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A DISCOVERY OF THE DIBARYON STATE WITH WASA-AT-COSY[*]

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The Juelich Cooler Synchrotron (COSY) has been dedicated to the investigation of nucleon–nucleon interactions. Together with the Wide Angular Shower Apparatus (WASA) detector, it has been particularly well-suited for the search of exotic phenomena in baryon–baryon systems. Recent experiments with WASA-at-COSY have now found support for a new resonant state in the two-baryon system with mass 2380 MeV and a width of 70 MeV — the first non-trivial dibaryon resonance. A review on this issue is given in this paper.

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1. Introduction

Exotic hadrons — strongly interacting particles that are neither quark–antiquark pairs (mesons) nor three-quark states (baryons) — can now be hardly enumerated due to massive discoveries during last decade. In addition to well-established $f^0(500)$ and $a^0/f^0(980)$ meson–meson molecules, we have a vast amount of new molecular/tetraquark states in the charm sector (irreducible $4q$ configuration) [1]. Various meson–baryon molecules in the light sector like $\Lambda(1405)$ [2] and $N^*(1535)$ [3] extended by recent observations of similar states in the charm sector by LHCb ($5q$ states) [4]. Search for possible ppK^- clusters suggests an existence of $\Lambda(1405)$–N state ($5q+3q$ — 8 quark state). In such a company, the discovery of the first non-trivial dibaryon (a state with baryon number $B=2$ without inference on its internal structure [hexaquark/baryonic-molecule]) by WASA-at-COSY stays in line [5–11].

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The lesson we learn from years of searching for exotic hadrons is that one need a dedicated detector equipment and distinctive production mechanism to become successful. The discovery of the $d^*(2380)$ dibaryon required intensive nucleon beam, high density proton/neutron target, high-acceptance and high rate detector with the possibility to measure the four-momenta of both neutral and charged particles. The WASA detector with a nearly full solid angle coverage in combination with COSY delivering a cooled beam with high momentum resolution and pellet target system was uniquely adapted to search for resonances in the nucleon–nucleon collision process. In the following, a review is given on the finally successful search for dibaryon resonances at WASA.

2. The WASA detector

The 4π detector facility WASA was designed for studies of production and decays of light mesons in an internal-target experiment at the CELSIUS accelerator and cooler storage ring [12]. It was working in Sweden till 2005 providing complete dataset of multi-pion production in pp-collisions from threshold up to $\sqrt{s} = 2.5$ GeV. While moving to COSY accelerator in 2006, it was upgraded to cope with higher energies and luminosities of the COSY ring [12].

Close to 4π acceptance, sensitivity to neutral and charged particles together with very high efficiency make the WASA detector to be a perfect tool for baryon–baryon interaction studies at moderate energies. Uniformity in azimuthal angle also simplify analysis of polarisation data.

3. Background

Searches for exotic particles can be affected by background. One needs to be confident that the bumps observed in the system with exotic quantum numbers do not originate from conventional process. Systematic study of two-pion production in pp-collisions at CELSIUS/WASA allowed to identify major production mechanisms and fix conventional-type background to sub-microbarn level. As a result of these studies, it was found that isovector induced two-pion production can be quantitatively well-understood by the conventional process of t-channel meson exchange leading to the excitation of Roper resonance close to threshold followed by the excitation of the $\Delta\Delta$ system at higher energies. To some extent, also the $\Delta(1600)$ excitation is seen to play some role [13–15]. But no hint for an exotic resonance production was observed. The situation changed drastically, when pn-induced two-pion production was looked at.

4. First non-trivial dibaryon

pn-induced two-pion production is more complicated than isovector case, since free neutrons are not available — neither as beam nor as target particles. Hence, we utilised the quasi-free process with deuterons being the source of quasi-free neutrons. This process has the additional advantage that the Fermi motion of the neutron within the deuteron provides a range of collision energies with a single beam energy setting. That way the energy dependence of a reaction can be conveniently scanned, which is particularly well-suited for the search of narrow resonances. However, a precondition for a successful use of the quasi-free process is that the four-momenta of all ejectiles (including spectator nucleon) are determined experimentally, which necessitates exclusive and kinematically complete measurements.

First such measurements were conducted still with WASA at CELSIUS [7]. Though the statistics was limited, a strong deviation from conventional physics was observed in the reaction $pn \to d\pi^0\pi^0$ at around $\sqrt{s} = 2.38$ GeV. As it turned out later, this was the golden channel for the dibaryon issue, since it possesses a very low background from conventional processes [8, 9]. Experimentally, it was only accessible with instruments like WASA being able to detect both charged and uncharged particles over essentially the full solid angle. Hence, it is not a surprise that there are no data for this channel from previous experiments. Another measurements of $pd \to {}^3\mathrm{He}\pi^0\pi^0$ [16, 17] and $dd \to {}^4\mathrm{He}\pi^0\pi^0$ [18] at similar energy range supported the idea that *pn*-related two-pion production is far more complex than anticipated before.

