ON MESOATOMS OF THE DEUTERIUM AND POSSIBLE EXISTENCE OF EXOTIC DIBARYONS

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Abstract

As a desirable supplement to the reaction \( pp \rightarrow pp2\gamma \), proposed earlier (nucl-th/9712064 and references therein) to probe for the NN–decoupled dibaryon resonances we suggest to use for the same goal the radiative capture processes in mesoatoms of the deuterium which we consider to be especially feasible for further test and investigation of possible low-lying exotic resonance states.

1. The experimental discovery of dinucleon (or, generally, multibaryon) resonances not decaying into two (or more) nucleons in the ground state would be one of the most spectacular explications of nonpotential, nonnucleon degrees of freedom and would imply important consequences in further development of nuclear and hadron matter physics. The nonstrange NN-decoupled dibaryons with small widths appear to be the most promising and interesting candidates for experimental searches. Among available candidates to be confirmed (or rejected) in future dedicated and, hopefully, more sensitive experiments we wish to mention the indications of the existence of a narrow \( d' \) dibaryon slightly above the \( \pi NN \) threshold, coming from data on pion double charge exchange (DCE) on nuclei \cite{4}, and \( d_1 \)-enhancement below \( \pi NN \)-threshold, seen in preliminary data on the proton-proton double bremsstrahlung reaction at \( 200\, MeV \) \cite{3}.

It would be of undoubted interest to try different reactions to search for these states. With the pion probe, the presumed \( d_1 \)-dibaryon can be excited via strong interactions only on the three- (or more) nucleon states. With the deuteron targets, most thoroughly investigated and most easy to deal with theoretically, we have to resort to radiative processes.

This report aims at drawing attention to the real feasibility and suitability of radiative \( \pi (\mu) \)-meson capture processes in the deuterium mesoatoms for the sake of inquiry on possible nucleon and dinucleon exotics. In what follows we concentrate mainly on the radiative pion capture processes because they are experimentally easier to investigate. This proposal is not entirely new. In fact, there is the work devoted to search for the exotic isotensor (with the isospin \( I = 2 \)) dibaryon resonance done at TRIUMF \cite{5}. We, however, propose to look for a rather specific object, which seemed to be beyond the design and kinematics area covered by the abovementioned experiment. Furthermore we relay on what can be taken into account from an analysis \cite{6} of situation connected with the double bremsstrahlung experiment \cite{3}.

A few remarks are to be made about quantum numbers of the mentioned candidates. The isospin 0 assignment for the \( d' \) resonance with quantum numbers \( J^P = 0^- \) was motivated...
by calculations within a QCD string model, while the isospin 2 assignment was made in [7] on the basis of the \( \pi NN \) bound system model and within the Skyrme model approach. With the \( d' \) quantum numbers 0− and isospin 2, the dominant isobar in the pion-nucleon sub-system is \( P_{33} \) or \( \Delta \), so that nucleon and isobar have relative orbital angular momentum 1 and total spin 1. With the isospin 0 assumed, the dominant pion-nucleon sub-system in three-body model is the \( S_{11} \) isobar and the nucleon-isobar quasi-two-body system has the relative orbital momentum and total spin both equil to 0.

For the \( d_1 \)-state, presumably seen in the proton-proton double bremsstrahlung reaction below the pion threshold, we suggest the \( \Delta N \) with relative orbital momentum 0 as the dominant cluster configuration. Of the possible values 1 or 2 for spin and isospin, we consider the unit spin/isospin value as more natural for the state with lowest mass. In this case the NN decay channel is strictly forbidden by the exclusion principle, and if the \( \pi N \) decay mode is kinematically forbidden we have the radiative decay as the only possible one with the width of \( \sim \) KeV scale. It might, however, be that the isospin 2 assignment for \( d_1 \) is dynamically preferable, like in the case of the \( d' \)-state mentioned above. In that case the \( d_1 \to NN \) decay mode is possible though strongly suppressed being of order \( O(\alpha^2) \) versus the radiative decay of the order \( O(\alpha) \). To discriminate between two options (\( I = 0 \) vs 2), it is important to study several reactions differently sensitive to different isospin values. It is with this feature in view, that we propose to make use of the double radiative capture process in the pionic deuterium in addition to the nucleon-nucleon double bremsstrahlung reactions. As will be seen in the next section, the transition operator between the deuteron and dibaryon resonance state vectors is transformed, by construction within the assumed model, as the isovector under rotations in the isospin space. This means that, unlike the proton-proton double bremsstrahlung reaction, the narrow dibaryon will not be excited in the radiative pion capture on the isosinglet deuteron if the isospin of this resonance equals 2.

