Pion production in nucleon-nucleon collisions and the issue of dibaryons

T. Skorodko[1,2,*], H. Clement[1], and M. Bashkanov[3]
for the WASA-at-COSY Collaboration

[1]Physikalisches Institut, Eberhard Karls Universität Tübingen, Auf der Morgenstelle 14, D-72076 Tübingen, Germany
[2]Department of Physics, Tomsk State University, 36 Lenin Ave., Tomsk, 634050 Russia
[3]School of Physics and Astronomy, The University of Edinburgh, James Clark Maxwell Building, Peter Guthrie Tait Road, Edinburgh EH9 3FD, Great Britain

Abstract. Pion production in nucleon-nucleon collisions is tightly connected with the issue of dibaryons. After having established the existence of the narrow dibaryon resonance $d^*(2380)$ with $I(J^P) = 0(3^+)$ by two-pion production and elastic proton-neutron scattering experiments, the discussion focuses now on its structure, whether it is a dilute molecular-like or a compact hexaquark object. These scenarios are confronted with experimental branching ratios and other observables. New WASA data for the $pp \to pp\pi^+\pi^-$ reaction give evidence for the existence of an isotensor ΔN threshold state with $J^P = 1+$ as calculated recently by Gal and Garcilazo and predicted earlier by Dyson and Xuong. New ANKE results suggest the dibaryon spectrum to be richer than expected.

1 Introduction

Since pions are the lowest-mass messengers of subnucleonic degrees of freedom, the production of one or more pions in nucleon-nucleon collision processes is outstandingly suited to search for resonances in the two-baryon system.

Already in the fifties first experiments on single-pion production found first indications for a resonance near the ΔN threshold. The nature of this resonance structure seen in the single-pion production reaction $pp \to d\pi^+$ as well as in πd and pp scattering — in the latter in the $^1D_2$ isovector nucleon-nucleon (NN) partial wave — has been discussed controversially as an t- or s-channel object all the time since then. For a detailed review on this and other dibaryon searches see Ref. [1].

It took until the beginning of this millennium, when the first non-trivial, narrow dibaryon resonance could be established by WASA at CELSIUS and COSY. The dibaryon resonance $d^*(2380)$ with $I(J^P) = 0(3^+)$ and a width of only 70 MeV – first observed in the double-pionic fusion to the deuteron [2–5] – has meanwhile been detected by WASA in all relevant two-pion production channels [6–10]. In addition, its resonance pole has been revealed in neutron-proton scattering [11–13].

Theoretical calculations describe this state either as a compact hexaquark [14, 15] or as a dilute molecular-like object [16, 17]. Remarkably, this state was properly predicted already

*e-mail: skorodko@pit.physik.uni-tuebingen.de

in 1964 by Dyson and Xuong [18] as one of six non-strange dibaryon states. Denoted by the nomenclature $D_{IJ} = D_{03}$ they predicted a bound $\Delta\Delta$ system with $I(J^P) = 0(3^+)$ at a mass of 2350 MeV and proposed to search for it in $NN \to NN\pi\pi$ reactions. The other members of that dibaryon multiplet were associated by Dyson and Xuong with the deuteron groundstate (D_{01}), the virtual $^1S_0$ state (D_{10}) as well as with ΔN threshold states D_{12} and D_{21} and a strongly bound $\Delta\Delta$ system D_{30} at 2350 MeV with quantum numbers mirrored to those of $d^*(2380)$. Whereas D_{12} can be identified with the pole in the $^1D_2$ isovector NN partial wave, D_{21} and D_{30} are still purely hypothetical. However, recent state-of-the-art Faddeev calculations by Gal and Garcilazo predict all theses states, too, at similar masses [19, 20].

2 Status of $d^*(2380)$

The excitation and decay of $d^*(2380)$ has meanwhile been observed in all pn induced two-pion production channels containing isoscalar contributions [2–10] as well as in elastic pn scattering [11–13]. The extracted branching ratios are given in Refs. [1, 12, 21].

