Narrow widths of Λ single particle states in hypernuclei

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The narrow widths of highly excited Λ single-particle states are discussed in comparison with large widths of nucleon deep hole states.

Recoilless (K^-,π^-) reactions have produced a Λ particle in various single-particle orbits and disclosed basic properties of the Λ single-particle potential.[1] Figure 1 shows the experimental data on ${}^{40}_{\Lambda}$Ca.[2] Let us look at the widths of the peaks. The width of the $(0d)_\Lambda$ orbit [the peaks corresponding to the $(d_{5/2,\Lambda}d^{-1}_{5/2,n})$ and $(d_{3/2,\Lambda}d^{-1}_{3/2,n})$ configurations] looks to be 3–4 MeV, while the energy resolution of the π^- measurement is 2–3 MeV. This indicates that the physical width $\Gamma_\Lambda(0d)$ is quite narrow. It is noticed that the $(0d)_\Lambda$ orbit is in $2\hbar\Omega_\Lambda \simeq 20$ MeV excitation. A good contrast to this is the nucleon deep hole, for example, the $(0s)_N$ and $(0p)_N$ holes of ^{40}Ca have very large widths, $\Gamma_N(0s)\simeq 22$ MeV and $\Gamma_N(0p)\simeq 12$ MeV.[3] The $(0s)_N$ hole state is also in $2\hbar\Omega_N$ excitation of ^{40}Ca. The situation is schematically shown in Fig. 2. We try to understand how such a big difference arises between the widths of the Λ particle and nucleon-hole states.

Let us consider the second-order contribution to the single-particle (hole) energy $\Delta\epsilon_B(a)$ $(B=\Lambda$ or N) as shown in Fig. 3. The width $\Gamma_B(a)$ due to this diagram process is given by $-2\,\mathrm{Im}\Delta\epsilon_B(a)$, which is expressed explicitly as

$$\Gamma_\Lambda(a_\Lambda)=\sum_{b_\Lambda}\sum_{p_N h_N}(4M_N k_p)\sum_{LST}\frac{[L][S][T]}{[l_a][s_\Lambda][t_\Lambda]}\,|\mathscr{V}_{\Lambda N}(a_\Lambda b_\Lambda p_N h_N;LST)|^2\ , \tag{1}$$

$$k_p^2/2M_N=\epsilon_\Lambda(a_\Lambda)+\epsilon_N(h_N)-\epsilon_\Lambda(b_\Lambda)\ , \tag{2}$$

and

$$\Gamma_N(a_N)=2\sum_{h'_N}\sum_{p_N h_N}(4M_N k_p)\sum_{LST}\frac{[L][S][T]}{[l_a][s_N][t_N]}\,|\mathscr{V}_{NN}(h'_N a_N p_N h_N;LST)|^2\ , \tag{3}$$

$$k_p^2/2M_N=\epsilon_N(h_N)+\epsilon_N(h'_N)-\epsilon_N(a_N)\ , \tag{4}$$

where $[L]=2L+1$, etc., $\mathscr{V}(LST)$ is the particle-hole coupling interaction matrix elements with orbital angular momentum L, spin S, and isospin T. $\mathscr{V}_{NN}$ here is defined as $\sqrt{(1+\delta_{ap})(1+\delta_{hh'})/4}$ times the normalized and antisymmetrized matrix element and the factor 2 in front of the right-hand side of Eq. (3) takes account for the exchange term. Equations (2) and (4) are the energy conserving conditions in the intermediate states of Fig. 3, where the momentum k_p is associated with the nucleon particle state p brought up into the continuum. The wave function of p is normalized as $\sin(k_p r+\cdots)/k_p r$ asymptotically.

Before going to numerical calculations, we make some qualitative discussions on what can be different between Γ_Λ of Eq. (1) and Γ_N of Eq. (3).

