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Can the $\Sigma^- nn$ system be bound?

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Motivated by the Σ-hypernuclear states reported in $(K^-, \pi^\pm)$ experiments, we have explored the possibility that there exists a particle-stable $\Sigma^- nn$ bound state. For the Jülich $\tilde{\text{A}}$ hyperon-nucleon, realistic-force model, our calculations yield little reason to expect a positive-parity bound state or resonance in either the $J = \frac{1}{2}$ or the $J = \frac{3}{2}$ channels.

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The question of the existence of Σ hypernuclei bound states — narrow structure in hypernuclear spectra near the threshold for Σ production in (K^-, π), etc., reactions — has intrigued physicists for more than a decade [1]. The widths of such states were estimated to be rather broad ($\sim$ 20 MeV) due to strong $\Sigma N \to \Lambda N$ conversion [2], except in special cases. Particularly interesting special cases are the maximum isospin few-body systems such as $\Sigma^- nn$, which cannot decay via $\Sigma N \to \Lambda N$ conversion because of charge conservation. However, the analysis by Dover and Gal [3] of such maximum isospin states indicates that they are not expected to be the most bound. They concluded, based upon the strong spin-isospin dependence of the ΣN interaction, that the $T = 0, J = \frac{1}{2}$ ΣNN state should lie lowest in energy — lower than the two $T = 1, J = \frac{1}{2}$ states or the $T = 1, J = \frac{3}{2}$ and the $T = 2, J = \frac{1}{2}$ configurations. Unfortunately, the intrinsic width of the $T = 0, J = \frac{1}{2}$ state was predicted to be much larger than the others. Thus, it was not anticipated that narrow Σ-hypernuclear few-body states would be observed.

The interest in ΣNN states was recently rekindled by the report of Hayano *et al.* [4] that narrow structure was observed below the Σ threshold in the stopping kaon reaction $^4\text{He}(K^-, \pi^-)$. The structure in these data was confirmed by later inflight measurements [5] and is supported by earlier bubble-chamber data [6] for the exclusive K^- $^4\text{He} \to \pi^- \Lambda pd$ reaction, which were recently reanalyzed [7]. This was surprising in view of the Dover and Gal analysis, in which the $T = \frac{1}{2}$ states were predicted to lie lower in energy, but the $T = \frac{3}{2}$ states were predicted to have the narrower instrinsic widths. Narrow structure was actually observed in the $^4\text{He}(K^-, \pi^-)$ reaction below the threshold for Σ production, whereas no evidence for an enhancement in that region was observed in the $^4\text{He}(K^-, \pi^+)$ spectra. The (K^-, π^-) reaction leads to both $T = \frac{1}{2}$ and $T = \frac{3}{2}$ channels, while the (K^-, π^+) reaction leads only to the $T = \frac{3}{2}$ channel. Thus, the observed structure was interpreted as a bound $^4_\Sigma\text{He}$ hypernucleus with quantum numbers $T = \frac{1}{2}, J = 0$. [The (K^-, π) spin-flip amplitude is small.] In fact, Harada *et al.* [8, 9] had predicted such an $A = 4$ bound state, based upon a central force approximation to the Nijmegen model D [10] hyperon-nucleon (YN) potential.

In spite of the theoretical analysis of Dover and Gal that suggests formation of a bound $\Sigma^- nn$ state is unlikely, the unexpected narrow structure observed by the Japanese leads one to ask whether state-of-the-art calculations based upon contemporary YN potential models might indicate a possibility that the $T = 2, J = \frac{1}{2}$ or $J = \frac{3}{2}$ states could be observed experimentally, either as a bound state in the continuum or as a three-body resonance. (Garcilazo [11] argued on the basis of rank-one separable potentials that such a system is unbound.) One would prefer to explore all ΣNN states, because $^3\text{He}(K^-, \pi^\pm)$ experiments [12] can excite only $T_z = \pm 1$ states. [Target complications make the $^3\text{H}(K^-, \pi^+)$ reaction to the $T_z = -2$ state more difficult.] However, including the $\Sigma N - \Lambda N$ coupling required by the $T = 1$ states leads to the technically difficult requirement that one must solve the three-body equations for the continuum. This has been accomplished for separable potentials [13], but not for local potential calculations. For that reason we have confined our investigation to the possible existence of a $T = 2$ bound state.

