From CELSIUS to COSY: on the observation of a dibaryon resonance

H Clement¹,², M Bashkanov¹,² and T Skorodko¹,²,³

¹ Physikalisches Institut der Universität Tübingen, Auf der Morgenstelle 14, D-72076 Tübingen, Germany
² Kepler Center for Astro and Particle Physics, University of Tübingen, Auf der Morgenstelle 14, D-72076 Tübingen, Germany
³ Department of Physics, Tomsk State University, 36 Lenina Avenue, 634050 Tomsk, Russia

E-mail: heinz.clement@uni-tuebingen.de

Received 22 October 2014, revised 14 December 2014
Accepted for publication 29 December 2014
Published 26 November 2015

Abstract

Using a high-quality beam of storage rings in combination with a pellet target and a hermetic WASA detector covering practically the full solid angle, two-pion production in nucleon–nucleon collisions has been systematically studied by exclusive and kinematically complete measurements—first at CELSIUS and subsequently at COSY. These measurements resulted in a detailed understanding of the two-pion production mechanism by \( t \)-channel meson exchange. The investigation of the ABC effect, which denotes an unusual low-mass enhancement in the \( \pi \pi \)-invariant mass spectrum, in double-pionic fusion reactions led the trace to the observation of a narrow dibaryon resonance with approximately 80 MeV below the nominal mass of the conventional \( \Delta \Delta \) system. New neutron–proton scattering data, taken with a polarized beam at COSY, produced a pole in the coupled \( D_1 \) partial waves at \((2380 \pm 10 - i 40 \pm 5)\) MeV, establishing thus the first observation of a genuine \( s \)-channel dibaryon resonance.

Keywords: two-pion production, dibaryon, delta-delta system

(Some figures may appear in colour only in the online journal)

1. Introduction

The question of whether the two-baryon system possesses more eigenstates than just the isoscalar deuteron groundstate and the isovector virtual \( ^3S_0 \) state (known from the nucleon–nucleon final state interaction) has been awaiting an answer for decades. This fundamental question was first connected to the question about six-quark systems in 1964, when Dyson and Xuong [1] correlated this topic with symmetry breaking of SU(6)—just shortly after Gell-Mann’s famous publication [2] of the quark model. However, this topic did not receive overwhelming attention until 1977, when Jaffe predicted the so-called H dibaryon [3], a bound \( \Lambda \Lambda \) system, based on quantum chromodynamics. It was this paper which initiated a real dibaryon rush, with a copious number of theoretical calculations and an even greater number of dibaryon searches resulting in a vast number of experimental claims—but finally none survived careful experimental investigations. For a review see, e.g. [4].

The reasons for this striking failure of previous dibaryon searches may be found, at least partly, in the insufficient quality of data based either on low-statistics bubble-chambers or inclusive measurements performed mainly with single-arm detectors [4].

Recently the question of dibaryons received renewed interest after it was realized that there exist more complex quark configurations than just the familiar \( qq \) and \( qqq \) systems—in favor also of hidden color aspects [5].

2. Exclusive and kinematically complete experiments—observation of a dibaryon resonance

Since two-pion production was little investigated, but had the potential to contain unusual phenomena, a systematic study of this process was started in the 1990s at the CELSIUS storage ring, where by the start of the new millennium the WASA detector with close to \( 4\pi \) angular coverage had gone into operation in combination with a hydrogen/deuterium pellet target [6]. This provided the possibility of measuring meson production in \( pp \), \( pd \) and \( dd \) collisions for the first time...
Figure 1. Left: Dependence of the total cross section for the reaction $pn \to d\pi^+\pi^-$ (red) and its isospin decomposition [20] into an isoscalar part—corresponding to $2\sigma (pn \to d\pi^+\pi^0)$ (blue)—and isovector part—corresponding to $1/2 \sigma (pp \to d\pi^+\pi^0)$ (black)—on the center-of-mass energy $\sqrt{s}$. Right: Energy dependence of the analyzing power in $\bar{n}p$ scattering near $90^\circ$, where the effect of a $I(J^P) = 0(3^+)$ resonance shows up most clearly. Filled circles denote WASA results, open symbols previous work. The solid line gives the current SAID solution SP07, while the dashed line represents the new SAID solution containing the resonance pole [22, 23].

exclusively and kinematically completely—even with up to six overconstraints. In addition, the high-quality beam in combination with the pellet target ensured a low background situation. In this way such measurements delivered data of unprecedented quality.

In 2005 the WASA detector was moved to the COSY ring, taking advantage of the superior beam quality and intensity there [7]. This made it possible to move the studies from $pp$ induced to $pn$ induced reactions by measuring the quasifree scattering process with high accuracy over a wide energy region.

