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Search for non-strange dibaryons

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Abstract. Inspite of tremendous interest there has been sporadic searches for dibaryon resonances in the past few decades. The main hurdle one faces in this search is their identification, their signature and practically no guide to their location. With the identification of the pentaquark-θ^+ resonance one is encouraged to look for the discovery of strange dibaryons also. However where and how to look for non-strange dibaryons is not clear. The transition from a bipolar to a unipolar non-strange dibaryon may possibly be seen in the $(p, 2p)$ reactions on heavy nuclei. The change of the finite size of the p–p interaction vertex can be identified as a sudden change in the extracted DWIA spectroscopic factor. The DWIA anomalies are to be searched for in the existing $(p, 2p)$ reaction data for the identification of non-strange dibaryons.

Keywords. Multiquark bound states; $(p, 2p)$ reactions.

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1. Introduction

The resonances with baryon number equal to two ($B = 2$), called dibaryons, are being searched in the past couple of decades with a view to provide additional support to the Standard Model. These six quark states have been theoretically modelled [1] in terms of Bag model, similar to the description of baryons and mesons in this model. This of course is done without any additional parameters. This model however, predicted basically only one bound state of s-wave flavour-singlet dihyperon ($H, J^P = 0^+$ at 2150 MeV) which was to decay only weakly. The other dibaryon state ($H^*, J^P = 1^+$ at 2335 MeV) was to decay strongly into $\Lambda\Lambda$ or $N\Xi$. Experimentally, however, the situation is very confusing as regards the observation of narrow dibaryons. The narrowness arises due to the hindered decay either dynamically due to their exotic configuration or due to quantum numbers prohibiting their decay by strong interaction. Claims for observations – but unconfirmed results arise due to weakness of dibaryon's signatures compared to the physical background in a given process. It has however been argued that the measurement of total cross section is not a suitable characteristic to study the dibaryon resonances. There have been attempts to obtain the non-strange characteristics from the p–p total cross sections [2]. The possibility of having different analysing powers of a resonance and its background has led Tatischeff [3] to look for dibaryons in $^1\mathrm{H}(\vec{d}, pp)X$ reaction at around $T_d \simeq 2$ GeV. These resulted in tensor analysing power with small oscillatory pattern around $M_{pp} \simeq 1.646$ GeV. A reaction mechanism assuming the physics of mesons and nucleons in interaction to give rise to a continuous background and a simple spectator mechanism calculation however, do not show any oscillations. Thus the narrow structure around 1.945 GeV and lack of any signal in the corresponding calculation led them to associate it with a dibaryon.

Searches have been made for narrow isoscalar and isovector resonances which couple to the γd channel. The search for these are made both in the charged pion production channel [4,5] as well as in the neutral pion production channel [6]. However, the π^0-production channel is better suited for this purpose since in the energy region of interest below Δ-resonance down to the threshold the cross section for the conventional π^0-production is much lower than the $\pi^{\pm}$-production channels. Due to this there is much less background leading to better signal-to-background ratio for searching the narrow structures. Here use is made of the tagged photons in the $\gamma d \longrightarrow \pi^0 X$ reaction in the energy range $E_\gamma \sim 140$–300 MeV. Both total $\pi^0 X$ production as well as partial integral cross-sections were measured. The coherent $\pi^0 X$ production is forward peaked whereas the incoherent channel dominates the backward angles. The dibaryon resonance being produced incoherently should be present at the backward angles and hence should be enhanced by the large angle cuts. Except for three structures the excitations were found to be rather smooth. These three structures were however found to be consistently present in all the cuts. The most prominent one was found to be at 2084 MeV. This matched closely with one of the three sharp resonances reported by Tatischeff *et al* [7]. After subtraction of the smooth background the fluctuations fitted with a Gaussian of full-width at half-maximum equal to 1 MeV led to a resonance production of $\sim$2–5 $\mu\mathrm{b}\cdot\mathrm{MeV}$. This therefore puts the stringent constraint on the sensitivity of the dibaryon production to the level of a few $\mu\mathrm{b}\cdot\mathrm{MeV}$.

Tatischeff *et al* [7] are more confident in their claim to have dibaryon resonances at 2050, 2122 and 2150 MeV. They corroborate their weak dibaryonic findings with the phenomenological mass formula by Mulders *et al* [8] for two clusters of quarks situated at the end of a stretched bag. In the mass formula, the clusters are taken as a combination of q^2–q^4 with two phenomenological parameters. It was found that with these two parameters all the experimental energy levels are reproduced from 2 GeV to 2.2 GeV. In these and many other examples of experimental data it becomes obvious that the signals for the observation of dibaryons are very weak. Thus either one has to look for improving the signal-to-background ratio through better technological inputs or one has to look for some other characterstics of dibaryons which are more discernible.

