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Status of the Dibaryon Resonance $d^*(2380)$

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The dibaryon resonance $d^*(2380)$ with $I(J^P) = 0(3^+)$ — first observed in the double-pionic fusion to the deuteron — has meanwhile been detected in all relevant two-pion production channels by incident neutron-proton collisions. In addition, its resonance pole has been revealed in neutron-proton scattering. Theoretical calculations describe this state either as a compact hexaquark system or a dilute molecular-like object. Whereas the d^* decay into two-pion channels does not discriminate between these two scenarios, the decay into single-pion channels is very discriminatory. In the hexaquark case this decay is heavily suppressed with a branching of less than 1%. 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 smaller than 9%. This is in support of the hexaquark interpretation – at least as the dominant configuration, possibly surrounded by a cloud of molecular-like configurations. Other dibaryon candidates are currently under investigation.

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1. Introduction

Dibaryons denote systems with baryon number B = 2. Hence formally the discovery of the deuteron in 1932 marks also the discovery of the first dibaryon. Due to its small binding energy the deuteron is a very loosely bound molecular object, where its constituents, proton and neutron hardly overlap. Of course, much more exiting would be a dibaryon state, where the six valence quarks reside within a single bag forming thus a compact hexaquark system.

The question, whether there are more eigenstates in the system of two baryons than just deuteron groundstate, has been around in principle all the time since the discovery of the deuteron. Experimentally searches for dibaryons date back at least to the fifties, where first dedicated experiments above the pion production threshold were carried out and first hints for a $I(J^P) = 1(2^+)$ state near the ΔN threshold were observed in the $pp \to d\pi^+$ reaction.

Though there were theoretical predictions of dibaryon multiplets already in the sixties by Dyson and Xuong [1], it was left to Jaffe [2] predicting the so-called H-dibaryon — a bound $\Lambda\Lambda$ system — to initiate predictions of a vast number of dibaryon states, which in consequence initiated a rush of experimental dibaryon searches. Unfortunately, none of the many experimental claims in this "dibaryon rush era" survived a careful inspection — with the possible exception of the above mentioned $I(J^P) = 1(2^+)$ state (named D_{12} in Ref. [1]) near the ΔN threshold exhibiting just the width of the Δ resonance, *i.e.* pointing to a loosely bound molecular state between Δ and N.

Despite their long painful history experimental dibaryon searches have recently received renewed interest by the recognition that there exist more complex quark configurations than just the familiar $q\bar{q}$ and qqq systems including hidden color aspects [3]. Also, lattice QCD calculations are now approaching the precision needed for reliable predictions of six-quark states — in particular, if combined with effective-field methods for the extrapolation to the real pion mass [4].

For a recent review of the dibaryon issue see Ref. [5].

2. Observation of a Narrow Dibaryon Resonance: $d^*(2380)$

A lesson learned from the failures in the dibaryon rush era was that for such searches the best suited equipment should be used allowing exclusive and kinematically complete measurements free of background.

In addition systems to be studied should contain at least two pions to allow also the investigation of systems containing two exited baryons, *e.g.* $\Delta\Delta$ configurations. According to the Los Alamos theory group the so-called "inevitable dibaryon" with $I(J^P) = 0(3^+)$ should exist — a $\Delta\Delta$ system deeply bound by nearly 400 MeV [6]. It was argued that due to the special symmetries, such a state should be present in all models based on one-gluon exchange and confinement. Indeed, also a number of other calculations based on MIT and cloudy bag models found this state, however, bound by only about 100 MeV. The latter agrees with the early prediction of such a state by Dyson and Xuong [1] based on $SU(6)$ symmetry breaking.