The Faddeev equations for the $\Sigma^- nn$ system were solved in momentum space using the technical apparatus described in Ref. [14]. The complication beyond standard triton calculations is that the Σ can be distinguished from the two neutrons, which leads to a coupled pair of three-body equations instead of only the single equation that one finds for the comparable three-identical-particle problem. A more detailed presentation of YNN three-body bound-state equations can be found in Ref. [15].

The baryon-baryon interactions are assumed to act in all partial waves with $j \leq 1$ and with positive parity. This restriction yields a reasonable approximation to the converged binding energy in the three-nucleon system and can be expected to be sufficient for the purpose of determining whether a $\Sigma^- nn$ bound state might exist. The effect of higher partial waves is certainly smaller than the variations induced by the use of different baryon-baryon interaction models.

Because we work in momentum space, we considered the Jülich [16] hyperon-nucleon interaction models. In particular, we used the Jülich model $\tilde{\text{A}}$, an energy-

TABLE I. The Σ^+p scattering lengths and effective ranges in fm for the Jülich potential models listed.

Model	Ref.	a^s	r_0^s	a^t	r_0^t
Jülich A	[16]	−2.28	4.96	−0.76	2.50
Jülich Ã	[16]	−2.26	5.22	−0.76	0.78

independent one-boson-exchange approximation to the energy-dependent model A interaction. The s-wave effective range parameters for Σ^+p scattering in these models are given in Table I; we assumed equivalence for the Σ^-n interaction for the purpose of this exercise. We would point out, however, that the Jülich model differs qualitatively from the Nijmegen models [10, 17, 18]. The Jülich models are attractive for both spins, whereas the Nijmegen models exhibit a repulsive spin-triplet interaction. Thus, we have chosen the realistic ΣN potential model that is most likely to support a Σ^-nn bound state. For the nn interaction we employed the Nijmegen one-boson-exchange potential of Ref. [19].

Our search for a bound Σ^-nn system with $J^\pi = \frac{1}{2}^+$ proved negative. In retrospect this is not surprising in view of the fact that the spin-singlet ΣN interaction is stronger, whereas the spin-triplet potential dominates: the average interaction is $\frac{1}{4}V^s + \frac{3}{4}V^t$. Gal has argued, on the basis that the Λnn system is not bound, that binding should not be expected for the Σ^-nn system, because the same statistical combination of s-wave interactions enter each and the Λn interaction is stronger than the Σ^+p interaction [20]. (Lack of binding was also found for the hypertriton using the $T = \frac{1}{2}$ $\Lambda N - \Sigma N$ potentials of this same Jülich Ã model [15].) To understand how far away a resonance might lie, we have multiplied the total interaction by a variable factor, increasing that factor until binding was achieved. A plot of the strength factor versus the binding energy obtained is shown in Fig. 1. Because the factor needed to produce binding is greater than 1.7, we do not expect any low-lying resonance in the Σ^-nn system. In the $J^\pi = \frac{3}{2}^+$ case, a spectator Σ^- must be at least in a p-wave relative to the nn pair in order to reach spin 3/2, because s-wave neutrons will necessarily be paired to spin 0. Therefore, it was expected that the $J = \frac{3}{2}$ state will be unbound in view of the finding that there is no $J = \frac{1}{2}$ bound state. Indeed, that was the case.

