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Recent results from WASA-at-COSY

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The detector system WASA-at-COSY has been operated at the Cooler Synchrotron COSY in the years from 2006 till 2015. In this article we report on recent results of the analyses of the meson production reactions in nucleon-nucleon, nucleon-deuteron and deuteron-deuteron collisions with spin-polarized and unpolarized beams emphasizing the evidences for the existence of the dibaryon state in the proton-neutron system and the perspectives for the search of the η-mesic helium.

KEYWORDS: η-meson, dibaryon, η-mesic nuclei

1. Introduction

The WASA-at-COSY collaboration performed experiments dedicated primarily to study of η and ω meson production and its rare decays [1, 2] and to search for new kind of exotic nuclear matter in form of dibaryons [3, 4] and η-mesic nuclei [5, 6]. The experiments were carried out in the Forschungszentrum Jülich, Germany with the WASA (Wide Angle Shower Apparatus) detector [7] installed at COSY accelerator [8].

In the paper we concentrate on the discovery of the dibaryon in pp and np induced two-pion production processes and the status of the search for the η-mesic ^{4}He in $dd \to {}^3\mathrm{He}p\pi^-$ and $dd \to {}^3\mathrm{He}n\pi^0$ reactions.

2. Two-Pion Production and the Observation of a Dibaryon Resonance

Since on the one hand the data base on two-pion production in nucleon-nucleon collisions was very marginal and since on the other hand this reaction was expected to have the potential to reveal exotic phenomena, the WASA collaboration performed a program to systematically study the various two-pion production channels by exclusive and kinematically complete high-statistics experiments. Corresponding measurements with the hermetic WASA detector setup started still at CELSIUS (Uppsala) and were then continued at COSY which much superior beam conditions.

2.1 Proton-proton induced two-pion production

The program started out with measurements of two-pion production in proton-proton collisions from close to threshold up to $T_p = 1.4$ GeV ($\sqrt{s} = 2.5$ GeV) [9–17]. Special attention was paid to the $pp\pi^0\pi^0$ channel, where the previous bubble-chamber results suggested a kink in the total cross section around $T_p = 1.2$ GeV. High-statistics measurements with WASA confirmed this kink. In subsequent isospin decomposition of the total cross sections according to the formalism presented in Refs. [18, 19] it could be demonstrated that baryon resonance excitation and its subsequent decay into the two-pion channel are the leading processes [13]. At low energies the excitation of the Roper resonance by t-channel meson exchange and its subsequent decay into the $N\pi\pi$ channel is the dominating process. At higher energies this is replaced by the mutual excitation of the colliding nucleons into their first excited state, the Δ resonance with subsequent decay into the $N\pi$ channel – the so-called t-channel $\Delta\Delta$ process – as properly predicted by the Valencia theory group [20] and later-on also by the Beijing model calculations [21].

Still much more information about the reaction process is, of course, contained in the various differential distributions, which have been all available from the kinematicaly complete measurements. By fine adjustments of resonance and interaction parameters in the Valencia model calculations all differential distributions could be described quantitatively.

As a result of these systematic 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 the 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 might play some role.

This conclusion also applies to the isovector double-pionic fusion process $pp \to d\pi^+\pi^0$. Measurements of its differential cross sections around $\sqrt{s} \approx 2.4$ GeV are in good agreement with t-channel $\Delta\Delta$ calculations. The energy dependence of the total cross section conforms well with these calculations, too, exhibiting a resonance-like structure with a width of about $2\Gamma_\Delta$ [14, 22].

2.2 Neutron-proton induced two-pion production

The situation changed drastically, when pn-induced two-pion production was looked at. These measurements were carried out with either a deuteron beam or deuterium target utilizing the quasi-free process.

For the $d\pi^0\pi^0$ channel there existed no previous measurements, since at other hadron research installations no hermetic detector like WASA has been available, which is capable to detect charged and neutral particles over a solid angle of nearly 4π. By use of isospin relations [18, 19] the cross section of the t-channel $\Delta\Delta$ process in the $d\pi^0\pi^0$ channel can be estimated to be 1/5 of that in the $d\pi^+\pi^0$ channel, *i.e.*, a peak cross section of only 0.06 mb at $\sqrt{s} \approx 2.5$ GeV.