Additionally, two-pion production was also studied at COSY with a polarized beam utilizing the TOF detector, which also covered practically the full solid angle [8].

As a result of these kinematically complete and exclusive two-pion production measurements at CELSIUS and subsequently at COSY, it was shown that all $pp$ induced, i.e. all isovector channels, behave as expected from conventional $t$-channel Roper excitation, $\Delta\Delta$ (mutual excitation of the colliding nucleons into their first excited state $\Delta(1232)$) and $\Delta(1600)$ resonances [8–17].

The situation changes strikingly in $pn$ initiated two-pion production. Especially in the case of the purely isoscalar $pn \to d\pi^+\pi^0$ reaction, for which the cross section from the conventional processes was expected to be particularly small and for which also no data yet existed, a strikingly narrow Lorentzian structure in the total cross section was exhibited. The first indications of that were observed at CELSIUS [18]. Later on this resonance structure was measured in detail at COSY with much improved statistics and accuracy [19] leading to $m \approx 2370$ MeV and $J \approx 70$ MeV for mass and width. The latter is more than three times smaller than expected from a conventional $\Delta\Delta$ excitation via the $t$-channel meson exchange. Nevertheless the Dalitz plot clearly shows that this resonance structure decays predominantly via a $\Delta\Delta$ intermediate state, though the resonance mass is about 80 MeV below the nominal mass $2m_\Delta$ of the $\Delta\Delta$ system. The angular distributions measured for this reaction determine the spin-parity of this structure to be $J^P = 3^+$ [19].

Subsequent measurements of all three reactions leading to the double-pionic fusion to the deuteron uniquely determined this structure as being of isoscalar nature. Figure 1, left, shows the experimental decomposition of the isospin-mixed $pn \to d\pi^+\pi^-$ reaction (red symbols) into its isoscalar (blue) and isovector (black) components corresponding to the $d\pi^0\pi^0$ and $d\pi^0\pi^0$ channels, respectively [20]. Note that the latter does not show the resonance structure.

If this structure, indeed, represents a genuine $s$-channel resonance, it has to show up also in the entrance channel, though its effect in $np$ scattering is expected to be very small [21]. For such an investigation the $np$ analyzing power is the most promising observable. Since it consists only of partial-wave interference terms, it is particularly sensitive to small contributions. Hence, in the absence of data from previous experiments, polarized $\bar{n}p$ scattering measurements were conducted with WASA at COSY [22, 23]. The resulting data show a resonance structure in the energy dependence—right at the expected position. On the right-hand side of figure 1, the results are depicted for a center-of-mass scattering angle near $90^\circ$, where the effect of a $J^P = 3^+$ resonance is largest. Inclusion of the WASA data in the SAID data base and its subsequent partial-wave analysis, indeed, produces a pole in the coupled $^3D_3 - ^3G_3$ partial waves at $(2380 \pm 10) - i(40 \pm 5)$ MeV, in agreement with the resonance hypothesis based on the double-pionic fusion results [22, 23] and denoted now accordingly $d^*(2380)$.

In addition to its decay into fusion channels this resonance should decay also into all isospin allowed non-fusion two-pion production channels, i.e. the channels $ppn^0\pi^-$, $pnn^0\pi^-$ and $pnn^0\pi^-$. Again, for lack of appropriate data, the first two channels were studied with WASA at COSY in the energy region of interest. The results (blue solid dots) for the total cross sections are shown in figure 2 together with data from previous experiments (open symbols) [24, 25]. The experiments are again consistent with the appearance of the $d^*$
resonance as expected from isospin relations. Note that the resonance effect does not appear as pronounced here, since it sits on the steep slope of a strongly rising four-body phase-space from conventional processes.

For the $pπ^+π^−$ channel there exist as yet solely bubble-chamber data [26–28]. Within their very limited precision they agree reasonably well with our calculation for this channel, as depicted in figure 2, right. This calculation uses the same conventional background description as used for the other $Nαπ\pi$ channels. For the resonance strength it utilizes the prediction of Albaladejo and Oset [29] and includes also contributions and blue dash-dotted lines their coherent sum. Filled blue circles give the WASA data, while open symbols show previous experimental results, see [24–28].

Figure 2. Dependence of two-pion production to the non-fusion channels $pp → ppπ^0$ (left), $pn → pn\pi^0\pi^0$ (middle) and $pn → ppπ^+π^−$ (right) on the center-of-mass energy $\sqrt{s}$. Black solid lines denote calculations of conventional $\pi$-channel processes leading to Roper, $ΔΔ$ and $Δ(1600)$ excitations in the modified Valencia model. Red dashed lines show the $δ^0$ contributions and blue dash-dotted lines their coherent sum.

