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SYSTEMATICS OF THE Σ^-, Σ^0 and Σ^+ HYPERNUCLEAR SINGLE PARTICLE STATES

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ABSTRACT

Local density dependent Hartree-Fock potentials in analogy with the Λ^0 hypernuclear single particle state description by Millener, Dover and Gal were employed to investigate the systematics of the Σ hypernuclear single particle states. Both charge and isospin dependent (Lane potential) one-body potentials were used to describe the Σ^-, Σ^0 and Σ^+ single particle (s.p.) states for Σ hypernuclei in the mass range 6–40 with core-nucleus isospin $T_c = 1/2$. Due to the smaller magnitude of the Σ-nucleus potential the coulomb effects are dominant, especially for nuclei towards A = 40, while the isospin dependent potential has strong effect for the lighter nuclei due to the A^{-1} dependence of the Lane potential.

INTRODUCTION

Experimentally, narrow structures (Γ < 5-10 MeV) have been found in (K^-, π^-) and (K^-, π^+) reactions on light nuclei (A = 6-16).[1] The interpretation of these structures, which occur a few MeV into the Σ continuum, remains controversial. The fact that the observed peaks are a few MeV less bound than well established Λ substitutional states, which are formed by the transformation of a p-shell neutron into a Λ in the same orbit, suggests a similar interpretation in terms of Σ^- hypernuclear states. However, Σ single-particle p states 3 MeV or more in the continuum are very broad and the bound-state shell-model approach[2] used for Λ hypernuclei should not be applicable. The analysis of the experimental data is also complicated by a quasi-free Σ production background. Thus, questions of Σ-hypernuclear structure are best addressed in terms of the continuum shell model.[3] Even then, there is as yet no satisfactory way of including the effects of the $\Sigma N \rightarrow \Lambda N$ conversion process which is expected to give rise to large widths for Σ-hypernuclear states. For example, there is no evidence for the s-wave Σ states which are believed to be located in the bound region.

The ΣN interaction is believed to give rise to an average central well which is somewhat shallower than the well for the Λ particle.[4] This is consistent with experimental observations described above and with the Σ^- atom data. The central ΣN interaction based on two-body data has a strong spin and isospin dependence[1] so that the ΣN effective interaction is not necessarily weak even if the spin-isospin average force is weak.

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We investigate the behaviour of Σ single–particle states for the three charge states Σ^-, Σ^0 and Σ^+ where the Coulomb force plays an important role. A Lane potential is used to roughly estimate the effect of the isospin dependence of the Σ–nucleus interaction.

THE POTENTIAL MODEL

For Λ hypernuclei, recent data[5] from the (π^+, K^+) reaction have determined the binding energies of many Λ single particle states up to A = 90. The Λ single–particle energies can be accounted for[6] by a density dependent potential of the Skyrme type.[7] The equivalent local potential, $V_L(r,E)$, is of the approximate form

$$V_L(r,E) = \frac{m*(r)}{m}\ U(r) + (1 - \frac{m*(r)}{m})E \tag{1}$$

$$U(r) = \tilde{t}_0\ \rho(r) + \frac{3}{8}\ t_3\ \rho^2(r) + \frac{1}{4}\ (t_1 + t_2)\ T(r)$$

$$T(r) = \frac{3}{5}\ (\frac{3}{2}\ \pi^2)^{2/3}\ \rho^{5/3}(r)$$

$$\frac{\hbar^2}{2m*(r)} = \frac{\hbar^2}{2m} + \frac{1}{4}\ (t_1 + t_2)\ \rho(r)$$

With a proper choice of $\tilde{t}_0$, t_3 and ($t_1 + t_2$) Millener, Dover and Gal[6] were able to describe Λ hypernuclear single–particle states for mass ranging from 6–90. Experimentally determined charge densities were used for $\rho(r)$. The effect of the repulsive $\rho^2(r)$ is to give a potential well with half–value radius greater than that of the underlying density. This, and the non–locality, are important in obtaining the correct level spacings over a wide range of A.