Our measurements for this channel depicted Fig. 1 revealed the cross section around 2.5 GeV to be, indeed, such small. However, the big surprise was that below this energy a much larger cross section with a very pronounced narrow resonance-like structure was observed corresponding to a mass m = 2370 MeV and width $\Gamma = 70$ MeV. From the measured deuteron angular distribution it was deduced that the resonance structure is in accord with a spin $J = 3$ assignment [23]. Together with the isoscalar character of this reaction this gives $I(J^P) = 0(3^+)$ for the resonance structure. The Dalitz plot as well as the pion and $N\pi^0$ angular distributions suggest a $\Delta\Delta$ configuration in relative s-wave as an intermediate configuration, which according to the mass of the resonance structure must be bound by about 90 MeV [23, 24].

In subsequent measurements of the $pn \to d\pi^+\pi^-$ reaction (Fig. 1, red symbols) and isospin decomposition of its total cross section according to [18, 19, 22]

$$\sigma(pn \to d\pi^+\pi^-) = 2\sigma(pn \to d\pi^0\pi^0) + \frac{1}{2}\sigma(pp \to d\pi^+\pi^0). \tag{1}$$

it has been demonstrated that the resonance structure shows up only in the isoscalar

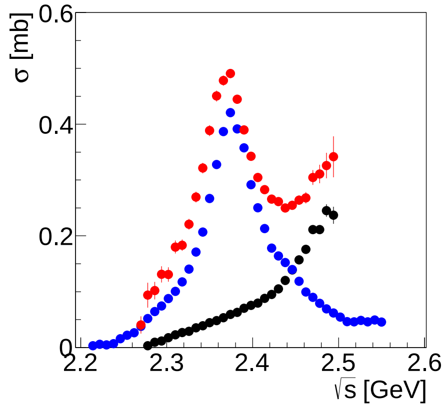

Fig. 1. WASA measurements of the total cross sections in double-pionic fusion [22]. Shown is the energy dependence of the cross section of the $pn \to d\pi^+\pi^-$ reaction (red symbols) isospin decomposed into its isoscalar part ($2\sigma_{pn\to d\pi^0\pi^0}$, blue symbols) and its isovector part ($\frac{1}{2}\sigma_{pp\to d\pi^+\pi^0}$, black symbols).

part (Fig. 1, blue symbols), but not in the isovector part (Fig. 1, black symbols) of the double-pionic fusion to the deuteron, *i.e.* has definte isospin $I = 0$.

Next, also the non-fusion two-pion production channels $pn \to pp\pi^0\pi^-$ [25], $pn \to pn\pi^0\pi^0$ [26], $pn \to pn\pi^+\pi^-$ [27] have been investigated. Since these reactions are only partially isoscalar, the contributions of the conventional processes relative to the expected isoscalar d^* contribution are here much larger. Though the d^* signal here does not appear as pronounced as in the golden double-pionic fusion channel $pn \to d\pi^0\pi^0$, it still could be observed clearly.

As as result all two-pion production channels are consistent with the hypothesis of an $I(J^P) = 0(3^+)$ dibaryon resonance at 2.37 GeV with a width of 70 MeV. The observed d^* decay branchings into the diverse two-pion channels are consistent with expectations from isospin decomposition [28] as well as explicit theoretical calculations [29–31].

2.3 $d^*(2380)$ *– a genuine dibaryon resonance*

In order to establish the resonance structure observed in two-pion production as a true resonance, *i.e.* a s-channel resonance, it has to be observed also in the entrance channel, *i.e.* in np scattering.

From the knowledge of the resonance contributions to the various two-pion production channels the expected resonance contribution to elastic np scattering has been estimated [28] to be in the order of about 170 μb. This number has to be compared to a total np cross section of nearly 40 mb. The only easily accessible observable with the potential to sense such a small contribution, is the analysing power, since it contains only interference terms in the partial waves and hence can sense even small contributions in the partial waves. Due to the spin of the resonance the resonance contribution is expected to be largest at 90°, *i.e.*, at the angle, where the differential cross section is smallest. For the sensitivity of other observables to the d^* resonance contribution see Ref. [32]

Since there were no analyzing power data in the region of interest, corresponding analyzing power measurements extending over practically the full angular range were carried out with WASA at COSY — again in the quasi-free mode, but in inverse kinematics by use of a polarized deuteron beam hitting the hydrogen pellet target [33, 34].