2. The branching ratios of different \( \pi^- \) - capture channels in the pionic deuterium:
\[
\pi^- d \to nn(0.7375 \pm 0.0027), nn\gamma(0.2606 \pm 0.0027), nne^{-}(1.81 \pm 0.02) \cdot 10^{-3}, nn\pi^0(1.45 \pm 0.09) \cdot 10^{-4}
\]
measured at TRIUMF [8, 9], give the total probability \( w(\pi^- d \to X(measured) = 1.000 \pm 0.038 \). Therefore, the upper bound of still undetected channels is not much larger than \( \simeq 0.38\% \), well within capability of measurements if there is good signature. We estimate which could be the yield of two \( \gamma's \) from consequent processes of the radiative excitation and de-excitation of the exotic \( d_1(1920) \), presumably seen in the proton-proton double bremsstrahlung:
\[
(\pi^- d)_{\text{atom}} \to \gamma d_1 \to \gamma\gamma X
\]

The radiative decay branching ratio \( Br(d_1 \to \gamma X) = 1 \), hence we need to calculate only the \( d_1 \) - excitation probability, i.e. the transition \( (\pi^- d)_{\text{atom}} \to \gamma d_1(1920) \). The radiated photon takes off the energy \( \omega = 92.9 MeV \) thus enabling the resonance state to be on its mass-shell. As a hint for possible qualitative estimate we note that the probability of ordinary radiationless \( \pi^- \)-capture \( w((\pi^- d)_{\text{atom}} \to nn) \) is only three times as large as that of the radiation capture. This is indication of the dominantly short-range nucleon-nucleon interaction dynamics involved in a pure strong capture channel, resulting in a poor overlap with the deuteron wave function having characteristically large spatial extensions. An essential feature of mechanisms of both the ordinary \( NN \)-channel [10] and the assumed \( d_1 \)-excitation is the appearance of the \( N\Delta \)-configuration in an intermediate state of reactions.
considered. So, it seems reasonable to expect that

\[ BR((\pi^-d)_{atom} \to \gamma d_1) \sim \alpha_{em} BR((\pi^-d)_{atom} \to nn) \simeq 0.74/137 \simeq 0.5\%. \]  

(2)

More quantitative estimation is made within a model used previously [6] for the reaction \( pp \to \gamma d_1 \). Namely, we assume the reaction mechanism when \( \pi^- \) is radiatively captured by a nucleon to form the (virtual) \( \Delta \) that, in turn, is associated with a spectator nucleon to form the \( d_1(1920)-\)resonance.

We adopt the explicitly phenomenological approach in our estimations. Having in mind the completeness of colourless hadron states, we shall estimate the probability of the radiative transition \( (\pi^-d)_{atom} \to \gamma d_1(IJ^P = 1^+) \) as a two-step process, where the presumably lowest \( NN \)-decoupled state with the \( J^P = 1^+ \), we are tentatively calling \( d_1 \), is coupled with the initial or final hadron states through the intermediate \( N\Delta \)-state with the same quantum numbers. The ”\( \Delta \)” - symbol may also be referred to the virtual \( \pi N \)-complex with quantum numbers of the \( \Delta(1232) \)-resonance but with a different invariant mass. We make use of standard formulas for a capture from atomic states following from the assumption that the hadronic reaction is much shorter in range than the atomic orbit radii. The rate is, schematically,

\[ w(L = 0 \text{ atomic state}) \sim |\psi(0)|^2 |\langle f|T_{\gamma N}(0)|i\rangle|^2 \]  