2. Other characteristics of dibaryons

It has been the main point of this paper to discuss other characteristics besides the energy position and the sharpness in the time domain. Here it means that one is looking for a longer life-time of six-quark complex. It can be further argued that for dibaryon one is looking for six-quarks confined in a smaller volume than that in the neighbouring energy region where these are more or less separated in the form of three-quark clusters of baryons. Therefore instead of looking for $\Delta t, \Delta E$ domain if one looks for $\Delta x, \Delta p$ domain then this will open up another way altogether to look for dibaryons. This aspect requires some means for looking at the reactions producing dibaryons which can measure sizes and distances, or otherwise their Fourier transforms in terms of momentum distributions. The direct nuclear reactions are normally such that they can be employed to determine the Fourier transform of the overlap integral of the initial and final bound states. In this therefore the dibaryons have to be first produced through some reaction mechanism and then have to detect them in the life span of their existence. The width of the dibaryonic states is expected to be around a few MeV which corresponds to a life-time of around 10^{-21} s. For such a short life-time one therefore has to have the detector of the dibaryon to be an attachment part of the reactants. This therefore leads to the main reactant target particle to be part of a bigger nucleus such that the residual or the spectator portion of the target nucleus acts as a detector of the dibaryon produced in its vicinity. Knockout reactions are the reactions where these conditions are ideally satisfied when the target is chosen to be a medium-heavy mass nucleus. Here the residual nucleus is close enough to act as a detector yet far away to act as a spectator for the purpose of the production of dibaryon. This is because when the kinematics is chosen such that the spectator residual nucleus is almost stationary in the laboratory frame then in the quasi-free approximation the reaction is extreme surface-localized.

It can be visualized that the reaction $A(p, 2p)B$ if performed at appropriate incident proton energy where the two protons are predicted to produce dibaryon resonance then one can look for the energy sharing spectrum of the final two protons. As is expected for a dibaryon to have a compact six-quark structure one should be able to observe a change of cross section in the summed energy spectrum in the region where the two protons formed the dibaryon. In fact one need not change the energy of the incident proton beam to scan the region of the dibaryon resonance. The Fermi motion of the struck proton will lead to a spectrum of the residual spectator momenta corresponding to a variation of the relative p–p energy. If, however, the dibaryon width, ΔE is large, corresponding to a shorter life-time, it will reflect in the overall reduction of the absolute cross-section over the whole summed energy spectrum peak. Similar changes were seen in the $(\alpha, 2\alpha)$ reaction where the resonance at 19.8 MeV observed in the α–α scattering have been very clearly seen in the $^{6}\text{Li}(\alpha, 2\alpha)$ reaction at 42.8 MeV [9,10]. Through this experiment the authors could experimentally prove the validity of the post form prescription for the off-shell behaviour of the quasi-free vertex in the knockout reactions. This is a separate point that the 19.8 MeV ^{8}Be resonance seen in the experiment is a resonance corresponding to a dumb-bell shape of the ^{8}Be nucleus. In fact the aim of the experiment was not to look for the shape of the ^{8}Be nucleus at 19.8 MeV excitation energy. Supplementary observation of the effect of the sharp variation in the quasi free vertex in the knockout reaction angular correlation cross-sections in the 55 MeV $^{6}\text{Li}(\alpha, 2\alpha)$ also provide further evidence for this effect.

Another aspect connected with the behaviour of the quasi-free scattering vertex is the effect of optical distortions on the final reaction products. Sharing of the incident particle energy between the quasi-free scattered particles leads to almost half the relative energy between the residual nucleus and the two outgoing particles.

The optical potentials are normally not much affected by this change in the relative energy from the initial state to the final state. However with this reduction in energy the optical distortions are enhanced simply because the ratio of the potential to relative kinetic energies is increased. In fact it has been very clearly seen [11] in the detailed distorted wave impulse approximation (DWIA) calculations that the distortions in the initial state are not much effective in changing the behaviour of the cross-sections in the knockout reactions.

One of the disturbing feature of the knockout reactions, which has been a matter of concern for several decades is the large anomaly observed in the predictions and the corresponding observations of the absolute cross sections. In fact in the case of cluster knockout reactions on medium mass nuclei the anomaly is of few orders of magnitude too large. Moreover the DWIA analyses of the energy sharing distributions of these reactions indicate that the optical distortion effects are to be reduced substantially to fit even the energy-dependent shape of these distributions. This as well as other observations can be consistently understood if the finite range of the quasi-free vertex (where the large energy and/or momentum is transferred) is incorporated properly. Now the distortions (confined to few fms) make orders of magnitude change in the cross sections and in fact the plane wave impulse approximation (PWIA) calculations are most of the time closer to the observed cross-sections. This therefore implies that one has to incorporate the finite range of the quasi-free vertex non-perturbatively. In this connection it is to be remarked that in the $(\alpha, 2\alpha)$ reactions the strong α–α repulsion below 2 fms does not allow the two α's to get closer than $\sim$2 fms (see figures 1 and 2). From figure 2, however, it can be seen that in any of the $l_{\alpha-\alpha} = 0, 2$ or 4 partial waves the two α's cannot come closer than this distance. These three partial waves are the main partial waves contributing to the $\theta_{\rm cm} = 90^\circ$ scattering. In the impulse approximation therefore the $r_{\alpha-\alpha}$, instead of being zero, is $\sim$2 fms. This range is however, comparable to the sizes of the nuclei under investigation. In the zero range program, for fitting the data, it would appear that the incoming α-particle meets bound α at a distance $\sim$2 fms outside the nucleus than actually it was. In other words, the bound state wave function has to shift outwards by $\sim$2 fms to reproduce the data. In fact it has been found that the $\sim$2 fms shifted wave function overlaps the wave function generated by a bound potential of $2.52 \times A^{1/3}$ fm radius. This $\sim$2 fms hard core of the α–α potential therefore explains the observation of the need to use a large radius to fit the absolute cross-sections. It has however been neglected that the wave function generated by the $2.52 \times A^{1/3}$ fm radius potential contains comparatively lesser amount of the larger-momentum components leading to the sharper energy sharing distributions as compared to the experimental data.

