PHYSICS OF Λ AND Σ HYPERNUCLEI*,**

J. DĄBROWSKI

Theoretical Division, Sołtan Institute for Nuclear Studies
Hoża 69, 00-681 Warsaw, Poland

(Received September 20, 1993)

This talk gives an overview of selected topics in the physics of Λ and Σ hypernuclei.

PACS numbers: 21.80. +a

1. Introduction

The $J^\pi = {}^1\!/_2{}^+$ particles which I will talk about are members of the barion octet: nucleons $N = n, p$ and hyperons $Y = \Lambda, \Sigma^+, \Sigma^0, \Sigma^-, \Xi^-$. Their properties are collected in Table I, in which I denotes the isosopin

TABLE I

Properties of the members of the barion octet

	M(MeV)	I	S	τ(sec)	$\Gamma = \hbar/\tau$ (MeV)	Major decay modes
p	938.3	$^1\!/_2$	0	∞	0.0	
n	939.6	$^1\!/_2$	0	898	$0.7 \cdot 10^{-24}$	$n \to p + e^- + \bar{\nu}_e + 0.78$ MeV
Λ	1115.6	0	-1	$2.6 \cdot 10^{-10}$	$2.5 \cdot 10^{-12}$	$\Lambda \to p + \pi^- + 37.8$ MeV (64%)
						$\Lambda \to n + \pi^0 + 41.1$ MeV (36%)
Σ^+	1189.4	1	-1	$0.8 \cdot 10^{-10}$	$0.8 \cdot 10^{-11}$	$\Sigma^+ \to p + \pi^0 + 116.1$ MeV (52%)
						$\Sigma^+ \to n + \pi^+ + 110.2$ MeV (48%)
Σ^0	1192.5	1	-1	$5.8 \cdot 10^{-20}$	$1.1 \cdot 10^{-2}$	$\Sigma^0 \to \Lambda + \gamma$
Σ^-	1197.3	1	-1	$1.5 \cdot 10^{-10}$	$4.4 \cdot 10^{-12}$	$\Sigma^- \to n + \pi^- + 118.2$ MeV
Ξ^0	1314.9	$^1\!/_2$	-2	$2.9 \cdot 10^{-10}$	$2.3 \cdot 10^{-12}$	$\Xi^0 \to \Lambda + \pi^0 + 64.3$ MeV
Ξ^-	1321.3	$^1\!/_2$	-2	$1.6 \cdot 10^{-10}$	$4.0 \cdot 10^{-12}$	$\Xi^- \to \Lambda + \pi^- + 66.1$ MeV

* Presented at the XXIII Mazurian Lakes Summer School on Nuclear Physics, Piaski, Poland, August 18–28, 1993.

** This research was partly supported by Komitet Badań Naukowych under Grant No. PB 2-0956-91-01.

and S the strangeness. All hyperons decay via weak processes ($\Delta S = 1$) and their lifetime $\tau \simeq 10^{-10}$ sec. In the time scale of nuclear dynamics they are practically stable. This applies also to the exceptional case of Σ^0 which decays electromagnetically.

All the members of the barion octet interact strongly and may form bound states: nuclei (systems of nucleons) and hypernuclei (systems of nucleons and hyperons). The first hypernucleus, observed in 1952 by Danysz and Pniewski [1] in a photographic emulsion exposed to cosmic rays, was a Λ hypernucleus (Λ hyperon + nuclear core). This discovery started the hypernuclear physics, a new field of research on the border between nuclear and particle physics. In 1963 an analysis in Warsaw [2] of an event observed in an emulsion irradiated by kaon beam led to the identification of the first double Λ hypernucleus (two Λ hyperons + nuclear core). The nuclear emulsion technique, in which the emulsion acts both as target and detector, was the only experimental method in hypernuclear physics till the late 1960's. At that time, the development of intense beams of the strange K^- mesons (with $S = -1$) with low momentum (< 1 GeV/c) made it possible to apply counter technique to detect the production of hypernuclei in the (K^-, π) strangeness exchange reaction. This led in 1979 to the observation in CERN [3] of the first Σ hypernucleus (Σ hyperon + nuclear core).