(3)

where \( \psi(r) \) is the \( L = 0 \) pionic atom wave function, \( |\langle f|T_{\gamma N}(q)|i\rangle|^2 \) is the amplitude of the reaction \( \pi(q) + N \to \gamma + \Delta \) with the free plane wave of a pion with momentum \( q \simeq 0 \), taken between the initial \( NN \)-bound state (i.e. the deuteron) and the final \( \Delta N \)-state (i.e. the \( d_1 \)-resonance). As we deal with the threshold-type process, we proceed with keeping only the seagull Feynman graph, approximating the \( N\pi\gamma\Delta \) block (the corresponding \( N\gamma\pi N \)-graph is known to give the low-energy Kroll-Ruderman threshold theorem for the charged pion photoproduction on nucleons). The \( \Delta N\pi \)-coupling constant is defined by the \( SU(6) \) symmetry through the known pion-nucleon coupling. It seems justified also to neglect the retardation corrections, i.e. we are using the long-wave approximation for the matrix element of electric-dipole radiative transition.

The \( d_1\Delta N \)-vertex is described by a simple form of the quasi-two-body wave function, for which the Hulthen-type radial dependence was chosen by analogy with the deuteron radial wave function:

\[ R(r) = N \frac{1}{r} \exp(-\alpha r)(1 - \exp(-\beta(r - r_c))) \]  

(4)

where \( N \) is the normalization constant, \( \alpha = \sqrt{2M_{\text{red}}\varepsilon_1}, \varepsilon_1 = M + M_\Delta - M_{d_1}, M_{\text{red}}^{-1} = M^{-1} + M_\Delta^{-1}, \beta = 5.4 \text{fm}^{-1}, r_c = 0.5 \text{fm} \) and \( R(r) = 0 \) for \( r \leq r_c \) is understood. The second factor in Eq.(2), describing the behavior of wave function in the ”interior” region outside the hard core with the radius of \( r_c = 0.5 \text{fm} \) is taken the same as in the deuteron case. The radial part of the deuteron wave function is obtained with \( \varepsilon_1 \to \varepsilon = 2.23 \text{MeV} \). Taking the measured value of the total width \( \Gamma_{\text{tot}} \simeq 1 \text{eV} \) [11] for the \( 1S \)-level of pionic deuterium, we obtain the following estimation for the (unobserved) decay channel

\[ BR((\pi^-p)_{atom} \to \gamma d_1 \to \gamma\gamma X)_{1S-\text{state}} = 6\%, \]  

(5)

surprisingly close to scale estimate (2) and not embarrassingly distant from the experimental bound \( \leq 0.4\% \), despite the adopted approximations being crude. We note also, that our
result does not depend strongly on variation of the "effective" mass $M_\Delta$ from $M + m_\pi$ to $M_\Delta = 1232\text{MeV}$, $(M = 939\text{MeV}, m_\pi = 139\text{MeV}$ being masses of the nucleon and pion), if $M_{d_1} = 1920\text{MeV}$ is taken for granted. To get an estimate of the background non-resonance $2\gamma$-emission rate, we take

$$BR(\pi^- d \rightarrow 2\gamma/1\gamma) \simeq BR(\pi^- p \rightarrow 2\gamma/1\gamma) \simeq 1.3 \times 10^{-4},$$

where the corresponding ratio for the pionic hydrogen was calculated by Beder [12].

