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Light supernuclei and SU(4) symmetry

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Light supernuclei with nonzero charm which are the analogs of hypernuclei have been studied using a one-boson-exchange potential model and SU(4) symmetry. Bound supernuclei such as C_1N ($I=\frac{3}{2}, J=0$), C_1NN ($I=2, J=0$), and C_0NN ($I=0$, $J=\frac{1}{2}$ and $\frac{3}{2}$) are predicted with reasonable binding energies. An estimate of C_0 binding in nuclear matter is also presented.

[NUCLEAR STRUCTURE Light supernuclei C_0N, C_1N, C_0NN, C_1NN; two-body low energy scattering parameters; OBEP model coupled channel method; three-body binding energies equivalent Faddeev method; C_0 binding energy in nuclear matter Bethe-Goldstone method.]

The discovery of charmed hadrons[1] has led to speculation on the possible existence of nuclei with nonzero charm, namely, supernuclei[2] which are the charm analogs of hypernuclei. Recent observation by Batusov *et al.*[3] seems to indicate the possible existence of such an object. In a recent paper[4] we reported preliminary estimates for the binding energies of light supernuclei assuming the validity of SU(4) symmetry for the strong interactions between the charmed baryon and nucleons. We present here revised and improved estimates for the binding energies of three-body supernuclei, which turn out to be somewhat different from the earlier values quoted when the effect of the tensor forces in the triplet states and the coupling to the second channel in the $I=\frac{1}{2}$ states is taken into account exactly.

We have analyzed the three-body supernuclear systems C_0NN and C_1NN to determine whether they have bound states if the strong interactions are taken to be SU(4) symmetric and the symmetry breaking effects enter only through the mass differences of the baryons and the exchanged mesons. We first obtained the low energy singlet and triplet state scattering parameters of the C_0N, C_1N system in the $I=\frac{1}{2}$ state and the C_1N in the $I=\frac{3}{2}$ state with the SU(4) symmetric interaction Hamiltonian and a one-boson exchange-potential model (OBEP). For example, the H_{int} for C_0N, and C_1N interactions with pseudoscalar meson exchanges is given by[5]

$$H_{\text{int}}=g\left\{2i(1-\alpha)\overline{C}_1\times C_1\cdot\pi+\frac{2}{\sqrt{3}}(1-\alpha)\overline{C}_1\cdot C_1\eta_8+\frac{2}{\sqrt{3}}(1-\tfrac{5}{3}\alpha)\overline{C}_0C_0\eta_8-\frac{1}{\sqrt{6}}(1-4\alpha)\overline{C}_1\cdot C_1\eta_{15}-\frac{1}{\sqrt{6}}(1+\tfrac{4}{3}\alpha)\overline{C}_0C_0\eta_{15}\right\} .$$

The method of approach was the standard one of solving the two-body Schrodinger equation where the two-body potential energy is computed from the exchange of the nonet scalar, pseudoscalar, and vector measons plus a phenomenlogical hard core. The numerical solutions obtained were matched with the appropriate asymptotic forms to obtain the S-matrix elements and the low energy scattering parameters a and r_0 through the usual effective range approximation. The unitary symmetric coupling constants, masses, and other parameters used in the calculation were those obtained by Brown *et al.*[6] by fitting the hyperon-nucleon scattering data. The phenomenological hard core radius was taken to be a variable parameter and the values of a and r_0 obtained for the radius states in which the B_cN system can exist are

TABLE I. Variation of a and r_0 with r_c. (All quantities are quoted in units of fm.)

			$r_c=0.46$		$r_c=0.50$	
System	I	J	a	r_0	a	r_0
C_1N	$\frac{3}{2}$	0	297.6	1.99	−3.47	3.06
C_1N	$\frac{3}{2}$	1	−0.74	4.63	−0.32	11.53
C_0N	$\frac{1}{2}$	0	−0.62	6.87	−0.26	20.95
C_0N	$\frac{1}{2}$	1	−0.37	12.74	−0.15	56.17

displayed in Table I. We draw attention here to the fact that the triplet parameters for the C_0N $(I=\frac{1}{2})$ system is significantly different from the values presented earlier.[4] This was partly due to the fact that in the present estimate we have taken into full account the coupling to the C_1N channel as well as the coupling between the $^3S_1$ and $^3D_1$ states due to tensor forces solving the full 4 channel problem and partly also due to the discovery of certain inadvertent mistakes in the earlier computation of the C_1N potential. Similarly, the C_1N $(I=\frac{3}{2})$ parameters have also been revised, but the differences are not so significant in this case. We find that the C_1N singlet state still exhibits a very lightly bound state whereas none of the other two-body systems are bound. Similar conclusions on the two-body systems have been drawn by Dover and Kahana[7,8] using the potential of Nagels *et al.*[9]

