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Shedding light on Hexaquarks

M. Bashkanov[∗†]
School of Physics and Astronomy, University of Edinburgh, James Clerk Maxwell Building, Peter Guthrie Tait Road, Edinburgh EH9 3FD,UK
E-mail: `mikhail.bashkanov@ed.ac.uk`

D.P. Watts
School of Physics and Astronomy, University of Edinburgh, James Clerk Maxwell Building, Peter Guthrie Tait Road, Edinburgh EH9 3FD,UK

Several new findings in the four, five and six quark systems reheat the interest in the field of multiquark states (beyond trivial $q\bar{q}$ and qqq). A lot of progress has recently been made in the 6q sector, on both the theoretical and experimental side. A resonance like structure observed in double-pionic fusion to the deuteron, at M = 2.38 GeV with Γ =70 MeV and $I(J^P) = 0(3^+)$ has been consistently observed in a wealth of reaction channels, supporting the existence of a resonant dibaryon state - the $d^*(2380)$. These studies include measurement of all the principle strong decay channels in pn collisions in the quasi-free mode by the WASA-at-COSY and HADES collaborations. The internal structure of the $d^*(2380)$ is largely unknown. It can contain various hidden color 6q configurations, ΔΔ molecular states with angular momentum L=0,2,4,6 as well as meson-assisted dressed dibaryon structures. The large set of experimental data obtained to date gives some constraints on the internal structure of the $d^*(2380)$ dibaryon, but does not settle the issue. The d^* is the only multiquark state which can be produced copiously at current facilities, offering unique access to information beyond its basic quantum numbers, particularly its physical size and internal structure.

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[∗] Speaker.

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1. Introduction

The matter in the visible universe is comprised mainly of protons and neutrons, bound systems each containing 3 quarks. For almost half a century the only bound system containing 6-quarks established in nature was the deuteron, a molecule composed of a proton and a neutron. The recent exclusive and kinematically complete measurements performed by the Wasa-at-COSY collaboration revealed first non-trivial 6-quark state - the $d^*(2380)$ hexaquark. This new exotic particle with quantum number $I(J^P) = 0(3^+)$ was successfully observed in five two-pion production channels: $pn \to d\pi^0\pi^0$, $pn \to d\pi^+\pi^-$, $pn \to pp\pi^0\pi^-$, $pn \to pn\pi^0\pi^0$, $pn \to pn\pi^+\pi^-$ [1, 2, 3, 4, 5] and in pn-elastic scattering reaction [6, 7]. For the later reaction a partial wave analysis was performed by the SAID group of George Washington University [6, 7]. For a recent review of dibaryon searches see Ref. [8].

Theoretical predictions of dibaryons, such as the d^*, have a long history. Calculations started with the pioneering work of Dyson and Xuong [9] in 1964 and have developed in many studies since then [10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25]. Various configurations were suggested to describe the d^* internal structure. Some can be tested experimentally.

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

All the data [6, 7, 1, 2, 3, 4, 5] collected so far suggest that in 88 percent of cases d^* decays into $\Delta\Delta$ and in 12% to pn [26, 27]. 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 ($L = 4$) [6, 7]. In case of the $\Delta\Delta$ branch at least 5% of the decays could be expected to proceed with two Δ's in relative $D-wave$ ($L = 2$) [28] - a remarkable feature for the 80 MeV sub-threshold system.