In order to systematically study the two-pion production in NN collisions with the best-suited equipment, we have conducted exclusive and kinematically complete high-statistics measurements

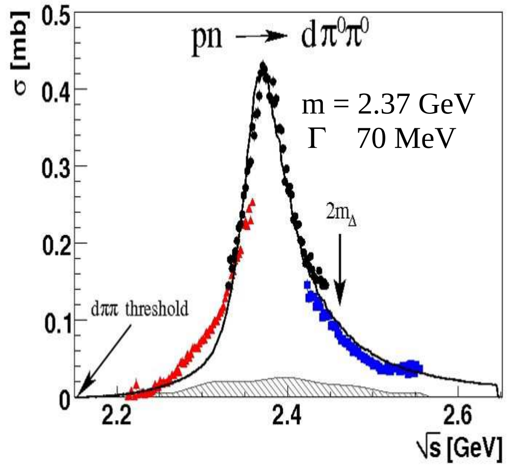

Figure 1: Total cross section of the reaction $pn \to d\pi^0\pi^0$ by WASA utilizing the quasifree process $pd \to d\pi^0\pi^0 + p_{spectator}$ at three different beam energy settings (red, black and blue symbols). Systematic uncertainties are indicated by the hatched area. The solid line resembles a Lorentzian with m= 2.37 GeV and Γ = 70 MeV. From Ref. [20].

with the 4π detector WASA containing a windowless pellet target system — first at CELSIUS and later-on at COSY.

At first pp-induced two-pion production was systematically studied from threshold up to 1.4 GeV [7, 8, 9, 10, 11, 12, 13, 14, 15]. By detailed analysis of the various channels it was shown that the conventional t-channel exchange leading to excitation of Roper resonance and ΔΔ system is the dominant process – as qualitatively properly predicted by Valencia [16] and Beijing [17] model calculations. By fine-tuning of coupling constants a quantitative description of both total and differential cross section data could be achieved ("modified Valencia" model) [13].

Having understood the pp-induced two-pion production on a quantitative level, the np-induced two-pion production was studied utilizing the quasifree reaction process in pd and dp collisions, respectively. Here we followed a trace led by the so-called ABC effect — a so far not yet understood huge low-mass enhancement in the $\pi\pi$-invariant mass spectrum obtained in double-pionic fusion reactions [18].

By measuring the basic double-pionic fusion reaction $pn \to d\pi^0\pi^0$ we discovered this low-mass enhancement (ABC effect) to be strictly correlated with a huge Lorentzian energy dependence of the total cross section (Fig. 1) pointing to pronounced resonance structure [19, 20]. From the deuteron angular distribution the spin J =3 was derived and since the investigated reaction was purely isoscalar, the quantum numbers of this structure had to be $I(J^P) = 0(3^+)$. Also, the low-mass enhancement (ABC effect) can now be well explained by the formfactor at the vertex of the decay of this resonance into the intermediate ΔΔ system [21].

By subsequent measurements of the channels $d\pi^+\pi^-$ [22], $d\pi^+\pi^0$ [12, 22], $pp\pi^0\pi^-$ [23], $np\pi^0\pi^0$ [24], $np\pi^+\pi^-$ [25], $[NN\pi]_{I=0}$ [26] and np elastic scattering [27, 28] all hadronic decay branchings could be measured [29] — see Table 1.

The partial-wave analysis of the analyzing power measurements in np scattering in the region

decay channel	experiment	theory [30, 31]	$NN\pi\pi$ isospin recoupling
$d\pi^0\pi^0$	$14\pm1\%$	12.8%	13%
$d\pi^+\pi^-$	$23\pm2\%$	23.4%	26%
$np\pi^0\pi^0$	$12\pm2\%$	13.3%	13%
$np\pi^+\pi^-$	$30\pm5\%$	28.6%	32.5%
$pp\pi^0\pi^-$	$6\pm1\%$	4.9%	6.5%
$nn\pi^+\pi^0$	$6\pm1\%$	4.9%	6.5%
$(NN\pi)_{I=0}$	$<9\%$	0.9%	–
np	$12\pm3\%$	12.1%	–

Table 1: Branching ratios of the $d^*(2380)$ decay into $NN\pi\pi$, $NN\pi$ and np channels. The experimental results [29, 26] are compared to results from theoretical calculations [30, 31] including isospin breaking effects. They are also compared to values expected from pure isospin recoupling of the various $NN\pi\pi$ channels [5]. In the latter case the branching into the $d\pi^0\pi^0$ channel is normalized to the data.

of the resonance structure revealed a resonance pole in the $^3D_3$ partial wave at $(2380\pm10)-i(40\pm5)$ MeV [27, 28] — fully consistent with the resonance structure observed in the $NN\pi\pi$ channels at 2.37 GeV having a width of $\Gamma = 70$ MeV, see Fig. 1. The $^3D_3$ partial wave exhibits a pronounced looping in the Argand diagram shown in Fig. 2 as expected for a genuine s-channel resonance — now named $d^*(2380)$.