A follow-up measurement with WASA-at-COSY with many orders of magnitude higher statistics provides the solution of this puzzle — first non-trivial dibaryon resonance with the quantum numbers $I(J^P) = 0(3^+)$, mass $M = 2380$ MeV and the width of $\mathit{\Gamma} = 80$ MeV. It has been denoted since then by $d^*(2380)$ following the nomenclature used for nucleon excitations [5, 6, 8–11, 19].

5. Experimental evidences for a dibaryon resonance

As mentioned before, the golden reaction channel for the observation of the $d^*(2380)$ dibaryon turned out to be $pn \to d\pi^0\pi^0$ [8, 9], due to the absence of the isovector background (present in $pn \to d\pi^+\pi^-$ [9]) and only moderate contributions from conventional processes due to *t*-channel Roper and $\mathit{\Delta\Delta}$ excitations [13–15]. Both deuteron and π^0-pair play as a powerful spin–isospin filter.

5.1. The $pn \to d\pi^0\pi^0$ reaction

A pronounced Lorentzian structure observed in the total cross section of the $pn \to d\pi^0\pi^0$ reaction around $\sqrt{s} = 2.38$ GeV corresponds to a narrow dibaryon resonance $d^*(2380)$. From pp-collisions, we know all sizable conventional contributions to two-pion production and can relate them to the pn-case. One finds that the Roper-resonance and the $\Delta\Delta$ production cannot build up such structure neither in size nor in shape [8]. There are no other baryonic resonances in the range, which can decay into the two-pion channel with sizable strength. Especially there are no resonances, which can be excited only in the neutron, hiding their existence in the pp-case. Thus, the only way to understand the total cross section behaviour is to assume the existence of a dibaryonic resonance d^* with mass $M = 2380$ MeV and width $\Gamma = 80$ MeV [5, 6, 19]. Since this resonance can interfere with known, conventional amplitudes, intrinsic mass and width can vary slightly.

In order to establish that the observed structure is a genuine resonance, among others, we need to demonstrate that it has specific quantum numbers. The $M_{d\pi}$ invariant mass distribution in the $pn \to d\pi^0\pi^0$ reaction is consistent with excitations of two Δ-resonances. Since $\sqrt{s} = 2.38$ GeV is below the nominal $\Delta\Delta$ threshold by 85 MeV, two Δ-resonances are expected to be predominantly in relative S-wave. The angular distribution of the reconstructed Δs are in agreement with this assumption. That limits quantum numbers of the possible resonance to be $J^P = 1^+$ or 3^+. The angular distribution of the deuteron in the Center-of-Mass System (CMS) is consistent with $J^P = 3^+$ assignment [8, 9].

5.2. The $pn \to d\pi^+\pi^-$ reaction

This reaction contains both isovector and isoscalar components. Assuming isospin conservation, its total cross section should equal the incoherent sum of $pn \to d\pi^0\pi^0$ and $pp \to d\pi^+\pi^0$ reactions: $\sigma(pn \to d\pi^+\pi^-) = 2\sigma(pn \to d\pi^0\pi^0) + 1/2\sigma(pp \to d\pi^+\pi^0)$. All invariant mass distributions can be also decomposed into pure isoscalar and pure isovector components. Such a triangular relation works very well barring isospin violations due to different masses of charged and neutral pions near thresholds [9].

5.3. The other two-pion decays of the d^* resonance

Adopting the quantum numbers and the total cross section for the $pn \to d\pi^0\pi^0$ reaction, one can estimate the d^* production cross section for the non-fusion channels. More refined calculations accommodating for the different phase-space situations have been carried out by Fäldt and Wilkin [20] as well as Albaladejo and Oset [21]. These estimates and calculations, respectively agree with experimental observations very well [19]. Due to the much higher level of conventional two-pion production background in the non-fusion reactions, *i.e.* $pp\pi^-\pi^0$, $nn\pi^+\pi^0$, $pn\pi^0\pi^0$ and $pn\pi^+\pi^-$, a determination of the d^* decay branches from these reactions is not easy [10, 11]. As well as the interpretation, the experimental extraction is challenging, involving neutron in the initial state, final state or both. Nevertheless, such measurements could be successfully performed by the WASA Collaboration. The d^* dibaryon decay properties were evaluated in Ref. [19].

5.4. d^* resonance in pn-elastic scattering

The principally simplest reaction, where the d^* resonance can be observed, is pn-elastic scattering [22]. It has several advantages over the two-pion production reactions. Elastic scattering is a two-body reaction, so one can reliably perform a model-independent partial-wave analysis. Also, one has good experimental access to polarisation observables, which are very sensitive to tiny contributions from rare processes. The reaction has been well-known since decades, among others it has also been used for intensive searches for dibaryons.