One can have another perspective from the bound α-side also where in the zero range limit of the impulse approximation, for fitting the data, it would appear that the bound α-cluster meets the incoming α particle at a distance of $\sim$2 fms inside the nucleus than actually it was. Or in other words, it effectively corresponds to the situation where the incoming α-particle has penetrated $\sim$2 fms more inside the α-residual nucleus potential. This gave rise to the observed phenomenological weak attenuation behaviour for the DWIA explanation of the $(\alpha, 2\alpha)$ reactions.

In the case of $(p, 2p)$ reactions on ^{12}C and ^{40}Ca where anomalies similar to the $(\alpha, 2\alpha)$ reactions have been observed, although to a much lesser extent, one can

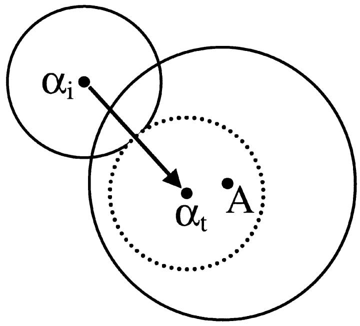

Figure 1. Alpha alpha repulsion shown schematically.

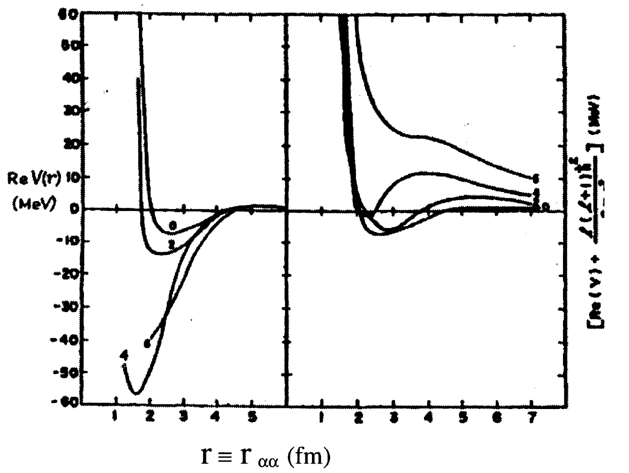

Figure 2. Alpha alpha potential as obtained from the scattering data up to 120 MeV [12].

seek a similar explanation. As one knows that the hard core in the p–p interaction is having a much smaller range, $\sim$0.8 fm, it is therefore expected that the influence of the hard core will be much smaller as compared to that in the $(\alpha, 2\alpha)$ reactions. However in the knockout from $l \neq 0$ case the shape of the momentum distribution will also manifest this lower attenuation characteristic as observed in the case of ^{7}Li$(\alpha, 2\alpha)$ reactions.

In any case strong indications of the observation of the pentaquark state, θ^+ has given lot of hopes to observe the dibaryon state also. The pentaquark, θ^+ itself has been observed as a weak resonance and it may be possible with the kind of arguments given here that it should be possible to see a much stronger evidence in the reaction $A(K^+, K^+n)(A-1)$ or more easily observable channel $A(K^+, K^0p)(A-1)$. The vertex $K^+ + n \rightarrow \theta^+ \rightarrow K^0 + p$ will have the same anomaly as in the case of the $(\alpha, 2\alpha)$ or the $(p, 2p)$ reactions except at the place where the resonance exists.

3. Conclusions

From the observations and explanation of various discrepancies in the understanding of the cluster knockout reactions it can be concluded that a non-perturbative treatment of the quasi-free vertex is necessary for the proper description of the data. The phenomenological description of these knockout reactions in terms of increasing the bound state potential or reducing the optical distortions have one common feature that there exists a strong repulsion between the quasi-free scattering partners. In terms of this background it also becomes evident that the behaviour of the $(p, 2p)$ reaction on some medium heavy nucleus will change drastically when the quasi-free p–p vertex makes a transition from normal two-separated three quark clusters to a compound 6-quark bag dibaryon. This transition will not only make a change in the extracted spectroscopic factor but will also change the shape of the energy sharing spectrum. The procedure described in this article makes a new way to look at the resonances not in the time-energy domain where the weak resonances almost merge with the background, but in the space momentum domain where the resonance is enhanced much above the background. Similar experiment is suggested to look for the pentaquark state more clearly in a knockout reaction using K^+ beam.

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