The pion optical potential generated by the hypothetical \( \pi NN \)-coupled \( NN \)-decoupled dibaryon resonance \( d'(2065) \) is calculated to the lowest order in nuclear matter density. The contribution to the pion optical potential is found to be within the empirical errors, so the \( d'(2065) \) existence currently does not contradict to the observed properties of the \( \pi^- \)-nucleus bound states. Future progress in the pionic X-ray spectroscopy can reveal contributions of \( \pi NN \) resonances to energy levels and widths of the pionic atoms.

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The possibility for existence of dibaryon resonances is discussed over two decades \cite{1, 2, 3, 4, 5}. The most popular candidates for exceptionally narrow dibaryon resonances are the \( \Lambda \Lambda \) dihyeron with a mass below the \( \Lambda \Lambda \) threshold, as predicted by Jaffe \cite{1} within the framework of the MIT bag model, and the nonstrange \( \pi NN \)-coupled \( NN \)-decoupled \( d' \) dibaryon with quantum numbers \( I = 0 \) and \( J^P = 0^- \) and a mass close to the \( \pi NN \) threshold \cite{2, 3}. The resonance-like shape of the DCE cross section \cite{6} was interpreted by Martemyanov and Schepkin \cite{7} as a manifestation of the \( d' \) dibaryon with a mass of 2065 MeV. Searches of the \( \Lambda \Lambda \) dihyeron did not give conclusive results \cite{5, 8, 9, 10, 11}. The upper limits for the \( d' \) production cross sections are settled experimentally \cite{12, 13}, while the most specific features of the DCE reaction have been described using conventional mechanisms \cite{14, 15}. Astrophysical constraints to masses and coupling constants of the dibaryons are derived from existence of massive neutron stars \cite{16, 17, 18, 19}.

The laboratory experiments with pionic atoms \cite{20, 21, 22, 23, 24} provide one more opportunity to test existence of the \( d' \) dibaryon: The \( d' \) is coupled to the \( \pi NN \) channel, so as illustrated by Fig. 1 it contributes to the pion optical potential to the second order in the nuclear matter density and, as a result, manifests itself in shifts and broadening of the atomic spectral lines.

The pion-nucleus interaction effects on the pion bound states and present experimental status of the pionic X-ray spectroscopy are reviewed recently by Kienle and Yamazaki \cite{25}.

The \( d' \) contribution to the \( \pi^- \) optical potential at the nuclear density \( \rho_0 \) has the form

\[
2\mu \delta V_{\text{opt}}(k) = \frac{g^2}{M \eta_F} \int \frac{dp_1}{(2\pi)^3} \frac{dp_2}{(2\pi)^3} \frac{1}{|D_J|^2} \left[ \frac{p_1^2}{(2m)^2} + \frac{p_2^2}{(2m)^2} + \frac{k^2}{(2\mu)} - \frac{(p_1 + p_2 + k)^2}{(2M)} - \Delta M + i\Gamma/2 \right]
\]

where \( p_1 \) and \( p_2 \) are momenta of two protons, \( k \) is the pion momentum, \( m \) is the nucleon mass, \( \mu \) is the pion mass, \( \eta_F \) is the Fermi momentum, \( \Delta M = M - 2m - \mu \), \( M = 2065 \) MeV and \( \Gamma \) are the \( d' \) mass and width, \( q = 9.2 \) GeV\(^{-1} \) is the \( \pi NN d' \) coupling constant determined from the width \( \Gamma = 0.5 \) MeV of \( d' \) decay in the vacuum \cite{6, 26}.

\[
\Gamma = \frac{3g^2}{64\pi^2} \sqrt{\mu M \Delta M^2}
\]

FIG. 1: Contribution to the pion optical potential of the \( d' \) dibaryon (solid double line). The single solid lines show the proton holes (\( p_h \)) in the Fermi sphere, the dashed lines show the pion propagating in the nuclear matter.
TABLE I: Contribution of the \(d'\) dibaryon to the parameters \(B_0\) and \(C_0\) of the pion optical potential in the symmetric nuclear matter at the saturation density \(\rho_0 = 0.17\) fm\(^{-3}\) and an effective density \(\rho_e \sim 0.6\rho_0\) where the pion-nucleus interaction has its maximum, as compared to the empirical values extracted form the pionic X-ray spectroscopy using the standard \(S\) model, Weise-Friedman (WF) model \[35, 36\], and Kiehe-Yamazaki (KYa) model \[26\]. The empirical data are from \[37\] and \[27\], respectively. The values in parenthesis refer to the case of in-medium width of \(d'\).