The obtained data for the analyzing power show the $d*$ resonance effect as expected. A subsequent SAID partial-wave analysis of all pn scattering data including the new WASA

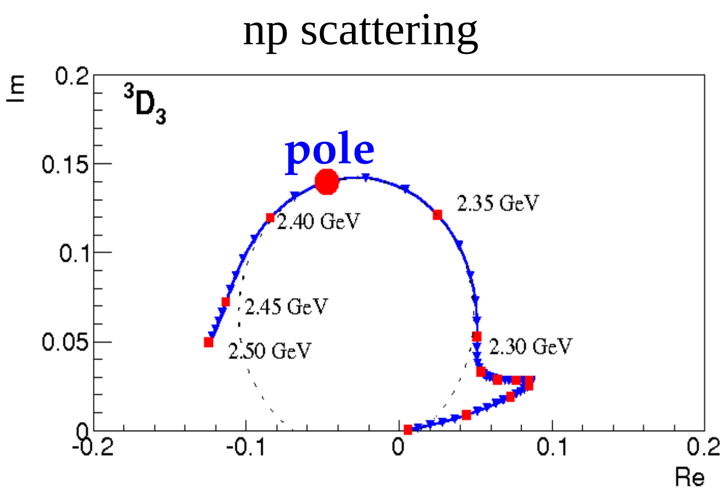

Fig. 2. Result of the SAID partial-wave analysis of np scattering data including the WASA analyzing power data. Shown is the resonating $^3D_3$ partial wave looping in its Argand diagram. From Refs. [32, 34].

results for the analyzing power, indeed, revealed a pole in the coupled $^3D_3 -^3 G_3$ partial waves at the position $(2380 \pm 10) - i(40 \pm 5)$ MeV – fully consistent with the findings in the two-pion production reactions [32–34]. The Argand plot of the resonating $^3D_3$ partial wave is shown in Fig. 2.

This result establishes the resonance structure observed in two-pion production as a true s-channel resonance in the proton-neutron system. Since it is of isoscalar character, $d^*(2380)$ has been chosen as its denotation in analogy to the notation for isoscalar excitations of the nucleon. The notation d^* was used already by Goldman *et.al.* [36] when predicting the so-called "inevitable dibaryon" with identical quantum numbers.

The first, who predicted such a dibaryon state were Dyson and Xuong [35] with a mass remarkably close to the now discovered one. The Los Alamos theory group [36] originally predicted its mass to be lower by as much as 200 MeV. However, its recent calculations [37] agree with the experimental value. Another real prediction of this state at the proper mass is from Z. Y. Zhang *et.al.* (IHEP) [38] based on a quark-model description in the framework of the resonating group method. This group also is so far the only one, who can reproduce the narrow width of $d^*(2380)$ by accounting for hidden color configurations [31]. A Faddeev-type calculation using hadronic interactions succeeded recently to reproduce the d^* mass [39, 40], too, though the calculated width is somewhat larger than the observed one.

2.4 ABC effect and double-pionic fusion

The so-called ABC effect denoting a low-mass enhancement in the $\pi\pi$-invariant mass spectrum of double-pionic fusion reactions has been found [23, 24] to be strictly correlated to the dibaryon resonance $d^*(2380)$ in the double-pionic fusion to deuterium, where it just reflects the vertex function of the decay $d^*(2380) \to \Delta\Delta$ [41]. Since the ABC effect had been observed earlier also in the double-pionic fusions to ^{3}He and ^{4}He, the corresponding reactions $pd \to ^3\mathrm{He}\pi\pi$ [42,43] and $dd \to ^4\mathrm{He}\pi^0\pi^0$ [44] have been measured as well by WASA in the region of the ABC effect. In fact, also here these reactions exhibit the $d^*(2380)$ resonance effect, however, being broadened by Fermi motion and collision damping. This means that $d^*(2380)$ obviously survives even in a nuclear surrounding. This conclusion is supported by a possible solution of the so-called DLS puzzle in heavy-ion collisions by accounting for a

$d^*(2380)$ excitation there [45].

