DIBARYONS — FAKE OR TRUE?*

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Dibaryons are thought to be six-quark objects, potentially constituting a new state of matter. A short review is given about the long-standing search for such objects, from the early days until present, when the first non-trivial dibaryon resonance has been established. Starting from the fifties, the dibaryon search experienced many ups and downs, the dibaryon rush era followed by periods of big frustration and renewed start-ups. The recent first firm observation of a narrow dibaryon resonance gives new impact to this field. Having found one such species raises immediately the question, are there possibly more? Also whether the new state represents a molecule-like object or rather a compact hexaquark system, will be discussed.

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1. Introduction

All the time since the discovery of the deuteron in 1932 [1], there has been the question around, whether there exist more eigenstates between two nucleons or — more generally speaking — between two baryons than just the deuteron groundstate. In the most general definition, the term dibaryon means an eigenstate with baryon number $B = 2$. In this sense, the deuteron groundstate constitutes certainly a dibaryon. Despite innumerable experimental searches, it has been the only known dibaryon state up to very recently.

With the successful introduction of the quark model [2] in 1964, where mesons were interpreted as colorless quark–antiquark and baryons as colorless three-quark objects, dibaryons were then thought as six-quark objects. In fact, only few weeks after Gell-Mann's publication of the quark

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model [2], there appeared a paper by Dyson and Xuong [3] predicting a sextet of (non-flavored) six-quark eigenstates including the deuteron as groundstate. Based on SU(6) symmetry breaking, they derived a mass formula for these predicted six dibaryon states. Note that at that time, mass formulas for baryons and mesons were very fashionable. With the adjustment of a few parameters, they worked amazingly well predicting mass values very close to the later-on experimentally observed ones.

Naturally, in the quark picture, the deuteron appears as a very trivial state, since due to its small binding energy of only 1.1 MeV/nucleon (compared to about 8 MeV/nucleon in heavier nuclei), the deuteron is a molecular-like object, where the centers of its constituents, proton and neutron, are 4 fm apart from each other on average. With the nucleon's r.m.s. radius of 0.86 fm, this means that both nucleons hardly overlap within the deuteron. In other words, the deuteron consists of two quark bags containing three quarks each, which are well-separated. That way, the internal structure of the nucleon and its quark bag, respectively, does not come into play and the deuteron may be described with high precision just by its meson–baryon degrees of freedom.

This situation changes drastically and hence gets much more interesting, if the constituents of a dibaryon state get bound so strongly that the two initial quark bags overlap leading to a single bag, where all six quarks are confined within its small confinement volume. That way a compact hexaquark system would be formed in contrast to a largely extended loosely bound molecular system, as it is realized by the deuteron groundstate.

2. On the history of dibaryon searches

Early searches showed that there exist no excited boundstates of the deuteron, which is meanwhile well-understood by the current knowledge of the nucleon–nucleon (NN) interaction. Also there are no boundstates in the neutron–neutron (nn) and proton–proton (pp) systems. However, in all three systems — nn, pp and np — there exists the isovector $^1S_0$ virtual state, which is unbound by solely 66 keV [4]. In the paper by Dyson and Xuong [3], this state was associated with the second state in the predicted dibaryon sextet.

First experimental searches for dibaryon states other than the deuteron date back to the fifties of last century. But intense searches began only after predictions based on the quark model appeared. Whereas those by Dyson and Xuong [3] did not yet initiate a big rush, the subsequent one by Jaffe in 1977 [5] predicting the so-called H dibaryon (a bound $\Lambda\Lambda$ system) served as an initial boost both in theory and experiment. Follow-up quark-model calculations predicted a wealth of dibaryon states, which, in turn, lead to innumerable experimental searches. In this so-called dibaryon rush era, many claims on the observation of dibaryon states have been made. Except of one none of the claims survived a careful experimental inspection. For a recent review on the history of dibaryons, see Ref. [6].

The possibly only surviver from the dibaryon rush era is a state with $I(J^P) = 1(2^+)$, mass $m \approx 2150$ MeV and width $\Gamma \approx 120$ MeV. Since this state resides just near the ΔN threshold with a width compatible with that of the Δ resonance, it is not clear whether it is a true (s-channel) resonance or just a reflection of the single Δ decay. But since it produces a pole in the combined partial-wave analysis of pp, πd scattering as well as the $pp \to d\pi^+$ reaction, the tendency currently is in favor of the first interpretation — for a more detailed discussion, see Ref. [6]. Anyway, since this state has just the width of the Δ, it is believed to be a slightly bound extended molecular-like object, where quark degrees of freedom do not yet play a significant role — in agreement with recent theoretical calculations [7–10]. This state, for which first indications were already known from experiments in the fifties and early sixties, was associated by Dyson and Xuong [3] with their third predicted state. That way Dyson and Xoung could fix all parameters of their mass formula and predict the masses of the residual three higher-lying states.