| Model  | \(\mu^4\text{Re}B_0\) | \(\mu^4\text{Im}B_0\) | \(\mu^6\text{Re}C_0\) | \(\mu^6\text{Im}C_0\) |
|--------|-----------------|-----------------|-----------------|-----------------|
| S      | \(-0.15 \pm 0.04\) | \(0.054 \pm 0.002\) | \(-0.28 \pm 0.01\) | \(0.062 \pm 0.003\) |
| WF     | \(-0.07 \pm 0.04\) | \(0.053 \pm 0.002\) | \(-0.28 \pm 0.01\) | \(0.067 \pm 0.003\) |
| KYa    | \(-0.02 \pm 0.02\) | \(0.047 \pm 0.002\) | \(0.004\) | \(0.010\) |
| \(d'\)[\(\rho_0\)] | \(0.004\) | \(0.002\) | \(0.004\) | \(0.013\) |
| \(d'\)[\(\rho_e\)] | \(0.005\) | \(0.001\) | \(0.008\) |

with enhancement factor \(\eta_F\) included to the coupling constant \(g^2\). The Jost function \(D_J\) in the effective-range approximation is given by [27]

\[
D_J = \frac{|p_1 - p_2|/2 + i\gamma}{|p_1 - p_2|/2 + i\alpha}
\]

where \(\alpha \approx 2/r_e\) and \(\gamma = 2/a/\alpha/r_e\), with \(a = 7.82\) fm being the effective proton-proton scattering length including the Coulomb interaction [23], and \(r_e = 2.67\) fm the effective radius. The enhancement factor \(\eta_F \approx 1 + 32/(r_e^2 M \Delta M) \approx 3\) according to [25]. It is determined as an average value of the \(1/|D_J|^2\) over the three-body \(\pi NN\) phase space.

The \(d'\) in-medium width is estimated to be \(\Gamma' = 10\) MeV [6]. It appears due to the reactions \(d'N \rightarrow pNN\). It is of the first order in the density, so formally we go beyond the lowest second-order calculation. The effect, however, is numerically large. The \(d'\) width is increased as compared to the vacuum value by a factor of 20. The vacuum decay channel \(d' \rightarrow \pi NN\) is blocked in our case, since the pion is bound. The collision broadening of the \(d'\) is the only effect contributing to the imaginary part of the \(d'\) optical potential.

The second-order pion optical potential is related to the non-resonant absorption of pions on nucleon pairs [30]. It is parameterized in the form

\[
2\mu\delta V_{opt}(k) = \delta q + \delta pk^2
\]

where

\[
\delta q = -16\pi(1 + \frac{\mu}{2m})B_0\rho_p\rho_n, \tag{5}
\]

\[
\delta p = -16\pi(1 + \frac{\mu}{2m})^{-1}C_0\rho_p\rho_n \tag{6}
\]

are the \(s\)- and \(p\)-wave parts of the pion optical potential, \(\rho_p\) and \(\rho_n\) are the proton and neutron densities. Eq.(1) determines the \(d'\) contribution to the parameters \(B_0\) and \(C_0\).

The results are summarized and compared to the experiment in Table 1. The empirical data are taken from [37] for two realistic models with a vanishing nucleon-nucleon correlations parameter. The results of fit of the \(s\)-wave part of the \(\pi^-\) nucleus potential [27] are also given. The real \(s\)-wave part should be of the same magnitude as the imaginary part [31, 32, 33, 34]. The result of the standard model \(|\text{Re}C_0| \sim 3|\text{Im}C_0|\) is not fully satisfactory. The phenomenological pion-nucleon isovector scattering length in the standard model also appears to be overestimated as compared to the free value [25, 37]. A specific version of the relativistic impulse approximation [38, 39, 40, 41, 42] and the recent WF model [35, 36] reconcile those problems, at least partially.

Due to a strong repulsive \(\pi^-\) nucleus interaction and an attractive Coulomb interaction, the pions are bound at the surface of nuclei at an effective density \(\rho_e \sim 0.6\rho_0\) [25]. The nontrivial momentum dependence of the Jost function and the Breit-Wigner amplitude results in a density dependence of the parameters \(B_0\) and \(C_0\). Table 1 shows, respectively, two sets of the \(d'\) parameters for \(\rho_0\) and \(\rho_e\). The in-medium \(d'\) width is scaled according to the reduced density.

The \(d'(2065)\) corrections to the \(B_0\) and \(C_0\) at \(\rho_e \sim 0.6\rho_0\) where the pion-nucleus interaction has the strongest effect on the pionic atoms are currently within the empirical errors. If \(\pi NN\)-coupled resonances exist, the progress in pionic X-ray spectroscopy can reveal their contributions to energy levels and widths of the \(\pi^-\) nucleus bound states.

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