the target entrance window.

Dedicated Monte Carlo studies have been performed showing that with the new designed experimental apparatus the \( K^-d \) experiment is feasible at DAΦNE (and at J-PARC as well). The following main assumptions were used as input for the Monte Carlo (Geant4) simulation: shift \( \delta_{\text{ls}} = -800 \) eV, width \( \Gamma_{\text{ls}} = 800 \) eV and X-ray yield = 0.1 % (a factor of ten less than measured for kaonic hydrogen).

In addition, the dedicated shielding structure and veto detector devices have been included in the SIDDHARTA-2 Monte Carlo simulations, leading to a signal to background ratio of 1:4. The performed Monte Carlo simulation in Fig. 4 shows the expected spectrum shape.
fitting theses produced spectra, the precision of shift and width was evaluated to be 30 eV and 75 eV, respectively for an integrated luminosity of 800 pb\(^{-1}\). These experimental results will lead to essential constraints in theory \cite{10,15-19} and will set the physics focus on the low-energy antikaon-neutron interaction, which is up to now an open question.

6. Conclusions

The kaonic deuterium X-ray measurement will provide the most important experimental information missing in the field of the low-energy antikaon-nucleon interactions today. The detector and target system are ready to be installed at DA\(\Phi\)NE, which is foreseen for Spring 2019.

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