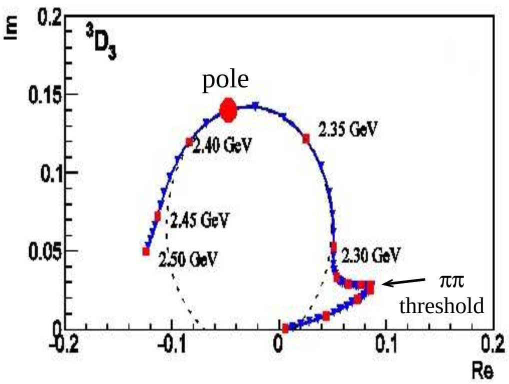

Figure 2: Argand diagram of the new SAID partial-wave solution [27, 28] for the $^3D_3$ partial wave exhibiting a resonance pole at 2380 MeV denoted by the thick solid circle in the figure. From Ref. [28].

3. Molecule or Hexaquark?

The data on $d^*(2380)$ suggest that hadronically this object constitutes a $\Delta\Delta$ system bound by 80 - 90 MeV. From simple use of the uncertainty relation this corresponds to an object size of about 0.5 fm. Detailed quark model calculations [31] predict this object to have a radius of 0.8 fm constituting a compact hexaquark system.

To the contrary, Faddeev calculations based on purely hadronic interaction predict this state to have asymptotically not a $\Delta\Delta$ configuration, but rather a $D_{12}\pi$ configuration representing a dilute molecular-like object [32]. Though the isospin relations for the decays into the various $NN\pi\pi$ channels are identical for intermediate $\Delta\Delta$ and $D_{12}\pi$ configurations, the expected decay into the isoscalar $[NN\pi]_{I=0}$ channel is strongly different. Whereas a $\Delta\Delta$ configuration gives no decay to $[NN\pi]_{I=0}$ in leading order, the $D_{12}\pi$ configuration gives a 18% branching based on the corresponding branching of the decay $D_{12} \to NN$. Our measurement of the $NN \to [NN\pi]_{I=0}$ reaction gives no indication for a decay branch $d^*(2380) \to [NN\pi]_{I=0}$ yielding an upper limit of less than 9%.

Whereas the Faddeev calculations are at variance with part of the decay branchings and also predict a too large total width of the resonance, the IHEP quark model calculations [30, 31] are in full agreement with the experimental results including the narrow width, which they explain by the effect of hidden color.

In order to bring the Faddeev results in accord with the experimental results, A. Gal recently proposed a configuration-mixed situation for $d^*(2380)$, where a compact hexaquark core is surrounded by a molecular-like $D_{12}\pi$ cloud [33].

4. Outlook

After having measured now all possible hadronic decays of $d^*(2380)$ the open task are measurements of its electromagnetic decays as well as an experimental determination of its size. Another question concerns the behavior of $d^*(2380)$ in a nuclear surrounding. Our measurements of the double pionic fusion to ^{3}He [34] and ^{4}He [35] show that it survives also in nuclei albeit broadened by Fermi motion effects. Extrapolated to nuclear matter conditions the question arises, how it may modify the equation of state, *e.g.* for neutron stars [36].

Another striking point is that the mass of $d^*(2380)$ turns out to be already amazingly well predicted by $SU(6)$ symmetry breaking. This success supports the hope that also the remaining two dibaryon resonances D_{21} and D_{30} might exist. Since these have isospins I = 2 and 3, they are decoupled from NN and have to be searched in reactions like $pp \to D_{21}^{+++}\pi^- \to pp\pi^+\pi^-$ and $pp \to D_{30}^{++++}\pi^-\pi^- \to pp\pi^+\pi^+\pi^-\pi^-$, respectively. The latter process has been investigated at WASA, but only an upper limit for D_{30} could be derived [37]. The other process looking for D_{21} is under current investigation.

Acknowledgments

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