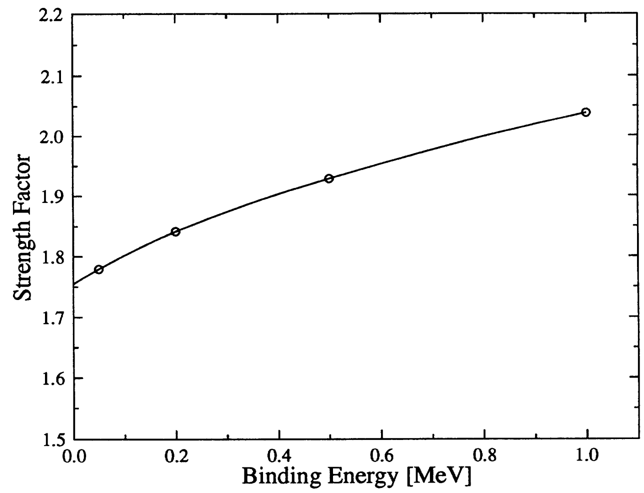

FIG. 1. Strength factor by which the total ΣN interaction is multiplied versus the Σ^-nn binding energy. The circles represent the actual calculations; the solid line is drawn to guide the eye.

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[1] See, for example, the review by Th. Walcher, Nucl. Phys. **A479**, 63c (1988) and the related papers on Σ hypernuclei in that volume.
[2] A. Gal, Nukleonik **25**, 447 (1980); A. Gal and C. B. Dover, Phys. Rev. Lett. **44**, 379 (1980).
[3] C. B. Dover and A. Gal, Phys. Lett. **110B**, 433 (1982).
[4] R. S. Hayano, T. Ishikawa, M. Iwasaki, H. Outa, E. Takada, H. Tamura, A. Sakaguchi, M. Aoki, and T. Yamazaki, Phys. Lett. B **231**, 355 (1989); Nuovo Cimemto A **102**, 437 (1989).
[5] R. S. Hayano, Nucl. Phys. **A547**, 151c (1992).
[6] P. A. Katz *et al.*, Phys. Rev. D **1**, 1267 (1970).
[7] R. H. Dalitz, D. H. Davis, and A. Deloff, Phys. Lett. B **236**, 76 (1990).
[8] T. Harada, S. Shinmura, Y. Akaishi, and H. Tanaka, Soryusiron-Kenkyu **76**, 25 (1987); Nuovo Cimento A **102**, 76 (1990); Nucl. Phys. **A507**, 473 (1990).
[9] T. Harada and Y. Akaishi, Phys. Lett. B **262**, 200 (1991).
[10] M. M. Nagels, T. A. Rijken, and J. J. de Swart, Phys. Rev. D **15**, 2547 (1977).
[11] H. Garcilazo, J. Phys. G **13**, L63 (1987).
[12] M. Barakat and E. V. Hungerford, Nucl. Phys. **A547**, 157c (1992).
[13] I. R. Afnan and B. F. Gibson, Phys. Rev. C **47**, 1000 (1993).
[14] A. Stadler, W. Glöckle, and P. U. Sauer, Phys. Rev. C **44**, 2319 (1991).
[15] K. Miyagawa and W. Glöckle, Phys. Rev. C **48**, 2576 (1993).
[16] A. Reuber, K. Holinde, and J. Speth, Czech. J. Phys. **42**, 1115 (1992); K. Holinde, Nucl. Phys. **A547**, 255c (1992); B. Holzenkamp, K. Holinde, and J. Speth, *ibid.* **A500**, 485 (1989).
[17] M. M. Nagels, T. A. Rijken, and J. J. de Swart, Phys. Rev. D **20**, 1633 (1979).
[18] P. M. Maessen, T. A. Rijken, and J. J. de Swart, Phys. Rev. C **40**, 2226 (1989).
[19] M. M. Nagels, T. A. Rijken, and J. J. de Swart, Phys. Rev. D **17**, 768 (1978); T. A. Rijken, R. A. M. Klomp, and J. J. de Swart, Nijmegen Report No. THEF-NYM-91.05.
[20] A. Gal, in *Common Problems in Low- and Medium-Energy Nuclear Physics*, edited by B. Castel, B. Goulard, and F. C. Khanna (Plenum Press, New York, 1979).