In recent years various theoretical investigations of the nature of $d^*(2380)$ appeared based either on quark-gluon [14, 15, 22–27] or hadronic [16, 17, 19, 20] interactions. A correct prediction of the mass of $d^*(2380)$ – before its experimental observation – has been given in Ref. [25], where this state was studied in the chiral SU(3) constituent quark model within the resonating group method. Meanwhile also a QCD sum rule study has found this state at the right mass region [27], whereas a QCD-based work without inclusion of hadronic degrees of freedom can construct such a state as a compact object only at much higher masses [28]. Most recently first lattice QCD calculations were presented by the HAL QCD collaboration [29] finding evidence for a bound $\Delta\Delta$ system with the quantum numbers of $d^*(2380)$. Since in these calculations the pion mass is still unrealistically large, the lattice results were recently extrapolated down to the real pion mass by methods based on effective field theory with the result that indeed such a state is likely to exist [30].

Model calculations based on hadronic interactions [16, 17, 19, 20] predict for $d^*(2380)$ a molecule-like structure having a $D_{12}\pi$ configuration of size as large as that of the deuteron. To the contrary, quark model calculations [14, 15, 23, 31] predict a compact hexaquark object of size 0.8 fm possessing asymptotically a tightly bound $\Delta\Delta$ configuration.

Whereas the d^* decay into two-pion channels does not discriminate between these two scenarios, since the isospin selection rules are identical for both $d^* \to \Delta\Delta \to NN\pi\pi$ and $d^* \to D_{12}\pi \to NN\pi\pi$ [1, 16], the decay into single-pion channels is very discriminatory. In the hexaquark case this decay is heavily suppressed with a branching less than 1% [32]. In the molecular-like case a branching of as much as 18% is expected. In order to clarify this situation we have measured the isoscalar single-pion production in the energy region of d*(2380). As a result we find no evidence for such a decay with an upper limit of 9% (90% C.L.) [33]. This is in support of a compact hexaquark system being the dominant configuration. In Ref. [16] it is demonstrated that $d^*(2380)$ must consist to at least 5/7 of the $\Delta\Delta$ configuration, in order to account for the measured width and branching ratios of $d^*(2380)$. The IHEP quark model calculations [14, 23–25, 31, 32] agree with all so far measured quantities of $d^*(2380)$ by accounting also for hidden-color six-quark configurations, a basic feature of QCD as discussed in Ref. [34].

A major discussion point at MESON 2018 was the question, how the Fermi motion of the two Δs confined within a d^* radius of 0.8 fm would affect the observables of the d^* resonance process. As demonstrated in Refs. [16, 35], a Δ particle in such a scenario would need to have a Fermi momentum $p_\Delta(Fermi) = 0.37$ GeV/c reducing thus the effective Δ mass within the confinement region to 1131 MeV. Assuming a momentum dependence as in the free case the effective Δ width shrinks thus to 33.5 MeV. A similar result is reached in Refs. [36, 37].

On the one hand, the result of this consideration is very gratifying, since it tells us that the Δs bound in $d^*(2380)$ have a much longer lifetime than $d^*(2380)$ itself in support of a true sequential process $d^* \to \Delta\Delta \to NN\pi\pi$. On the other hand the question arises, whether the Fermi motion consideration has any consequence on observables like, *e.g.*, the total width of $d^*(2380)$ and also of the Δs emerging from its decay as well as the momentum distribution of the emitted Δs.

