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Binding Energies of Two-Delta Bound States

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Bound states of the two-delta system are investigated by employment of the realistic one-boson exchange potential. It is found that there exist many bound states in each isospin channel and also that the tensor interaction plays an important role in producing these bound states. The relationship between these bound states and dibaryon resonances is discussed.

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Experimental studies on the proton-proton, pion-deuteron, and γ-deuteron scatterings suggest the existence of several dibaryon resonances.[1] These dibaryon resonances are believed to be deuteron-type bound states (d^* states) of baryons and their threshold effects[2] or six-quark states. The d^* states of baryons have been studied in terms of bound states of the N-Δ (Ref. 3) and the Δ-Δ (Ref. 4) systems or the πNN and $\pi\pi NN$ states.[5] The existence of d^* states in the N-Δ and Δ-Δ systems has been predicted by Dyson and Xuong in the early sixties from a symmetry argument on two-baryon states.[6] Although the d^* model is a reasonable and interesting extension of ordinary nuclear physics compared to the introduction of the exotic six-quark states, there exists a serious objection to this model, especially to the $T=0$ bound states in the Δ-Δ system.[7,8] The lowest $T=0$ bound state in the Δ-Δ system, which has been studied by Kamae and Fujita (KF) with nonrelativistic S-state one-boson exchange potentials (OBEP) having a reasonable hard core,[4] is the 3^+ state and has a binding energy of about 100 MeV.[9] On the other hand, phase-shift analysis indicates the existence of a negative-parity state ($^{2S+1}L_J={}^1F_3$) at 2.2 GeV (the corresponding binding energy is 260 MeV).[10] The objection to the d^* model is how to explain this negative-parity state within the model. Here, although this objection looks like a real puzzle, we have two questions about it. The first question is on the reliability of the KF calculations without the tensor part of the OBEP, because it is well known that the tensor interaction plays an essential role in producing the deuteron state. The second is on the experimental level assignment, i.e., whether the state found is really the $T=0$, 3^+ state or not,[9] and also whether the dibaryon resonance of the $T=0$ negative-parity state at 2.2 GeV is the $^1F_3$ state or not.[10] In this Letter we study the bound states of the Δ-Δ system with the OBEP having a tensor part, and show that the second question is partially resolved. We employ the following nonrelativistic OBEP as the Δ-Δ potential:

$$V_{\Delta\Delta}(r)=\begin{cases}\infty, & r\le r_c\\ [V_\eta(r)+V_\sigma(r)+V_\omega(r)]+[V_\pi(r)+V_\rho(r)+V_\delta(r)](\vec{\tau}_1\cdot\vec{\tau}_2), & r>r_c\end{cases}$$

with

$$V_\alpha(r)=\int\frac{d^3k}{(2\pi)^3}\,(-1)\left(\frac{f_\alpha}{m_\alpha}F_\alpha(k^2)\right)^2\frac{(\vec{\sigma}_1\cdot\vec{k})(\vec{\sigma}_2\cdot\vec{k})}{k^2+m_\alpha{}^2}e^{i\,\vec{k}\cdot\vec{r}},\quad \alpha=\eta,\pi,$$

$$V_\beta(r)=\int\frac{d^3k}{(2\pi)^3}F_\beta{}^2(k^2)\left[\frac{g_\beta{}^2}{k^2+m_\beta{}^2}+\left(\frac{f_\beta}{m_\beta}\right)^2\frac{([\vec{k}\times\vec{\sigma}_1][\vec{k}\times\vec{\sigma}_2])}{k^2+m_\beta{}^2}\right]e^{i\,\vec{k}\cdot\vec{r}},\quad \beta=\omega,\rho,$$

$$V_\gamma(r)=\int\frac{d^3k}{(2\pi)^3}\,(-1)[g_\gamma\cdot F_\gamma(k^2)]^2\frac{1}{k^2+m_\gamma{}^2}e^{i\,\vec{k}\cdot\vec{r}},\quad \gamma=\sigma,\delta,$$