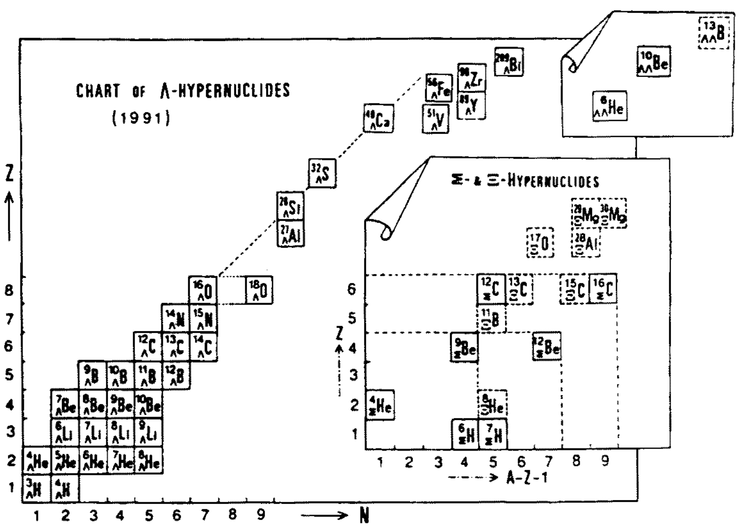

Fig. 1. The hypernuclear chart as of 1991.

The present state of hypernuclear physics is illustrated in Fig. 1. The authors [4] included into the chart also Ξ hypernuclei whose identification, however, is not fully convincing and their existence is one of the open problems in hypernuclear physics. Also the existence of $^4_\Sigma$He is not quite certain yet.

In my talk, I shall give an overview of selected problems in the physics of Λ and Σ hypernuclei.

2. Λ hypernuclei

The early emulsion research led to the identification of several light hypernuclei in their ground states (g.s.) and to the determination of the Λ binding (separation) energies B_Λ. The analysis of the B_Λ values, plus some low energy Λp scattering data (obtained in the hydrogen bubble chamber) led to the first determination of the ΛN interaction $v_{\Lambda N}$. This interaction turned out to be: *(i)* slightly weaker than the nuclear interaction v_{NN}, as it does not lead to a ΛN bound state (the lightest observed hypernucleus is the hypertriton $^3_\Lambda$He, *i.e.*, the Λpn system); *(ii)* more attractive in spin singlet ($J_{\Lambda N} = 0$) than in spin triplet ($J_{\Lambda N} = 1$) state — contrary to the case of v_{NN}; *(iii)* of shorter range than v_{NN} (the exchange of one pion ($I_\pi = 1$) between N ($I_N = {}^1\!/_2$) and Λ ($I_\Lambda = 0$) is not possible).

Two difficulties ("the overbinding problem") could not be resolved with this $v_{\Lambda N}$:

(A) Whereas the measured value of Λ binding in $^5_\Lambda$He, $B_\Lambda(^5_\Lambda\mathrm{He})_{\mathrm{exp}} = 3.12 \pm 0.2$ MeV, calculations with $v_{\Lambda N}$ led to $B_\Lambda(^5_\Lambda\mathrm{He})_{\mathrm{calc}} \gtrsim 5$ MeV.

(B) By extrapolating the measured values of $B_\Lambda(^A_\Lambda Z)$, we get for $A \to \infty$ the semi-empirical value of Λ binding in nuclear matter, $B_\Lambda(\infty)_{\mathrm{se}} \simeq 30$ MeV. On the other hand, all theoretical calculations (of Brueckner or Jastrow type) led to a much bigger value of $B_\Lambda(\infty)_{\mathrm{calc}} \gtrsim 40$ MeV.

It appears that the overbinding problem may be solved — as suggested by Bodmer [5] — by taking into account the coupling to the Σ channel due to the fast process $\Lambda N \leftrightarrow \Sigma N + \Delta$, where $\Delta = M_\Sigma - M_\Lambda \simeq 80$ MeV. Let us consider the $^5_\Lambda$He hypernucleus, *i.e.*, the $\Lambda + \alpha$ system which in its g.s. has the isospin $I = 0$. The lowest order in which the $\Lambda\Sigma$ coupling contributes to $B_\Lambda(^5_\Lambda\mathrm{He})$ is the second order with the $\Sigma + \alpha$ intermediate state with $I = 0$. This requires (since $I_\Sigma = 1$) that the α particle in the intermediate state should have $I_\alpha = 1$. Now the threshold for excitation of the $I_\alpha = 1$ states of α is at least 20 MeV above the g.s., and this leads to a strong suppression of the contribution of the $\Lambda\Sigma$ coupling to $B_\Lambda(^5_\Lambda\mathrm{He})$. Unfortunately, a full calculation of $B_\Lambda(^5_\Lambda\mathrm{He})$ with the $\Lambda\Sigma$ coupling has not been performed so far.

The mechanism of the suppression of the $\Lambda\Sigma$ coupling in the Λ + nuclear matter system is similar, and the Brueckner type calculation of $B_\Lambda(\infty)$ with the Nijmegen barion-barion interaction [6, 7], which contains the $\Lambda\Sigma$ coupling, gives $B_\Lambda(\infty) \simeq 30$ MeV [8] (recently, a similar result was obtained with the Bonn interaction extended to the strange sector [9]). Unfortunately, the calculations in [8, 9] are burdened by the uncertain accuracy of the applied approximate form of the Brueckner theory.