Very recently Gal and Garcilazo showed that the dynamical process $\Delta\Delta \to D_{12}\pi \to \Delta\Delta$, where $D_{12}(2150)$ is the $I(J^P) = 1(2^+)$ $N\Delta$ state [11, 12], leads to an extra attraction in the $\Delta\Delta$ system and large reduction of the $I(J^P) = 0(3^+)$ $\Delta\Delta$ decay width. To clarify the amount of $D_{12}\pi$ configuration in the $d^*(2380)$ a dedicated study was performed [29]. The D_{12} has a sizable pionless decay branch $D_{12} \to NN$ nicely seen in $pp \to D_{12} \to d\pi^+$. So single pion decay of the d^* dibaryon can naturally arise from the $d^* \to D_{12}\pi \to NN\pi$ process. To check this possibility the isoscalar single-pion production has been extracted, from $pp \to pp\pi^0$ and $pn \to pp\pi^-$ reactions measured at Wasa [29]. No evidence for a decay of the dibaryon resonance $d^*(2380)$ into the isoscalar $NN\pi$ I=0 channel was found. It also restricts a possible $D_{12}\pi$ configuration to less than 50%. If it exists, possible $D_{12}\pi$ configuration should predominantly decay into the $NN\pi$ channel with two nucleons in a relative $D-wave$ and a pion in relative $P-wave$. Future partial wave analysis of the isoscalar single pion cross-section should allow further restriction of the $D_{12}\pi$ configuration. Ultimately, a measurement of the $d^*(2380)$ transition form-factor would enable the different possibilities for d^* structure to be evaluated, including various exotic options, like di-quark dominated or benzine-like hexaquark [30].

3. d^* photoproduction

Prior to d^* form-factor measurements one needs to verify another very important channel -

$\gamma d \to d^*$. The reaction $\gamma d \to d\pi^0\pi^0$ appears to be attractive, since conventional nucleon resonant processes are expected to be particularly small [31, 32] of the order of only 10 nb at $T_\gamma = 550$ MeV with a smooth energy dependence. The next "best" two-pion production channel $\gamma d \to d\pi^+\pi^-$ has a background two orders of magnitude higher peaking around the position of d^* due to the Kroll-Ruderman term, unfortunate for d^* photoproduction studies. The very first results on $\gamma d \to d^* \to d\pi^0\pi^0$ had recently appeared from Tohoku [33] and Mainz [34]. They estimate the cross section of the $\gamma d \to d^* \to d\pi^0\pi^0$ reaction in the order of 20 nb indicating $\Gamma(\gamma d \to d^*) \approx 0.6$ keV. Both measurements currently experience large systematical uncertainties due to difficulties in removing background processes. Further measurements including different final states are crucial to firmly establish photocoupling.

A promising way forward is to exploit polarisation measurements. The situation in photoproduction looks similar to the one in elastic np scattering: the $d^*(2380)$ resonance contribution is about 0.17 mb, which is more than two orders below the total elastic cross section. However, with the help of the analysing power, which consists only of interference terms in partial waves, it was possible to filter out reliably the resonance contribution [6, 7]. The analogous case in photoexcitation of the $d^*(2380)$ constitute measurements of the polarisation of the outgoing proton or neutron in the reactions $\gamma d \to \vec{p}\vec{n}$. Last year this reaction was carefully studied at Crystal Ball experiment exploiting the Edinburgh Polarimeter [35]. The analysis of the data is ongoing, but the first exploratory studies confirm the feasibility.

Further important information about the $d^*(2380)$ can be extracted from the beam spin asymmetry (Σ) measurement. In Δ photoproduction quality data on Σ observable allowed extraction of the magnetic dipole (M1) to electric quadrupole (E2) moment ratio (M1/E2) in the nucleon to Δ transition [36]. Similar measurements in the d^* region would provide the information on relative strength of the E2/M3/E4 transitions.

4. $d^*(2380)$ in Nuclear medium

The $d^*(2380)$ is robust enough to survive even in the nuclear environment [37, 38, 39, 40]. It was recently demonstrated that d^* can potentially form dibaryonic matter deep inside neutron stars(NS), participate in neutron star cooling and influence neutron star mergers [41]. The nuclear Equation of State (EoS) with explicit d^* degrees of freedom is one of the few EoS on the market which fits new limits imposed by the GW170817 [42] gravitational wave NS merger measurement. Further studies of the d^* behaviour in nuclear matter may be important to clarify it's role in NS merger dynamics. Such studies can be performed with d^* photoproduction in nuclei.

5. Summary and outlook

After a vast number of unsuccessful searches support for a non-trivial dibaryon resonance has now been found and its major decay channels have been identified. A measurement of the $d^*(2380)$ electromagnetic form factor would uniquely identify its internal structure. Further experiments on d^* in-medium production would better constrain the potential role of the d^* in the nuclear EoS and help to verify the role of the d^* in determining neutron star properties.

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