where $\vec{\tau}$ and $\vec{\sigma}$ are respectively the isospin and spin operators for the Δ particles ($T=\frac{3}{2}$, $S=\frac{3}{2}$). We employ the following relationship for coupling constants[3,4]:

$$f_\pi=\tfrac{1}{5}f_{NN\pi},\quad f_\eta=\sqrt{3}\left(\frac{m_\eta}{m_\pi}\right)f_\pi,$$

$$g_\rho=g_{NN\rho},\quad f_\rho=\tfrac{1}{5}f_{NN\rho},\quad g_\omega=3g_\rho,$$

$$f_\omega=3f_\rho,\quad g_\sigma=g_{NN\sigma},\quad g_\delta=g_{NN\delta};$$

with meson masses

$$m_\pi=138\text{ MeV},\quad m_\eta=548.5\text{ MeV},\quad m_\sigma=650\text{ MeV},$$

$$m_\rho=763\text{ MeV},\quad m_\omega=782.8\text{ MeV},\quad m_\delta=960\text{ MeV}.$$

The form factors $F_\alpha(k^2)$ are given by

$$F_\alpha(k^2)=(\Lambda^2-m_\alpha{}^2)/(k^2+\Lambda^2).$$

In this work, we employ two sets of parameters: Case A,

$$\frac{f_{NN\pi}{}^2}{4\pi}=0.0778,\quad \frac{g_{NN\rho}{}^2}{4\pi}=0.89,\quad \frac{f_{NN\rho}{}^2}{4\pi}=3.17,$$

$$g_{NN\sigma}=g_{NN\delta}=0.0,\quad \Lambda=7\text{ GeV},\quad r_c=0.23\text{ fm};$$

and Case B,

$$\frac{f_{NN\pi}{}^2}{4\pi}=0.0778,\quad \frac{g_{NN\rho}{}^2}{4\pi}=0.78,\quad \frac{f_{NN\rho}{}^2}{4\pi}=4.407,$$

$$\frac{g_{NN\sigma}{}^2}{4\pi}=15.902,\quad \frac{g_{NN\delta}{}^2}{4\pi}=0.451,$$

$$\Lambda=1.4\text{ GeV},\quad r_c=0.30\text{ fm}.$$

The hard-core radii of both cases are adjusted so as to reproduce the binding energy of the deuteron state. The parameter set A is similar to that used by KF (here we employ $f_{N\Delta\pi}{}^2/4\pi=0.23$ instead of $f_{N\Delta\pi}{}^2/4\pi=0.35$).[11] The set B is chosen from Table 8 of Holinde.[12] The essential difference between the two parameter sets is the inclusion of the σ-meson exchange term. Numerical integration of coupled differential equations ($L\leq5$) is performed with the Numerov method by modifying the computing program for the deuteron state written by Lovitch and Rosati.[13] For convenience, the contributions from states of $L\geq6$ are neglected.

The binding energies obtained for $T=0$ states are summarized in Fig. 1. For the examination of the role of the tensor part, the binding energies obtained by switching off the tensor part of the OBEP are also shown in the same figure. In the case of the parameter set A, the FULL cal-