The important role of the Σ channel, only 80 MeV above the Λ channel, makes hypernuclei very interesting systems. A similar phenomenon in ordinary nuclei — an admixture of excited nucleon states (resonances) — is much more subtle. Here even for the lightest $\Delta(3,3)$ resonance the distance to the Δ channel is $M_\Delta - M_N \simeq 300$ MeV.

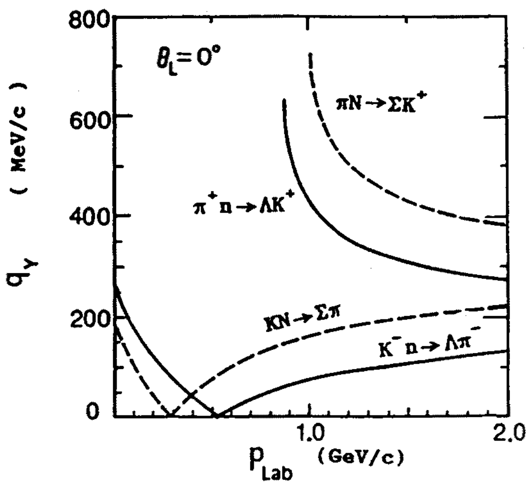

Fig. 2. The momentum q_Y transferred to the hyperon Y in the reaction $aN \to Yb$ at $\theta_b = 0°$ as a function of the projectile momentum p_a.

A new phase in hypernuclear research started with the production of hypernuclei with the strangeness exchange reaction (K^-, π), in which one unit of strangeness $S = -1$ is transferred to the target nucleus. From the detected pion momentum $\mathbf{p}_\pi$, we may determine (from energy and momentum conservation) the mass $M_{\rm HY}$ of the hypernucleus produced (in its ground or excited state). It is convenient to plot the number of detected pions (per unit of pion energy at a fixed scattering angle θ) as function of $\Delta M = M_{\rm HY} - M_{\rm T}$, where $M_{\rm T}$ is the mass of the target nucleus. We have $\Delta M = -B_\Lambda + B_N + M_\Lambda - M_N$, where B_N is the separation energy (binding) energy of N from the target nucleus. Notice that B_Λ is the energy required to remove Λ from the hypernucleus (in its ground or excited state) leaving the nuclear core in its g.s. In the (K^-, π) reaction with a charged, *i.e.*, negative pion, the elementary process $K^- + n \to \pi^- + \Lambda + 178$ MeV is exoenergetic, and the momentum transfer $q_\Lambda = p_\pi - p_{K^-} = -p_\Lambda$ vanishes for $\theta = 0$ at the "magic" laboratory momentum $p_{K^-} = 530$ MeV/c (see Fig. 2). At this magic momentum, the Λ recoil momentum $p_\Lambda = 0$, and we have the recoilless Λ production, and expect to produce the substitutional states in which Λ simply replaces a neutron in its state in the target nucleus.

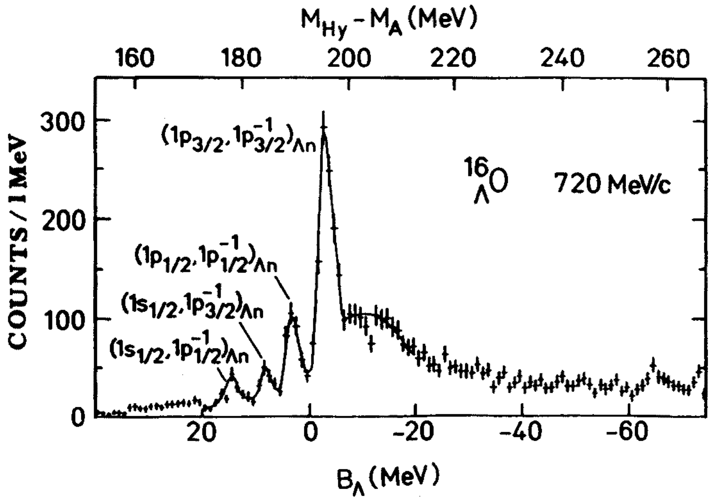

Fig. 3. Spectrum of pions emitted at $\theta = 0°$ in the (K^-, π^-) reaction on ^{16}O at $p_K = 720$ MeV/c [10].