3. Observation of a narrow dibaryon resonance

A reason for the striking failure of the dibaryon rush era was the insufficient quality of data, be it low-statistics bubble-chamber data or data from inclusive measurements, often done by single-arm detector setups.

In 1993, the PROMICE/WASA and subsequently the CELSIUS/WASA Collaboration started a systematic search of two-pion production in NN collisions using the WASA detector setup at the CELSIUS ring accelerator in Uppsala. Beginning with the year 2000, the WASA detector was completed as a hermetic detector providing nearly full solid angle coverage for the detection of both charged and neutral ejectiles. In addition, a windowless pellet target system supplying tiny frozen hydrogen and deuterium pellets crossing the beam provided an ideal situation for measurements with particularly low background.

At that time, the data basis on two-pion production in NN collisions was still very poor — though this reaction was ideally suited to look for dibaryon signals, in particular in the near threshold region. The WASA measurements were the first high-statistics measurements of the two-pion production, which have been carried out exclusively and kinematically complete covering nearly the full solid angle.

Naturally, the measurements started with pp-induced two-pion production in order to avoid complications with the availability of neutron target or beam. These measurements for the exit channels $pp\pi^0\pi^0$, $pp\pi^+\pi^-$, $pn\pi^+\pi^0$, $nn\pi^+\pi^+$ and $d\pi^+\pi^0$ demonstrated that these reactions can be well-described by t-channel meson exchange followed by excitation and decay of the Roper resonance $N(1440)$ in the near-threshold region. At higher energies ($T_{\rm lab} > 1$ GeV), it was shown that the t-channel meson exchange leads to the mutual excitation of the nucleons into their first excited state, the $\Delta(1232)$ resonance, forming thus an intermediate $\Delta\Delta$ system, which decays into the various two-pion channels [11–19]. These measurements supplemented by partially polarized measurements at COSY-TOF [20, 21] confirmed essentially the theoretical predictions of the Valencia [22] and IHEP [23] theory groups. By fine adjustments of some of the parameters in these calculations, a quantitative description of both integral and differential observables could be achieved. Also it could be demonstrated that the various two-pion production channels are tightly connected by isospin relations [15].

3.1. Emergence of a glaring resonance structure

After having understood the pp-induced two-pion production, the CELSIUS/WASA Collaboration turned to the investigation of np-induced two-pion production. For this endeavor, the quasi-free reaction on the deuteron — either in the beam or in the target — has been utilized providing thus measurements of the type, *e.g.*, $pd \to d\pi^0\pi^0 + p_{\rm spectator}$. Using this particular reaction has the advantage of dealing here with a purely isoscalar reaction — in contrast to the purely isovector pp-induced channels. *I.e.*, this particular reaction has the potential of providing completely new information about the two-pion production process. And indeed, it turned out as a big surprise that the total cross section of this particular reaction exhibits a pronounced narrow Lorentzian structure corresponding to a resonance energy of 2.37 GeV, which is about 90 MeV below the nominal $\Delta\Delta$ threshold of $2m_\Delta$, and a width of 70 MeV, which is substantially smaller than the width of the Δ resonance and more than three times smaller than the width of the t-channel $\Delta\Delta$ process [16].

Having seen first indications of this resonance structure in measurements of the $pn \to d\pi^0\pi^0$ reaction still at Uppsala [24], the measurements were repeated in 2006 at COSY, where the WASA detector was moved meanwhile, with hundred-fold better statistics and much improved beam conditions [25] — see Fig. 1. From the angular distributions, the spin of the resonance structure could be determined to be $J = 3$, so that in total its quantum numbers are $I(J^P) = 0(3^+)$.