There has been only one problem — no data existed in the region of interest. It was shown in Ref. [22] that the most sensitive observable for the detection of the d^* dibaryon in pn-elastic scattering is the vector analysing power A_y.

From isospin and angular momentum conservation, one can deduce that a $I(J^P) = 0(3^+)$ resonance can be seen only in pn scattering, *i.e.*, not in pp or nn and only if the pn system is in ${}^3D_3$ or ${}^3G_3$ partial waves.

The recent exclusive and kinematically complete measurements performed by the WASA-at-COSY Collaboration together with the partial wave analysis of the SAID Group suggested that there is a resonance pole at $(2380 \pm 10) - i(40 \pm 5))$ MeV in the ${}^3D_3$–${}^3G_3$ coupled partial waves of np scattering [5, 6, 23]. This finding matches with the $I(J^P) = 0(3^+)$ resonance structure observed at $\sqrt{s} = 2.38$ GeV and width of 70 MeV in the total cross section of four two-pion production reactions [7–11]. Having revealed the pole in the np scattering amplitudes means that this resonance structure constitutes a genuine s-channel resonance in the system of two baryons.

5.5. d^* resonance in nuclear matter

If dibaryons exist and if they even survive in a nuclear surrounding, then they should have an impact on the nuclear equation of state, which is of relevance not only for heavy-ion collisions but also for very compact stellar objects like neutron stars. Dibaryons are bosons, hence not Pauli-blocked, thus allowing for higher densities of compressed nuclear matter. The effect of dibaryons on the equation of state for nuclear matter has been considered in various theoretical investigations, see *e.g.* Refs. [24–27]. Therefore, investigation of the $d^*(2380)$ dibaryon behaviour in nuclear medium might be an essential step for future neutron star investigations.

d^* production with one or two accompanied nucleons was studied by the WASA Collaboration first at CELSISUS and later-on at COSY in details. The signature of $d^*(2380)$ resonance is observed also in the double-pionic fusion reactions to ^{3}He [16, 17] and ^{4}He [18], *e.g.* in reactions $pd \to {}^3\mathrm{He}\pi\pi$ and $dd \to {}^4\mathrm{He}\pi\pi$ respectively. Obviously, the $d^*(2380)$ is robust enough to survive even in the nuclear environment.

The enhancement in the dilepton spectrum observed in heavy-ion collisions for invariant electron–positron masses in the range of 0.15 GeV$< M_{e^+e^-} <$ 0.6 GeV has recently been traced back to a corresponding enhancement in pn collisions relative to pp collisions [28]. Whereas the dilepton spectra from pp collisions are understood quantitatively, theoretical descriptions fail to account for the much higher dilepton rate in pn collisions — in particular regarding the region $M_{e^+e^-} > 0.3$ GeV at beam energies below 2 GeV (“DLS Puzzle” [29, 30]). In Ref. [31], it has been shown that the missing strength can be attributed to ρ^0 channel $\pi^+\pi^-$ production, see Fig. 5 of Ref. [31], which is dominated by conventional $\Delta\Delta$ excitation due to the t-channel meson exchange and contributions from $d^*(2380)$.

6. Structure of the $d^*(2380)$

All the data [5–11] collected so far suggest that in 88 percent of cases d^* decays into $\Delta\Delta$ and in 12% to pn [19, 22]. It can be further specified that 90% of the pn decays proceed via $^3D_3$ partial wave (angular momentum $L = 2$ between nucleons) and 10% via $^3G_3$ partial wave ($L = 4$) [5, 6]. In the case of the $\Delta\Delta$ branch, at least 5% of the decays could be expected to proceed with two Δs in relative D-wave ($L = 2$) [32] — a remarkable feature for the 80 MeV sub-threshold system. One should also note that the S-wave $\Delta\Delta$ system cannot decay into the $L = 4$ pn state within one-step, whereas the D-wave $\Delta\Delta$ part can. Therefore, it might be reasonable to assume that at least 5% of the $\Delta\Delta$ component in the d^* wave function is a D-wave $\Delta\Delta$ — very similar to a deuteron with its 5% of D-wave pn admixture. The wave function of the $d^*(2380)$ can then be subdivided into 67% hexaquark, 31% S-wave $\Delta\Delta$ and 2% D-wave $\Delta\Delta$ configuration. [33].

7. Summary and outlook

After a vast number of unsuccessful searches, a support for a non-trivial dibaryon resonance has now been found and its major decay channels have been identified. What is missing, is a measurement of its electromagnetic form factor, in order to learn about the size of this object — whether it is of molecular type or a compact six-quark entity. Further experiments at MAINZ and JLab are expected to resolve this question. Other dibaryon resonances are still waiting to be discovered.

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