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# Binding energy of a Λ particle in nuclear matter with Nijmegen baryon-baryon interaction

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The binding energy of a Λ particle in nuclear matter $B_\Lambda$ is calculated with the models $D$ and $F$ of the NIjmegen baryon-baryon interaction. The result $B_\Lambda = 30.6$ MeV obtained for model $F$ agrees with semi-empirical value of $B_\Lambda$, and shows that suppression of $\Lambda\sum$ conversion in nuclear matter solves the hypernuclear overbinding problem.

[NUCLEAR STRUCTURE Binding energy of Λ particle in nuclear matter, ΛN interaction with ΛΣ coupling.]

The investigation of the binding energy of a Λ particle in nuclear matter (NM), $B_\Lambda$, is of considerable interest as it enables us to gain valuable information on the ΛN interaction, $v_{\Lambda N}$. Furthermore, the Λ + NM system, i.e., NM with a Λ "impurity," is an interesting testing ground for nuclear many-body theories.

The present status of the $B_\Lambda$ problem may be summarized as follows (for a recent review, see Ref. 1):

(i) The semiempirical value of $B_\Lambda$ is slightly smaller than 30 MeV.

(ii) Purely central ΛN potentials, fitted to Λp scattering and to Λ binding in $A = 3, 4$ hypernuclei, with hard cores of radius $r_c \gtrsim 0.4$ fm, and with suppression in odd-angular-momentum states lead to overbinding. The value of $B_\Lambda$, calculated with these potentials, is about 10 MeV larger than the semiempirical value.

(iii) The expected suppression of ΛΣ conversion in NM, first suggested by Bodmer,[2] appears to be the most promising solution of the overbinding problem.

The standard treatment of ΛΣ conversion is based on the Schrödinger equation appropriate to the two-channel approach,[3] with a 2×2 YN potential matrix ($Y = \Lambda, \Sigma$)

$$\hat{v} = \begin{pmatrix} v(\Lambda N \to \Lambda N) & v(\Sigma N \to \Lambda N) \\ v(\Lambda N \to \Sigma N) & v(\Sigma N \to \Sigma N) \end{pmatrix} = \begin{pmatrix} v_{\Lambda N} & v_{\Lambda\Sigma} \\ v_{\Sigma\Lambda} & v_{\Sigma N} \end{pmatrix}. \qquad (1)$$

The origin of ΛΣ suppression in NM is the following: The contribution of $v_{\Lambda\Sigma}$ to $B_\Lambda$ is at least of second order in $v_{\Lambda\Sigma}$, and is reduced by the exclusion principle and the excitation energy of the intermediate states in NM higher than in an isolated ΛN system. The magnitude of this reduction has been discussed for a variety of theoretically expected forms of $\hat{v}$ by Bodmer and Rote[4,5] who predict a substantial reduction up to ~15 MeV.

In the first attempts to construct a phenomenological YN interaction, and to calculate $B_\Lambda$ with it, the model of a simple attractive S-state separable form of $\hat{v}$ was applied.[6-11] The results of these attempts have shown that indeed a sufficiently strong ΛΣ suppression in NM may be expected to solve the overbinding problem. However, the crudeness of the model and the scarce experimental information on the YN system used in its construction did not allow the obtaining of a reliable result for $B_\Lambda$.

Recently an essential progress in constructing a realistic form of $\hat{v}$ has been made by the Nijmegen group.[12-14] The authors apply the OBE model and assume SU(3) relations for the coupling constants. The short-range behavior of the resulting local $\hat{v}$ is represented by phenomenological hard cores. Free parameters are determined from a combined analysis of the available NN and NY scattering data, up to the pion production threshold. Two recent forms of the Nijmegen potentials are models D and F. Model D[12-14] consists of potentials due to exchanges of members of pseudoscalar and vector meson nonets and the scalar meson ε taken as a unitary singlet. The breaking of SU(3) in model D is kinematical and also dynamical via different hard cores. Model F[14] differs from D by including exchanges of the whole nonet of scalar mesons, and by having the same hard cores within the same irreducible representation. Consequently the breaking of SU(3) in model F is purely kinematical. Important for hypernuclear physics is the improvement in the values of the ΛN scattering lengths, and the fact that the interaction in P waves is less attractive in model F as compared to model D.

In this paper we present results obtained for $B_\Lambda$ with models D and F of the Nijmegen potential $\hat{v}$. In both models each of the four components of $\hat{v}$ is local with central, tensor, spin-orbit, and quadratic spin-orbit terms. We neglect the small antisymmetric spin-orbit terms, and the charge symmetry breaking terms which would have a

 

TABLE I. The calculated values of $-V_\Lambda$ and $B_\Lambda$ (in MeV).

| Potential model | Partial-wave contributions to $-V_\Lambda$ $^3S_1+{}^3D_1$ | $^1S_0$ | $^3P_0$ | $^3P_1$ | $^3P_2$ | $^1P_1$ | $^3D_2$ | $^3D_3$ | $^1D_2$ | $-V_\Lambda$ | $B_\Lambda$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $D$ | 19.6 | 7.6 | 0.4 | 0.0 | 5.8 | 2.9 | 0.4 | 0.5 | 0.5 | 37.6 | 32.0 |
| $F$ | 20.7 | 10.2 | −0.1 | −1.7 | 2.6 | −1.4 | 0.4 | 0.4 | 0.4 | 31.4 | 26.7 |

negligible effect on Λ binding in symmetric NM.