(a) Difference in the spin-isospin (ST) of excited nucleon particle hole. The Λ particle with zero isospin excites only isoscalar $(T=0)$ p_N-h_N mode and furthermore, since ΛN spin-spin interaction is weak, the spin vector $(S=1)$ p_N-h_N mode is weakly excited. Thus, if we take only $S=T=0$ in Eq. (1), we have

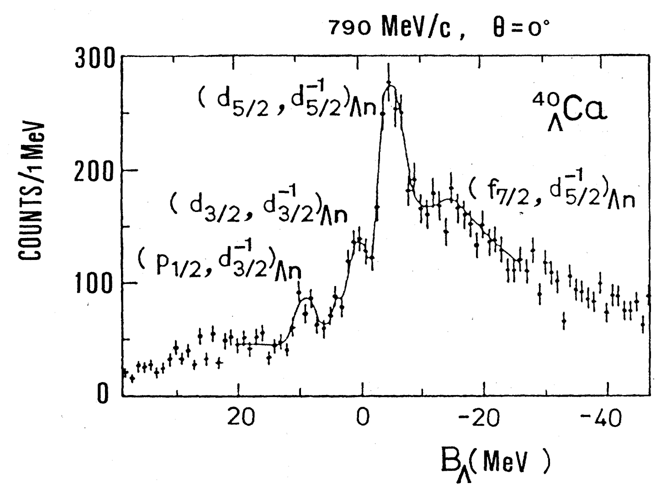

FIG. 1. Observed excitation function of the ^{40}Ca$(K^-,\pi^-){}^{40}_{\Lambda}$Ca reaction at forward angle (Ref. 2).

$$\sum_{ST}([S][T]/[s_\Lambda][t_\Lambda])|\mathscr{V}_{\Lambda N}|^2 \rightarrow ([0][0]/[\tfrac{1}{2}][0])|\mathscr{V}_{\Lambda N}(S=T=0)|^2=\tfrac{1}{2}|\mathscr{V}_{\Lambda N}(S=T=0)|^2 .$$

On the other hand, the NN interaction is strongly spin-isospin dependent and all (ST) $p_N - h_N$ modes contribute in Eq. (3), giving

$$\sum_{ST}([S][T]/[s_N][t_N])|\mathscr{V}_{NN}|^2 \rightarrow 4|\mathscr{V}_{NN}|^2_{av} .$$

(b) Difference in the interaction strengths. The ΛN interaction $\mathscr{V}_{\Lambda N}$ is generally weaker than the NN interaction $\mathscr{V}_{NN}$.

(c) The exchange factor 2 in Eq. (3) for the N-hole case reflects the antisymmetrization among nucleons, which is not required between Λ and nucleons.

(d) Difference in the excitation energies of, for example, $2\hbar\Omega$ excited states, $(1s0d)_\Lambda$ orbit for Λ particle and $(0s)_N$ orbit for N hole.

Considering these qualitative differences (a)–(d), we may expect a large factor of a couple of tens between Γ_Λ and Γ_N.

We now carry out a numerical calculation of Eqs. (1)–(4) to obtain $\Gamma_\Lambda(a)$ and $\Gamma_N(a)$. We employ the effective ΛN (Ref. 4) and NN (Ref. 5) interactions with three-range Gaussian form, which are designed to simulate the respective G matrices constructed from the Nijmegen model D ΛN potential[6] and the $G3RS$ NN potential.[7] Fine adjustments are made so as to reasonably reproduce the observed Λ and N single-particle energies. Used nucleon single-particle energies are $\epsilon_N(0s)=-56.0$, $\epsilon_N(0p)=-36.0$, $\epsilon_N(0d)=-15.0$, and $\epsilon_N(1s)=-14.0$ MeV. The wave functions of the N and Λ bound single-particle states are taken to be harmonic oscillator's with size parameters $b_N=1.94$ fm and $b_\Lambda=\sqrt{M_N/M_\Lambda}\,b_N$. The last choice is to allow the Moshinski transformation. The nucleon wave function in the continuum is obtained by solving the Schrödinger equation with a Wood-Saxon potential ($V_0=-55$ MeV, $R_0=4$ fm, and $a=0.67$ fm in the standard notations).

To make comparison clear, in the following computation we intentionally make the Λ single-particle spectrum $\epsilon_\Lambda(a)$ exactly the same as that of nucleon $\epsilon_N(a)$ and therefore the obtained $\Gamma_\Lambda(a)$ is somewhat overestimated. The result is thus

$$\Gamma_\Lambda(1s)<1.03\ \text{MeV},\quad \Gamma_N(0s)=14.0\ \text{MeV} ,$$
$$\Gamma_\Lambda(0d)<0.44\ \text{MeV} .$$

The obtained $\Gamma_N(0s)$ is smaller than the experimental value ≈ 22 MeV, but should be reasonable as only the simplest diagram contribution has been taken into consideration. The ratio $\Gamma_\Lambda(1s0d)/\Gamma_N(0s)<0.03-0.07$ may be of more significance. If the harmonic oscillator wave functions used above for Λ are replaced by more realistic ones pertinently to their loose bindings, the resulting widths $\Gamma_\Lambda(1s0d)$ should be further reduced. For example, the use of the Wood-Saxon wave functions[8] leads to about 20% reduction of Γ_Λ. Note that the nucleon wave functions relevant to the present discussion are quite well described by the harmonic oscillator's.