A solution of the three-body coupled equations with local OBEP two-body interactions involves coupled multiple integral equations. In order to reduce the problem to a tractable form we made use of equivalent nonlocal separable potentials of the Yamaguchi type[10] which reproduce the appropriate low energy two-body scattering parameters already obtained. In solving the coupled equations we made use of the identity of the nucleons for the symmetry of the wave functions. However, since the light supernuclei are expected to have rather small binding energies, we computed the binding energies of the different charge states separately using the appropriate interaction parameters. Even with the separable form for the two-body interactions finally one has to solve three coupled one-dimensional integral equations given below which reduce to two when the two particles of the system are identical

$$\phi_{ij}(p)\left[1-\lambda_{ij}\int\frac{f_{ij}^2(p'+p/2)\,d^3p'}{k_1p'^2+p^2+p\cdot p'+\alpha^2}\right]$$

$$=\lambda_{ik}\int\frac{f_{ij}(p'+p/2)f_{ik}\left(\frac{p'}{2}+p\right)\phi_{ik}(k')\,d^3p'}{k_1(p^2+p'^2)+(2k_1-1)p\cdot p'+\alpha^2}+\lambda_{jk}\int\frac{f_{ij}(p'+p/2)f_{jk}\left(\frac{p'}{2}+p\right)\phi_{jk}(p')\,d^3p'}{k_1p'^2+p^2+p\cdot p'+\alpha^2}$$

where $i\neq j\neq k$ and i,j,k can each take the values 1, 2, and 3, $f_{ij}(p)=1/p^2+\beta_{ij}^2$, and $E=-\alpha^2/\mu$ is the binding energy. In solving these coupled equations the following approximations had to be made. The effects of the coupling to the C_1NN intermediate states in the C_0NN problem was neglected. Similarly

TABLE II. Potential parameters λ and β.

			$r_c=0.46f$		$r_c=0.50f$	
System	I	J	$\lambda(f^{-3})$	$\beta(f^{-1})$	$\lambda(f^{-3})$	$\beta(f^{-1})$
C_1N	3/2	0	2.192	2.785	1.087	2.353
C_1N	3/2	1	2.803	3.45	2.757	3.58
C_0N	1/2	0	1.101	2.646	0.823	2.546
C_0N	1/2	1	0.763	2.463	0.561	2.343
np	0	1	0.414	1.449		
np	1	0	0.144	1.153		
nn	1	0	0.094	1.012		
pp	1	0	0.132	1.129		

TABLE III. Binding energies in MeV.

System	I_T	J_T	J_{NN}	$r_c = 0.46f$	$r_c = 0.50f$
C_1np	2	$\frac{1}{2}$	0	0.13	0.06
C_1nn	2	$\frac{1}{2}$	0	0.22	0.07
C_1pp	2	$\frac{1}{2}$	0	0.12	0.03
C_0np	1	$\frac{1}{2}$	0	0.02	Not bound
C_0nn	1	$\frac{1}{2}$	0	0.01	Not bound
C_0pp	1	$\frac{1}{2}$	0	Not bound	Not bound
C_0np	0	$\frac{1}{2}$	1	4.58	3.66
C_0np	0	$\frac{3}{2}$	1	3.59	3.15

where triplet state interaction was involved coupling to the D state through tensor forces was neglected. However, we must emphasize that the effective two-body interaction parameters used were exact with couplings to all channels taken into full account.

In Tables II and III we present the two-body interaction parameters used and the three-body binding energies of the various states obtained. It can be seen that the C_0NN $(I=1)$ and C_1NN $(I=2)$ states are extremely loosely bound. This is not unexpected since, even though the C_0 and C_1 particles are much heavier than the hyperons their interactions with the nucleons are somewhat smaller. Further, in the case of the C_1NN $(I=2)$ system even though the C_1N $(I=\frac{3}{2})$ singlet state is strong enough to bind, the two nucleons in the three-body system have to be in the singlet state due to Pauli principle thus leading to a very small total binding energy. The only system which has a significant binding energy turns out to be the $^{3}_{C_0}$H system, the charm analog of $^{3}_{\Lambda}$H. In this case we find that it is more strongly bound than the $^{3}_{\Lambda}$H and should therefore be amenable to experimental identification.

Finally, one can obtain a rough estimate of the C_0 binding energy in nuclear matter by solving the Bethe-Goldstone equations with the same two-body interaction parameters. We find that the C_0 binding in nuclear matter is approximately 22 MeV with the nucleon-nucleon interaction taken to be represented by the Reid potential. This estimate is somewhat smaller than the estimates of binding Λ in nuclear matter and considerably smaller than the estimate of C_1 binding in heavy but finite nuclei given by Dover and Kahana.[7] The possible existence of light C_0 and C_1 supernuclei raises further interesting questions on the possible existence of other light supernuclei with the other charmed baryons attached to them and double supernuclei, etc. Theoretical studies of such systems and an experimental verification of the results will serve to throw further light on the extent to which the SU(4) symmetry is valid. Some of these questions are already being studied and the results will be reported elsewhere.

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