We apply the Brueckner reaction matrix method, explained in Ref. 15 in the case of one channel ($\Lambda N$) with a central potential $v_{\Lambda N}$, and in Ref. 16 in the case of $v_{\Lambda N}$ with a tensor component. (The same method has been also applied by Bodmer and his collaborators.[17,18] There is only a technical difference between our and Bodmer's procedures: we use the integral form of the $K$ matrix equation whereas Bodmer uses an integro-differential equation.) In the present case of two channels, the reaction matrix $K$ for $YN$ interaction in NM is a 2 ×2 matrix, with the four components denoted by $K_{\Lambda N}$, $K_{\Sigma\Lambda}$, $K_{\Lambda\Sigma}$, and $K_{\Sigma N}$, similar to the four components of $\hat{v}$, Eq. (1). For $B_\Lambda$, we have

$$-B_\Lambda = V_\Lambda + V_R \,, \tag{2}$$

where the single particle potential

$$V_\Lambda = \sum_{\vec{k}_N}^{k_F} (\vec{k}_N \vec{k}_\Lambda = 0 \,|K_{\Lambda N}|\, \vec{k}_N \vec{k}_\Lambda = 0) \tag{3}$$

(to simplify the notation, spins and isospins are suppressed here), and where for the rearrangement potential $V_R$ we have the approximate expression[19]

$$V_R = -\varkappa V_\Lambda \,, \tag{4}$$

where $\varkappa$ is the ratio of the correlation volume to the volume per nucleon in NM.

In order to determine $K_{\Lambda N}$ we have to solve the system of two coupled equations for $K_{\Lambda N}$ and $K_{\Lambda\Sigma}$:

$$\begin{aligned} K_{\Lambda N} &= v_{\Lambda N} + v_{\Lambda N}\frac{Q}{e_N + V_\Lambda - \epsilon_N - \epsilon_\Lambda} K_{\Lambda N} \\ &\quad + v_{\Lambda\Sigma}\frac{Q}{e_N + V_\Lambda - \Delta - \epsilon_N - \epsilon_\Sigma} K_{\Sigma\Lambda} \,, \\ K_{\Sigma\Lambda} &= v_{\Sigma\Lambda} + v_{\Sigma\Lambda}\frac{Q}{e_N + V_\Lambda - \epsilon_N - \epsilon_\Lambda} K_{\Lambda N} \\ &\quad + v_{\Sigma N}\frac{Q}{e_N + V_\Lambda - \Delta - \epsilon_N - \epsilon_\Sigma} K_{\Sigma\Lambda} \,, \end{aligned} \tag{5}$$

where $\Delta = (M_\Sigma - M_\Lambda)c^2$, $\epsilon_{N(Y)}$ is the nucleon ($Y$ hyperon) kinetic energy, $e_N$ is the nucleon single particle energy in NM for states below the Fermi surface, and $Q$ is the exclusion principle operator.

To solve Eq. (5), we follow (with obvious modifications) the method of Refs. 15 and 16: we introduce wave functions for relative $\Lambda N$ and $\Sigma N$ motion in NM, and obtain for them a system of two coupled integral equations in configuration space which we decompose into separate partial waves after replacing $Q$ by its angle average (the error of the angle-average approximation has been estimated in Ref. 17). The hard core is treated exactly as in Refs. 15 and 16. Obviously, determining $V_\Lambda$ involves a self-consistency problem.

In our calculation of $B_\Lambda$, for the Fermi momentum of NM we use the value $k_F = 1.35\ \text{fm}^{-1}$. For $e_N$ we use the spectrum (i) of Ref. 15. For $\varkappa$, we use the value $\varkappa = 0.15$, obtained in recent NM calculation with Reid potential.[20] (Our present value of $\varkappa$ differs from the value $\varkappa = 0.10$ used in Ref. 15.)

Our results for $V_\Lambda$ and $B_\Lambda$ are shown in Table I. Partial waves not indicated in Table I have been neglected in our calculation. The difference in the two values of $B_\Lambda$ is caused by the difference in the $\Lambda N$ interaction in $P$ states in the two models. Whereas in model $D$ the interaction is attractive in all $P$ states, in model $F$ the attraction in the $^3P_2$ state is much weaker, the interaction in the $^3P_0$, $^3P_1$, and $^1P_1$ states is predominantly repulsive, and the total $P$ state contribution to $B_\Lambda$ is negative.

The striking feature of our result is the remarkable agreement of the value of $B_\Lambda = 26.7$ MeV calculated with the latest model $F$ of the Nijmegen interaction with the semiempirical value $B_\Lambda \sim 27-28$ MeV.[21] No doubt there are still problems concerning the accuracy of our low-order Brueckner method of calculating $B_\Lambda$.[1] Nevertheless, our result strongly supports the view that a realistic baryon-baryon interaction with $\Lambda\Sigma$ coupling leads to the correct value of $B_\Lambda$.

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