3. Search for η-mesic helium

The search for η-mesic bound states, postulated by Haider and Liu over thirty years ago [46], is performed by WASA-at-COSY group since 2008. We search for the signal of the production of the ^{4}He-η and ^{3}He-η bound states using the WASA detector system [7] with a deuteron target of pellet type installed at the COSY synchrotron [8]. COSY provided deuteron and proton beam for the search for ^{4}He-η and ^{3}He-η mesic nuclei, respectively. The main advantage of the used experimental setup was the possibility of continuous beam energy changing and for some of the channels it was possible to register all particles taking part in the reaction. The deuteron beam momentum was varying from 2.127 GeV/c to 2.422 GeV/c, while the proton beam momentum from 1.426 GeV/c to 1.635 GeV/c, crossing the kinematic threshold for η production. In both cases the beam momentum variation correspond to a range of excess energies Q from -70 MeV to 30 MeV.

The signatures of the η-mesic nuclei are searched for by studying the excitation function for the chosen decay channels of the ^{4}He-η and ^{3}He-η systems, formed in d-d and p-d collisions, respectively.

3.1 Results for the search of ^{4}He-η mesic nuclei

In 2008 and 2010 we performed the measurements dedicated to search for the ^{4}He-η bound states in deuteron-deuteron fusion reaction [47, 49]. The η-mesic nuclei were searched via studying of excitation function for the $dd \rightarrow {}^3\mathrm{He}p\pi^-$ (2008 and 2010) [5, 50, 51] and $dd \rightarrow {}^3\mathrm{He}n\pi^0$ [50, 52] (2010) reactions in the vicinity of the ^{4}Heη threshold. The maximum below the threshold would indicate the production of the $({}^4\mathrm{He}\text{-}\eta)_{bound}$ produced via the reaction: $dd \rightarrow ({}^4\mathrm{He}\text{-}\eta)_{bound} \rightarrow {}^3\mathrm{He}N\pi$. During the experiment the beam momentum was increasing slowly and continuously crossing the threshold for the $dd \rightarrow {}^4\mathrm{He}\eta$ reaction in each of acceleration cycle. In the first experiment, the beam momentum was changed in interval corresponding to the range of excess energy Q from about -51 MeV to 22 MeV, while in the second to the excess energy range from -70 MeV to 30 MeV.

Our first results did not reveal any statistically significant signal from the η-mesic ^{4}He nucleus. The upper limit for the cross-section for the bound state formation and decay in the $dd \rightarrow ({}^4\mathrm{He}\text{-}\eta)_{bound} \rightarrow {}^3\mathrm{He}p\pi^-$ process was determined at the 90% confidence level [5, 51]. The upper limit depends mainly on the width of the bound state and its dependence on the binding energy is only slight. It varies from 20 nb to 27 nb as the width of the bound state varies from 5 MeV to 35 MeV.

In 2015 we have completed analysis of the 2010 data sample with 20 times larger statistics with respect to the 2008 data. The excitation functions determined for $dd \rightarrow {}^3\mathrm{He}p\pi^-$ and $dd \rightarrow {}^3\mathrm{He}n\pi^0$ processes do not show any narrow structure which could be interpreted as a signature of the bound state with width larger than 5 MeV and less than 50 MeV. Therefore, the preliminary upper limit of the total cross-section for the η-mesic ^{4}He formation and decay was estimated for bound state production and decay in $dd \rightarrow ({}^4\mathrm{He}\text{-}\eta)_{bound} \rightarrow {}^3\mathrm{He}N\pi$ processes [6]. The analysis taking into account the isospin relation between the $n\pi^0$ and $p\pi^-$ pairs outgoing from the N^* decay (probability of $p\pi^-$ pair production is two times higher than in case of $n\pi^0$ production) results in the upper limit varying in the range from 2.5 to 3.5 nb for the $dd \rightarrow ({}^4\mathrm{He}\text{-}\eta)_{bound} \rightarrow {}^3\mathrm{He}n\pi^0$ process and from 5 nb to 7 nb for the $dd \rightarrow ({}^4\mathrm{He}\text{-}\eta)_{bound} \rightarrow {}^3\mathrm{He}p\pi^-$ process (for the fixed binding energy B_s=30 MeV and width range $\Gamma \in$(5,50) MeV). The obtained results are presented in Fig. 3. The green area presents the systematics errors [6].