We have then

$$BR((\pi^- d)_{\text{atom}} \rightarrow \gamma\gamma X)_{\text{nonres}} \simeq BR((\pi^- d)_{\text{atom}} \rightarrow \gamma nn) \times 1.3 \cdot 10^{-4} \simeq 3.4 \cdot 10^{-5}$$

which is considerably lower than the estimated resonance contribution. We point out also a qualitative difference of the $\gamma_1 - \gamma_2$ opening angle $\theta_{12}$ distribution following from the resonance and nonresonance mechanisms. In the resonance excitation mechanism, we have emission of the electric-dipole photon at the $d_1$-resonance excitation vertex and the magnetic-dipole photon emission in the $d_1 \rightarrow \gamma nn$ transition, the nn-pair being mainly in the $1S_0$ -state.

The polarization structure of the matrix element

$$T(\vec{\epsilon}_1, \vec{\epsilon}_2(k_1), \vec{\epsilon}_2(k_2),...) \sim a_1([\vec{\epsilon}_d \times \vec{\epsilon}_1] \cdot [\vec{\epsilon}_2 \times \vec{k}_2]) + (1 \leftrightarrow 2)$$

(8)

gives after the squaring and summation over polarizations

$$W(\theta_{12}, \varphi) = \frac{3}{16\pi} \cdot (1 + \frac{1}{2} \cdot \sin^2 \theta_{12})$$

(9)

which has a maximum at $\theta_{12} = 90^\circ$, while the corresponding distribution in the $\pi^- p \rightarrow 2\gamma n$ reaction, calculated by Beder [12], and, by our assumption based on the impulse approximation, in the $(\pi^- d)_{\text{nonres}} \rightarrow \gamma\gamma X$-reaction, shows a shallow minimum at $\theta_{12} = 90^\circ$.

It can be noted in this respect that a recent calculation [13] of the $\theta_{12}$-distribution in reactions $\pi^- A \rightarrow 2\gamma X$, ($A = ^9\text{Be}, ^{12}\text{C}$) approximately agrees with experiment [14, 15] for angles larger than $90^\circ$ but for $\theta_{12} \leq 90^\circ$ the calculations are consistently lower than data. A possible role of the exotic resonance excitation is suggestive here, but for a more quantitative estimation one has to take into account a number of very important many-body effects: the Pauli blocking, Fermi-motion smearing, collision broadening of the resonance propagating in nuclear matter. Indeed, each inelastic $d_1 N$-collision can transform the "$\Delta$-part" of the resonance into a nucleon via isovector, spin-dependent forces transmitted by pi- and rho-mesons, thus giving rise to a new decay channel $d_1 N \rightarrow 3N$.

Qualitatively, instead of $\Gamma_{\text{free}}(d_1) = \Gamma_{\text{rad}}(d_1) \simeq .5 \text{KeV}$ we are led to use $\Gamma_{\text{tot}}(d_1) \simeq \rho \cdot v \cdot \sigma_{\text{inel}}(d_1 N)$, and for $\rho \simeq .17 \text{fm}^{-3}$, $v = .2$ and $\sigma_{\text{inel}} \simeq 1 \text{mb}$, we get $\Gamma_{\text{tot}}(d_1)$ enhanced by 3 orders of magnitude as compared to $\Gamma_{\text{free}}$. That leads to $BR(\pi^- A \rightarrow 2\gamma X)$ of the order $\leq 10^{-5}$ in accord with measurements [14, 15]. To conclude this section, we are tempted to mention that the $\gamma$-spectra in radiative pionic deuterium decays can, in principle, test narrow baryon exotics of the type claimed in ref. [16], where the evidence was presented for three narrow baryon states with masses 1004, 1044 and 1094 MeV. The first two of them are within reach of pionic mesoatoms studies.
3. Our conclusion is: In addition to the planned [17] measurements of processes $\pi^-p \rightarrow 2\gamma n$ and double photon capture on complex nuclei [18], the radiative capture processes in pionic deuterium as well as the continuum pion energy reactions $\pi^+d \rightarrow \gamma(2\gamma)NN$ well deserve a devoted study being a perspective source of potentially very important information.

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References

[18] J. Deutsch, private communication to authors of Ref. [13].