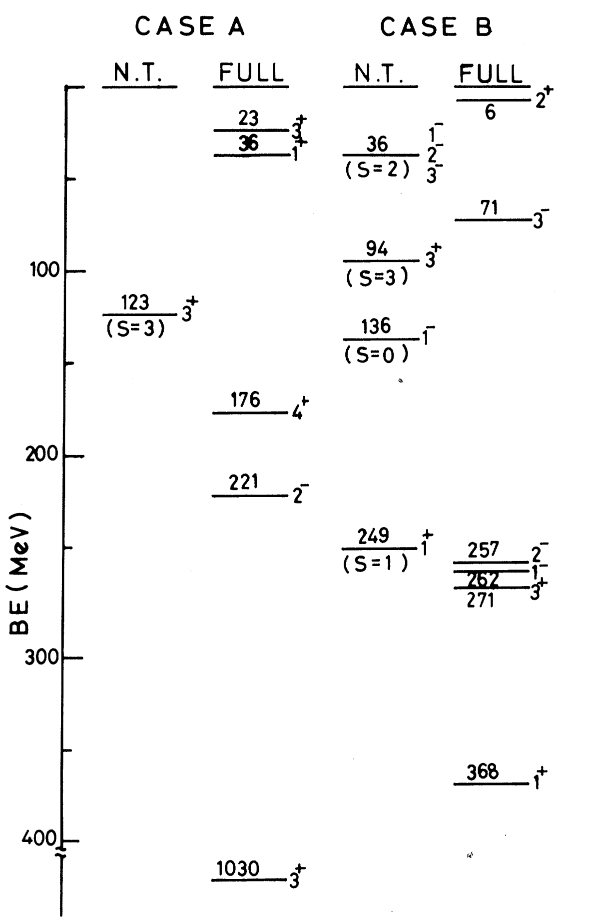

FIG. 1. $T=0$ binding energies of the two-delta system calculated with potential parameter sets A and B. FULL denotes full calculations. N.T. is obtained by switching off the tensor interaction.

culation shows completely different spectra from the N.T. calculation. The main spectra of the FULL calculation are determined by the off-diagonal tensor interaction. We obtain two 3^+ states, where the higher 3^+ state has one node ($r_{\rm rms}=1.7$ fm). The lowest state is unrealistically deep ($r_{\rm rms}=0.49$ fm) and should not be treated in a nonrelativistic way. In the case of the parameter set B, the number of bound states is not changed by switching off the tensor part, while the spectra are changed drastically.

With both parameter sets, the negative-parity states ($^5P_2$ and/or $^1P_1$) are produced at a binding energy of around 250 MeV ($r_{\rm rms}=0.7$ fm) and these levels may be related to that found in phase-shift analysis.[10] It is, on the other hand, an interesting question whether or not the lowest positive-parity state (1^+) can be observed in experiments.[1] For the case of the parameter set B, the spectra in each isospin channel are calculated and summarized in Fig. 2. The binding energy of the lowest state decreases with increasing isospin.

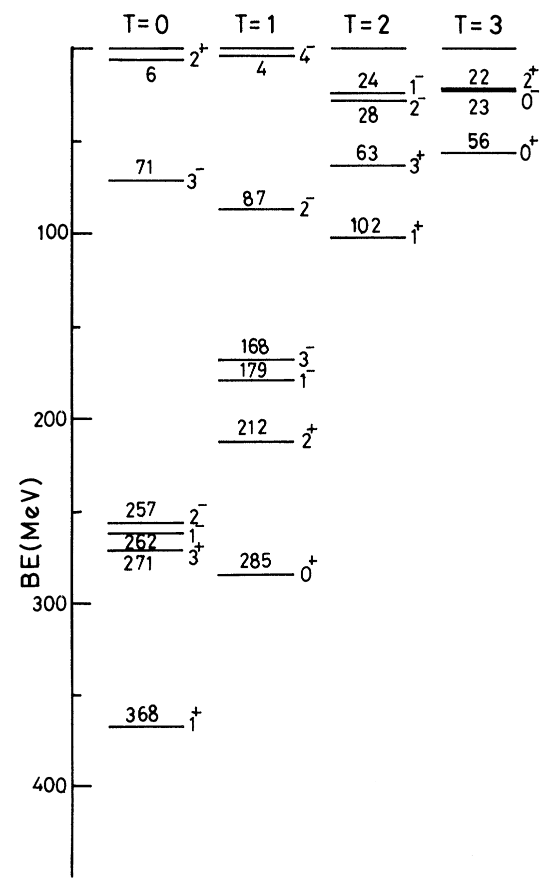

FIG. 2. Energy spectra of two-delta bound states calculated with the potential parameter set B.