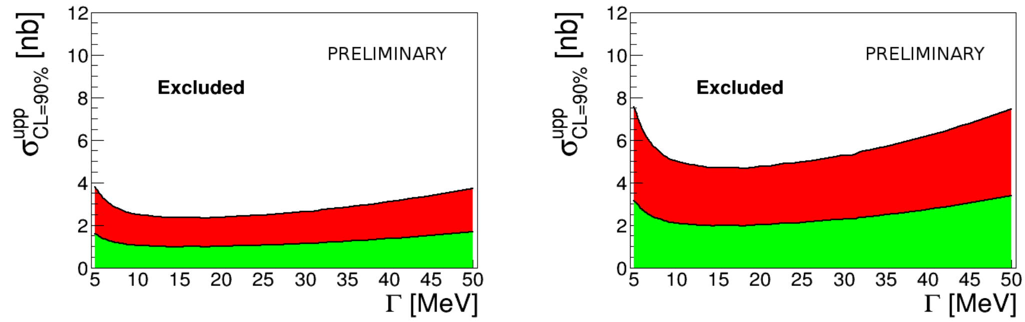

Fig. 3. Preliminary upper limit of the total cross-section for $dd \to (^4\text{He-}\eta)_{bound} \to {}^3\text{He}n\pi^0$ (left panel) and $dd \to (^4\text{He-}\eta)_{bound} \to {}^3\text{He}p\pi^-$ (right panel) reaction as a function of the width of the bound state. The binding energy was fixed to 30 MeV. The upper limit was determined via the simultaneous fit for both channels. The green area denotes the systematic uncertainties. The figure is adopted from [6].

We achieved a sensitivity of the cross-section of the order of few nb for the $dd \to (^4\text{He-}\eta)_{bound} \to {}^3\text{He}p\pi^-$ reaction that is about four times better result in comparison with those obtained from 2008 data [5]. Moreover, the obtained upper limit value does not exclude the cross-section σ_{tot} =4.5 nb estimated in Ref. [53]. The excitation function for the $dd \to (^4\text{He-}\eta)_{bound} \to {}^3\text{He}n\pi^0$ reaction was investigated for the first time. We may conclude that the data collected with the WASA-at-COSY detector in 2010 do not show a signal for a narrow ^{4}He-η mesic nucleus [6]. However, the theoretical interpretation with respect to very wide $(^4\text{He-}\eta)_{bound}$ or ^{3}He-N^* bound system is in progress [54, 55].

3.2 Perspectives

At present we continue the search for the η mesic ^{3}He. For this purpose a high statistics experiment was performed with the WASA detector in 2014 [56]. With respect to the previous search [48] we expect to improve by at least an order of magnitute both the statistical and systematic precision. We considered processes corresponding to the three mechanisms: (i) η meson absorption by one of the nucleons, which subsequently decays into N-π pair e.g.: $pd \to (^3\text{He-}\eta)_{bound} \to ppp\pi^-$, (ii) η meson decay while it is still "orbiting" around a nucleus e.g.: $pd \to (^3\text{He-}\eta)_{bound} \to {}^3\text{He}2\gamma$ reaction and (iii) few nucleon absorption of η meson e.g.: $pd \to (^3\text{He-}\eta)_{bound} \to ppn$. Analysis of the collected data is in progress.

Also another international collaborations perform experimental searches for η and η'-mesic nuclei [49] in hadro- and photo-production reactions [57, 58]. The Eta-prime/Super-FRS collaboration for the first time have performed the search for η' - mesic bound statess in inclusive measurement of the ^{12}C(p,d) process [59, 60] while, at J-PARC the search for η-mesic nuclei is planned in pion induced reaction [61]. The data analysis is in progress. In parallel to the experimental investigations, several theoretical studies are ongoing [53, 62–77].

4. Acknowledgments

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