We have checked these points by confronting them with the WASA data on the $pn \to d\pi^0\pi^0$ reaction [3]. This reaction is the golden channel for observation of $d^*(2380)$, since it is purely isoscalar and has a very low background of conventional reaction processes. In addition, the momenta of the emitted neutron and proton are equal to good approximation, since both are bound in the emitted deuteron with negligible Fermi motion. Hence the relative momentum of the two emitted (reconstructed) Δs is given just by the relative momentum of the two emitted pions, *i.e.* $p^2_{\Delta\Delta} \approx p^2_{\pi^0\pi^0}$ in good approximation. Therefore the momentum-squared distribution of the two Δs originating from the decay $d^*(2380) \to \Delta\Delta$ is given by the distribution of the $\pi^0\pi^0$ invariant mass-squared $M^2_{\pi^0\pi^0}$ by just rescaling the abscissa according to $p^2_{\Delta\Delta} = M^2_{\pi^0\pi^0} - 4m^2_{\pi^0}$, as shown in the left panel of Fig. 1. We see that experimentally the relative momentum-squared between the two Δs is very small — enhanced by the ABC effect [38] — in comparison to the relative momentum-squared of the Δs within the d^* confinement, which is $p^2_{\Delta\Delta} = 4p^2_{\Delta}(Fermi)$. The latter is far outside the kinematic range, since the deuteron cannot stand such a high recoil momentum.

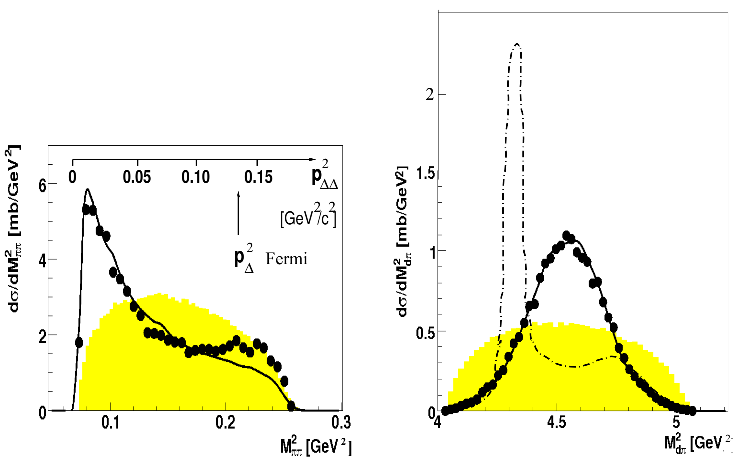

Figure 1. Distributions of the relative momentum-squared $p^2_{\Delta\Delta}$ between the two Δs (left) and of the $d\pi^0$-invariant mass-squared $M_{d\pi^0}$ (right) in the $pn \to d\pi^0\pi^0$ reaction at $\sqrt{s} = 2.38$ GeV. Data [3, 38] are shown by solid dots, phase space expectation by the shaded area. The solid lines represent the d^* calculations as described in Ref. [38]. In the left panel the vertical arrow marks the Δ Fermi momentum-squared as given in Ref. [16]. The dashed line in the right panel shows a calculation with Δs having a mass of 1131 MeV and a width of 33.5 MeV as expected in the Fermi motion scenario inside the d^* confinement region.

Next we check, whether the emitted Δs transport their mass and width as calculated inside the d^* confinement to the outside region. The right panel of Fig. 1 shows the spectrum of the $d\pi^0$-invariant mass-squared. The dashed line represents a Monte-Carlo simulation of the $pn \to d^*(2380) \to d\pi^0\pi^0$ process assuming the emitted Δs to have mass and width as obtained in the Fermi motion scenario within the d^* confinement. As we see, there are no narrow Δs, they do not transmit their in-medium mass and width to the outside. What we observe (solid line in Fig. 1) are Δs of mass 1190 MeV, *i.e.* reduced by the nominal binding energy, with a width of 80 MeV — as expected from the mass-width relation of a free Δ. This result is in line with the expectation that during the decay process $d^*(2380) \rightarrow \Delta\Delta$ the distance between the two Δs increases eliminating thus the Fermi motion and putting that way mass and width of the Δs back to their asymptotically correct values.

From this findings it also follows that the small total width of $d^*(2380)$ calculated in the Fermi motion scenario inside the confinement region is NOT transmitted to the outside and hence does not explain the observed narrow width of $d^*(2380)$ as speculated in the Fermi motion scenario.