3. Comparison to theoretical predictions

A dibaryon state with $I(J^P) = 0(3^+)$ having an asymptotic $ΔΔ$ configuration was already predicted by Dyson and Xuong [1] and even the predicted mass was close to the one observed now. Later on Goldman et al pointed out the unique features of such a state based on its particular symmetries due to its quantum numbers and called it the ‘inevitable dibaryon’ [30].

Recent state-of-the-art three-body [31, 32] and quark-model [33–35] calculations obtain this resonance at about the right mass and partly also reproduce its width.

4. Conclusions

For the first time a genuine dibaryon resonance has been identified by observing it in various decay channels—in particular also in the elastic $pn$ channel. This experimental success was only made possible by kinematically complete (even overdetermined) and exclusive measurements using the best suitable equipment consisting of high-precision storage-ring beams, a pellet target and a hermetic detector covering the full reaction phase-space.

Acknowledgments

We acknowledge valuable discussions with J Haidenbauer, C Hanhart, A Kacharava, E Oset, I Strakovsky, C Wilkin and R Workman on this issue. This work has been supported by BMBF, Research Center Jülich (COSY-FFE) and DFG (CL 214/3-1).

References

[1] Dyson F J and Xuong N-H 1964 Phys. Rev. Lett. 13 815
[2] Gell-Mann M 1964 Phys. Rev. Lett. B 8 214
[3] Jaffe R L 1977 Phys. Rev. Lett. 38 195 and 617(E)
[4] Seth K K 1988 Proc. Baryon-Baryon Interaction and Dibaryonic Systems (Germany: Bad Honnef) 41
[5] Bashkanov M, Brodsky S J and Clement H 2013 Phys. Lett. B 727 438
[6] Bargholtz C et al 2008 Nucl. Inst. Meth. A 594 339
[7] Adam H H et al arxiv: nucl-ex/0411038
[8] Abd El-Bary S et al 2008 Eur. Phys. J. A 37 267
[9] Johanson J et al 2002 Nucl. Phys. A 712 75
[10] Brodowski W et al 2002 Phys. Rev. Lett. 88 192301
[11] Pätzold J et al 2003 Phys. Rev. C 67 052202(R)
[12] Skorodko T et al 2008 Eur. Phys. J. A 35 317
[13] Kren F et al 2010 Phys. Lett. B 684 110
[14] Kren F et al 2010 Phys. Lett. B 702 312 arXiv:0910.0995v2 [nucl-ex]
[15] Skorodko T et al 2011 Phys. Lett. B 695 115
[16] Skorodko T et al 2011 Eur. Phys. J. A 47 108
[17] Skorodko T et al 2009 Phys. Lett. B 679 30
[18] Adlarson P et al 2011 Phys. Lett. B 706 256
[19] Bashkanov M et al 2009 Phys. Rev. Lett. 102 052301
[20] Adlarson P et al 2011 Phys. Rev. Lett. 106 242302
[21] Adlarson P et al 2013 Phys. Lett. B 721 229
[22] Pricking A, Bashkanov M and Clement H arxiv:1310.5532 [nucl-ex]
[23] Adlarson P et al 2014 Phys. Rev. Lett. 112 202301
[24] Adlarson P et al 2014 Phys. Rev. C 90 035204
[25] Adlarson P et al 2013 Phys. Rev. C 88 055208
[26] Adlarson P et al arxiv:1409.2659 [nucl-ex]
[26] Tsuboyama T et al 2000 Phys. Rev. C 62 034001
[27] Brunt D C, Clayton M J and Westwood B A 1969 Phys. Rev. 187 1856
[28] Abdigailiev A et al 1980 Nucl. Phys. B 168 385
[29] Albaladejo M and Oset E 2013 Phys. Rev. C 88 014006
[30] Goldman T et al 1989 Phys. Rev. C 39 1889
[31] Gal A and Garcilazo H 2013 Phys. Rev. Lett. 111 172301
[32] Gal A and Garcilazo H 2014 Nucl. Phys. A 928 73
[33] Huang H, Ping J and Wang F 2014 Phys. Rev. C 89 034001
[34] Yuan X Q, Zhang Z Y, Yu Y W and Shen P N 1999 Phys. Rev. C 60 045203
[35] Huang F, Zhang Z Y, Shen P N and Wang W L
  arxiv:1408.0458 [nuclth]