A similar situation will remain in heavier hypernuclei. In lighter hypernuclei, say in ${}^{16}_{\Lambda}O$, level densities of nuclear excitations which are responsible to Γ_Λ are much lower and therefore give further smaller widths for Λ single-particle states.

An analogous discussion can be applied to the spreading width $\Gamma_\Sigma^\downarrow$ for the Σ particle. The ΣN interaction is strongly spin-isospin dependent and we have

$$\sum_{ST}([S][T]/[s_\Sigma][t_\Sigma])|\mathscr{V}_{\Sigma N}|^2 \rightarrow \tfrac{8}{3}|\mathscr{V}_{\Sigma N}|^2_{av} ,$$

which implies the magnitude of $\Gamma_\Sigma^\downarrow$ intermediate between Γ_Λ and Γ_N. However, the observed Σ single-particle states are located above its escaping threshold and so the wave func-

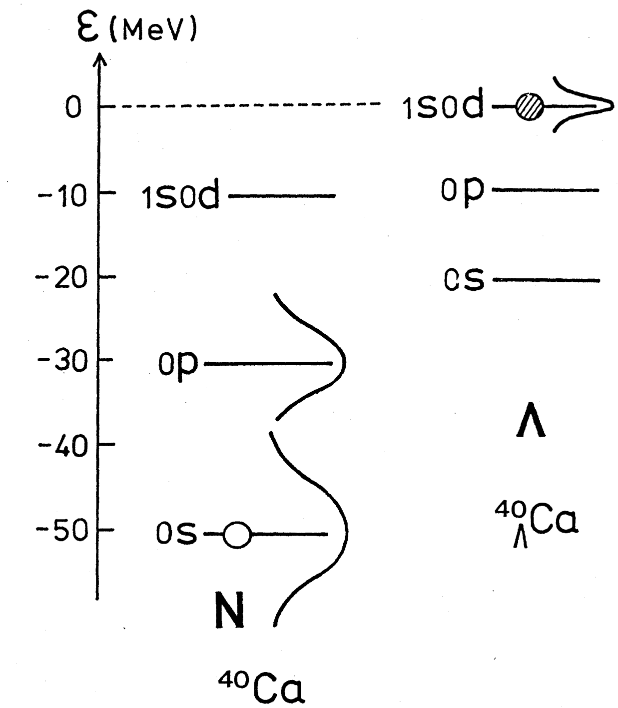

FIG. 2. Illustrative comparison between Λ particle and N hole.

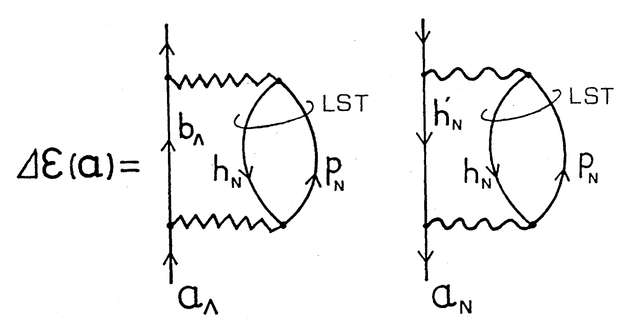

FIG. 3. Second-order diagrams which give rise to widths of Λ particle and N hole.

tion effect should largely reduce their $\Gamma_{\Sigma}^{\downarrow}$. For "narrow Γ_{Σ}," a mechanism to suppress the escaping width $\Gamma_{\Sigma}^{\uparrow}$ would be necessary, which is not required for the bound Λ single-particle states.

It is interesting that kinematical and dynamical characteristics of Λ particle and ΛN interactions simply lead to very narrow highly excited Λ single-particle states, which sound quite drastic when compared with the case of nucleon deep hole states.

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