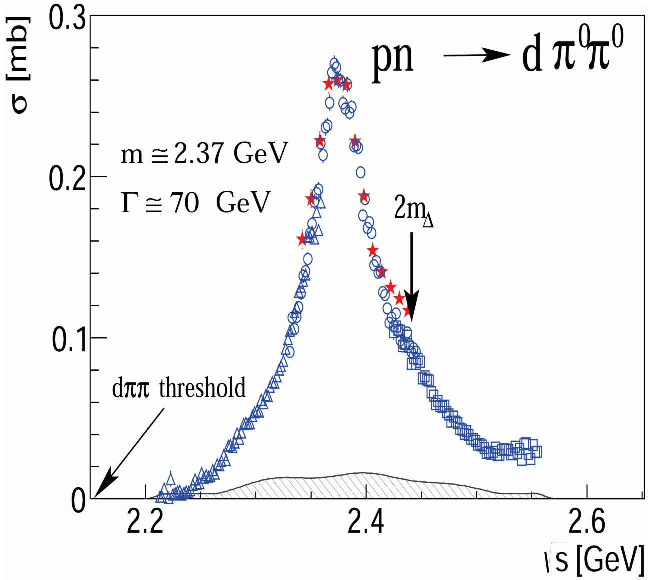

Fig. 1. (Color online) Total cross section of the "golden" reaction channel $pn \to d\pi^0\pi^0$ exhibiting the pronounced resonance effect of $d^*(2380)$. The gray/blue open symbols show the data of Ref. [25] normalized to the data of Ref. [26] given by the full red stars. The hatched area gives an estimate of systematic uncertainties. From Ref. [6].

In follow-up measurements at COSY, it could be demonstrated that all two-pion channels, which at least are partly of isoscalar character, exhibit a clear resonance signal around $\sqrt{s} = 2.37$ GeV. This concerns the channels $d\pi^+\pi^-$, $pn\pi^+\pi^-$, $pn\pi^0\pi^0$ and $pp\pi^0\pi^-$ [26–28]. That way, the decay branching of this resonance structure into all isoscalar two-pion channels could be determined [29]. It also could be demonstrated that there is no resonance signal in isovector channels [26], which explains, why no signal of this resonance structure was observed in the investigation of pp-induced channels.

If this resonance structure really corresponds to a true s-channel resonance, *i.e.*, a genuine dibaryon resonance, then it has to show up also in the entrance channel and produce a pole in np scattering. Since the resonance signal is expected to produce solely a per mille effect in the total np cross section, the only way to sense its signal is the measurement of the analyzing power, which contains just interference terms of partial waves and hence can boost a small resonance contribution in the $^3D_3$ partial wave to an observable resonance signal in the angular distribution of the analyzing power. And indeed, the polarized beam experiment over Easter 2012 providing highly precise analyzing data for pn scattering in the region of the anticipated dibaryon resonance led to the detection of a resonance pole in the $^3D_3$ partial wave at $2380 \pm 10 - i40 \pm 5$ MeV [30–32], which fully corresponds to the resonance structure observed in two-pion production. Since then, this dibaryon state is called $d^*(2380)$.

3.2. Hexaquark or molecular-like?

The observed resonance agrees remarkably well — both in mass and in quantum numbers — with the prediction of Dyson and Xuong [3], who characterized it as a tightly bound $\Delta\Delta$ system. The only other successful prediction stems from the IHEP group of Zhang *et al.*, who describe this resonance as a compact hexaquark system with an rms radius of only 0.8 fm [10, 33–35] — reproducing that way also all decay branchings [29, 36] and the narrow width. The latter has been attributed to the hidden-color [37] configuration of this state.

Alternatively, mass and quantum numbers of this resonance have also been reproduced successfully by Faddeev calculations with purely hadronic interactions [7, 8], but the calculated width of this now large-sized molecular-like object is significantly larger than the observed one. Moreover, the observed decay branchings are not all properly reproduced. In order to cure this deficits, Gal recently proposed a two-configuration model, where the compact hexaquark core is surrounded by a molecular-like $\Delta N\pi$ configuration [9].

4. Outlook

In order to determine the size of $d^*(2380)$, a measurement of its form factor appears to be in order. In principle, this can be achieved by electromagnetic excitation of this resonance. Though the expected cross sections are tiny, first experimental attempts in this direction have already been undertaken [38, 39].

Dibaryons influence also the equation of state for nuclear matter. Evidence that $d^*(2380)$ survives in a nuclear surrounding has been given in Refs. [40–42]. First attempts to incorporate $d^*(2380)$ in the equation of state have been undertaken, in particular in view of its role in neutron stars [43].

Having now established one non-trivial dibaryon immediately raises the question, whether there are more. According to the so far very successful prediction of Dyson and Xuong [3], there should be two more (unflavored) states. Since they are decoupled from the NN system due to their large isospins, a search for them is much more difficult. A first attempt has been reported recently [44].

In the strange sector, so far no sign of a dibaryon resonance has been sensed despite of many sophisticated searches. More hope for success offers the charmed sector, since it turned out to be very rich in exotic mesonic and baryonic states. Possibly this is also the place to find charming dibaryons.

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