HYPERNUCLEAR SINGLE PARTICLE STATES

We use a potential of the form given in Eq. (1) for Σ hypernuclear single–particle states. There is little information on Σ single particle states and we simplify the potential by setting $t_1 + t_2 = 0$, i.e. $\frac{m*}{m} = 1$, with some justification since space exchange terms in the ΣN interaction are small.[1] For the nuclear densities we use a two parameter Fermi distribution with diffuseness 0.54 fm and

$$r_0 = 1.15 - 1.12\ A^{-2/3} - 0.5\ A^{-4/3}$$

The Coulomb potential is taken to be that due to a uniformly charged sphere of radius $r_{0c}\ A^{1/3}$, where[8]

$$r_{0c} = 1.614 - 0.1067\ell nA + 0.005456(\ell nA)^2 + 6.112/(A - 1.76)^2$$

We introduce a Lane potential in the form

$$\tilde{t}_0 = t_0 + t_{0\ell}\frac{< t \cdot T_c >}{A} \tag{2}$$

where T_c and A refer to the isospin and mass number of the nuclear core and t refers to the isospin of the Σ particle. To maintain the shape of the potential we scale t_3 in the same way, i.e. $\tilde{t}_3 = t_3(\tilde{t}_0/t_0)$.

We choose the potential parameters with reference to the data[9] obtained from (K^-, $\pi^\pm$) reactions on a ^{12}C target. Crudely, speaking, if the three peaks seen are identified with $^{11}Bgs \times p_{3/2}$ Σ^-, $^{11}Cgs \times p_{3/2}$ Σ^0 and $^{11}Bgs \times p_{3/2}$ Σ^+ configurations, the Σ p states are 3–4 MeV unbound for all three charge states. For the charge states with a $T^c = \frac{1}{2}$ core, Eq. (2) becomes

$$\tilde{t}_0 = t_0 - \frac{t_{0\ell}}{2A} \times Z_\Sigma \tag{2'}$$

Thus $t_{0\ell} > 0$ compensates for the Coulomb interaction to some degree. In the shell-model,[10,11] the contributions from the ΣN interaction to the binding energies of the three states are $B_{3/2}$, $\frac{1}{3}B_{1/2} + \frac{2}{3}B_{3/2}$, $\frac{2}{3}B_{1/2} + \frac{1}{3}B_{3/2}$ where B_T is the contribution for total hypernuclear isospin T. The relative energies $-\frac{1}{3}(B_{1/2} - B_{3/2})$, 0, $\frac{1}{3}(B_{1/2} - B_{3/2})$ show a behavior similar to that for the potential well in Eq. (2′). We expect[11] $B_{1/2} > B_{3/2}$ corresponding to $t_{0\ell} > 0$.

The parameters chosen give rise, for the mass 12 hypernuclei, to the potentials listed in Table I, where a typical Λ potential[6] is given for comparison. The ratio $t_3/\tilde{t}_0$, which controls the radial size of the well for a given density distribution, is arbitrarily chosen since there is no information on single particle level spacings for Σ hypernuclei. The parameters chosen correspond to a large, shallow well with a central depth of 12.1 MeV for Σ^0. To get the same s-state binding energy for Σ^0 with $t_3 = 0$ requires a central depth of 22.9 MeV.

The Σ^-, Σ^0 and Σ^+ single-particle binding energies for A = 9–40 are shown in Fig. 1(a)–(c). The solid curves are for no Lane potential, which we can interpret as energies for an isospin zero core. The strong influence of the Coulomb potential is clearly evident. The parameters were chosen so that, when the Lane potential is switched on, the mass 12 s-state binding energies are similar for all three charge states and the mass 12 p states are unbound.

The curves for unbound levels are terminated when the width of the resonant states becomes comparable to the resonance energy. In the Σ^- case, the attractive Coulomb potential cancels out the centrifugal barrier and there are no narrow resonance states.

The binding energies shown in Fig. 1 give some guidance as to what might be expected for the basic Σ single-particle states. Then the effects of the ΣN residual interaction, isospin mixing and $\Sigma N \rightarrow \Lambda N$ conversion must be considered. However, until the experimental Σ hypernuclear spectroscopic information and the theoretical treatments are both improved it will be difficult to make comparisons between the predicted Σ hypernuclear states and experiment.

Table 1. Density Dependent Potential Parameters

	Λ	Σ^-	Σ^0	Σ^+	Units
$\tilde{t}_0$	-403	-160	-220	-280	MeV fm^3
t_3	3393	1600	2200	2800	MeV fm^6
$t_1 + t_2$	103	0	0	0	MeV fm^5
V(r=0)	27	8.8	12.1	15.4	MeV

[a]The Λ potential parameters come from ref. (5). The Σ^- and Σ^+ potential parameters are given for mass 12 [$t_{0\ell} = 1320$ MeV fm^3, A = 11 in Eq. (2')].

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Figure 1. Binding energies of Σ-hypernuclear single–particle states obtained with the density dependent potentials of Table 1. Solid lines correspond to $t_{\ell 0} = 0$ (no lane potential) and dashed lines to $t_{\ell 0} = 1320$ MeV tm^3.

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