3 Evidence for the isotensor dibaryon resonance D_{21}

Reexamining the $pp \rightarrow pp\pi^+\pi^-$ reaction at higher beam energies we find evidence for an isotensor dibaryon resonance near the ΔN threshold. Fig. 2 displays the total cross section in dependence of the beam energy. New WASA data [49, 50] shown by solid (red) circles are plotted together with previous measurements [39–47]. In contrast to the $pp \rightarrow pp\pi^0{}_,\pi^0$ reaction, which exhibits a pronounced kink in the total cross section around T_p = 1.2 GeV, the $pp \rightarrow pp\pi^+\pi^-$ cross section shows a very smooth energy dependence. This behavior is actually very surprising, since both two-pion production channels connected by isospin relations should behave similar, if there are no isovector pion pair (ρ channel) contributions [48–50]. Since the energy region of interest here is expected to be covered by just t-channel Roper and ΔΔ processes, such ρ channel contributions should be negligible. The isospin prediction based on the isospin decomposition of the $pp\pi^0\pi^0$ channel [48] is shown in Fig. 2 by the shaded band, which agrees well with the "modified Valencia" calculations [51] tuned to reproduce the $pp \rightarrow pp\pi^0\pi^0$ data.

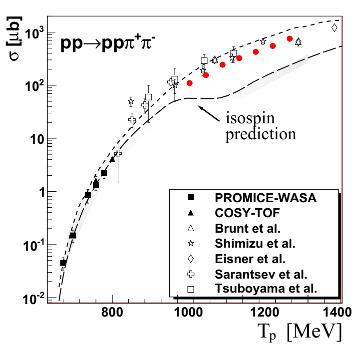

Figure 2. Total cross section of the $pp \rightarrow pp\pi^+\pi^-$ reaction in dependence of the proton beam energy T_p. Solid circles represent new WASA results. Other symbols give previous results [39–47]. The shaded band exhibits the isospin-based prediction, the dashed line the "modified Valencia" calculation [51], whereas the solid line is obtained, if an associatedly produced D_{21} resonance is added according to the process $pp \rightarrow D_{21}\pi^- \rightarrow pp\pi^+\pi^-$ with a strength adjusted to the data. From Ref. [49].

As can be seen, the discrepancy between data and expectation opens up scissor-like around 0.9 GeV, which coincides with the ΔN threshold. It appears that an important ρ-channel process connected with this threshold is missing. This is supported by the differential distributions [49, 50], which show that Roper and ΔΔ processes cannot be the dominating contributions. It looks that the only way out is the assumption of an isotensor ΔN resonance with $J^P = 1+$, which is produced associatedly with an s-wave pion via the $^3P_1$ pp partial wave. Such a ρ-channel process cannot contribute to $pp\pi^0\pi^0$ and $nn\pi^+\pi^+$ channels, however, leads to a quantitative description of both total and differential cross sections of the $pp \to pp\pi^+\pi^-$ reaction[49, 50].

The deduced mass and width of 2140(10) and 110(10) MeV, respectively, fit well to the calculations of Gal and Garcilazo [19, 20] as well as to the predictions of Dyson and Xuong [18] for D_{21}.

4 Summary and outlook

It is remarkable that now five out of the six dibaryon states predicted by Dyson and Xuong have been observed. For the sixth state with $I = 3$ so far only upper limits have been deduced from four-pion production [52], but this needs further, more detailed investigations — in particular, since latest lattice QCD calculations [57] predict a bound $\Omega\Omega$ state, which is a member of the same multiplet, where D_{30} belongs to.

Whereas all these resonances are asymptotically composed of baryons in relative s-wave, ANKE at COSY has recently found evidences for ΔN resonances with $I(J^P) = 1(0^-)$ and $1(2^-)$, where the two constituents are in relative p-wave [53]. This demonstrates that there are much more possibilities to form resonances in the system of two baryons than thought before — and there may be still many surprises to come in the dibaryon issue.

Finally we note that $d^*(2380)$ obviously also survives in nuclear surroundings as its appearance in the double-pionic fusion reactions to ^3He [54] and ^4He [55] as well as in heavy ion reactions [56] indicates. Even more fascinating is its influence on the equation of state and consequently on the formation of neutron stars, the center of which may consist of $d^*(2380)$ by possibly up to 20% [58].

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