To examine the potential dependence of the spectra, we switch off the interaction of each meson exchange and calculate the spectra. Then we find that the spectra with the parameter set B are not so changed by switching off heavy-meson exchanges, but seriously dependent upon the π- and σ-meson exchanges, which are not so affected with this choice of the hard-core radius. For example, if the π-meson exchange is switched off, the number of $T=0$ states is reduced to three (3^+ at 216 MeV, 1^+ at 200 MeV, and 3^- at 67 MeV), while the number of bound states does not change drastically in other isospin channels. Furthermore, if the σ-meson exchange is switched off, the total number of bound states in all the isospin channels becomes only two (3^+ at 38 MeV and 1^+ at 8 MeV, both in the $T=0$ channel). Hence one may say that the main feature of the two-delta bound states is determined by multi-π-meson exchanges with a reasonable choice of the hard-core radius, provided that the σ-meson exchange interaction is interpreted as a scalar part of the two-π-meson exchange interaction.

In the meantime, recently one of the authors (K.S.) has pointed out that the series of diabaryon resonances in p-p scattering experiments can be explainable as the Δ-N rotational band [the band head is the $^5S_2$ state (2.14 GeV) in the Δ-N system].[14] Hence we conclude that the spectra of dibaryon resonances are reasonably explainable within hadron clusters (within the π, N, and Δ system), and it is not always necessary to introduce compact six-quark states at this energy region. The tensor and π- and σ-meson exchange interactions play important roles in the determination of two-delta bound states. The tensor interaction is especially important in guaranteeing the negative-parity state in the $T=0$ channel, though the state is not the $^1F_3$ state.[10] The study of decay modes of the Δ bound states is now in progress.

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Results from a New Search for Proton Decay

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The authors have searched for the decay of protons and neutrons bound in nuclei using Soudan 1, a 31.5-metric-ton iron-loaded concrete tracking calorimeter, instrumented with 3456 proportional tubes. During a live time of 0.38 yr, the authors have observed one candidate event wholly contained within the detector. If this event is attributed to a background source, a lower bound (90% confidence level) can be established on the lifetime for nucleon decay through any of a wide range of modes of 1×10^{30} yr.

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An experimentally testable consequence of most grand unified models of the weak, electromagnetic, and strong interactions is that protons and bound neutrons are unstable.[1] Although proton lifetime predictions vary, many estimates are in the range of $10^{31\pm2}$ yr. A number of experiments have tested the assumption of proton stability,[2] the most sensitive of which were performed deep underground. Two of these experiments could detect only stopping muons[3,4] and one had more general sensitivity but coarse spatial resolution.[5] The stopping-muon experiments could measure the total nucleon decay rate only to the extent that theoretical models and Monte Carlo calculations could determine the fraction of decays which yielded stopping muons. The experiment in Ref. 5 has reported three proton-decay candidate events which are wholly contained within the detector. The recent nucleon stability experiment in the Mount Blanc tunnel has also reported one candidate event.[6]

For the past year, we have operated the Soudan-1 nucleon decay detector, a 31.5-metric-ton tracking calorimeter, which is instrumented with 3456 gas-filled proportional tubes. The detector is located 595 m underground in northeastern Minnesota. The overlying rock provides an attenuation of the cosmic rays equivalent to that of 1800 m of water. The detector is rectangular, 2.9 m × 2.9 m × 1.9 m high. As shown schematically in Fig. 1, it consists of 48 layers of 72 proportional tubes each. The tube axes are turned by 90° in alternate layers, in order to provide two views of each event. The 2.9-m-long proportional tubes are each 2.8 cm in diameter with an 0.8-mm-thick steel wall. The tube axes are spaced by 4 cm in the horizontal direction and adjacent tubes are staggered up and down by 0.45 cm from the layer center. The vertical distance between layers is 4.1 cm. The probability for a