As an example, we show in Fig. 3 the spectrum of pions emitted in the forward direction in the (K^-, π^-) reaction on ^{16}O at $p_{K^-} = 720$ MeV/c [10]. Here $q_\Lambda = 40$ MeV/c (see Fig. 2), and besides the substitutional states $(1p_{3/2}, 1p_{3/2}^{-1})_{\Lambda n}$, $(1p_{1/2}, 1p_{1/2}^{-1})_{\Lambda n}$, also the g.s. $(1s_{1/2}, 1p_{1/2}^{-1})_{\Lambda n}$ and the state $(1s_{1/2}, 1p_{3/2}^{-1})_{\Lambda n}$ are produced. The striking result here is the 6 MeV splitting between the two substitutional states, which almost coincides with the 6.1 MeV splitting between the $p_{3/2}$ and $p_{1/2}$ neutron states in ^{16}O. This indicates that the spin-orbit coupling in the Λ-nucleus potential is very small, in contrary to the nucleon-nucleus spin-orbit coupling which plays such an important role in nuclear physics. In a way, Λ behaves in a nucleus like a spinless neutron.

The use of the (K^-, π) in-flight reaction at CERN and Brookhaven, and the same reaction with stopped kaons at KEK initiated the hypernuclear spectroscopy. The special feature here is connected with the fact that Λ is a different particle and thus deep s.p. Λ states, including the $1s_{1/2}$ g.s., are easily accessible

In the mid-1980's the associated production reaction (π^+, K^+) started being used in producing Λ hypernuclei (K^+ has strangeness $S = 1$). One

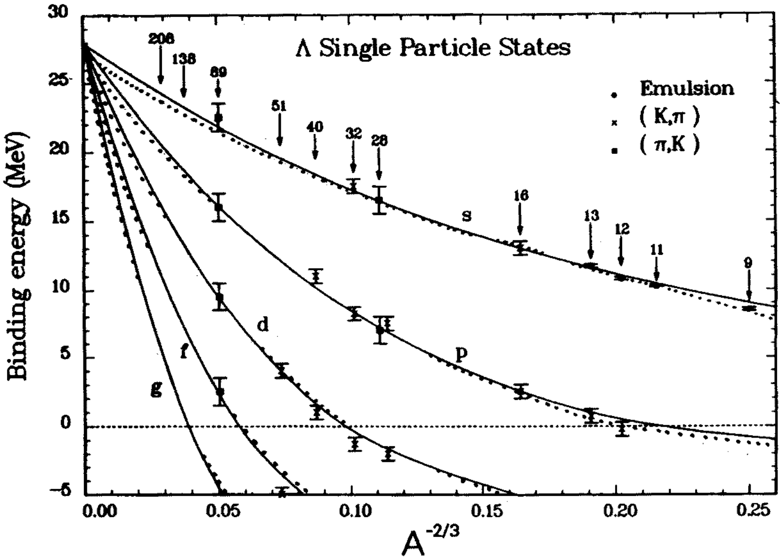

Fig. 4. Data on binding energies of Λ s.p. states as a functions of $A^{-2/3}$ [10].

obvious advantage is the relatively high intensity of the available pion beam, and also the weak K^+-nucleus interaction. Here the elementary process $\pi^+ + n \rightarrow K^+ + \Lambda - 530$ MeV is endoenergetic and the momentum transfer q_Λ is large (see Fig. 2). In the heavy hypernuclei, the Λ bound orbitals (with low l_Λ are coupled to holes of valence neutrons with high l_n. The large momentum transfer in the (π^+, K^+) reaction is well matched to these high l_n states. Consequently, the (π^+, K^+) reaction supplements the (K^-, π^-) reaction in producing heavy hypernuclei.

If we collect the results obtained with the emulsion technique for the hypernuclear g.s., and with the (K^-, π^-) and (π^+, K^+) reactions for the ground and excited states, we get [11] a textbook example of s.p. structure, shown in Fig. 4, where the curves were obtained with a Woods–Saxon s.p. potential of the depth $\sim$ 28 MeV [equal to $B_\Lambda(\infty)$]. In ordinary nuclei, only the valence nucleons reveal such s.p. structure, whereas the deep laying (hole) states — accessible by various knock-out reactions — have large widths $\sim 10 - 20$ MeV.

Let me say a few words about the decay of Λ hypernuclei. The mesonic decay $\Lambda \rightarrow N + \pi$ (see Table I) is strongly suppressed in heavier hypernuclei, because the final N momentum $p_N \sim 100$ MeV$/c$ is much smaller than the Fermi momentum $p_F \sim 266$ MeV$/c$. However, another decay mode, the nonmesonic decay $\Lambda + N \rightarrow n + N + 176$ MeV, takes place in hypernuclei. Because $p_{n(N)} \sim 400$ MeV$/c$ is much larger than p_F, it is not Pauli suppressed and becomes the dominant decay mode in heavier hypernuclei.

The combined effect of the two decay modes is that the lifetime of all Λ hypernuclei is approximately equal to the lifetime of a free Λ.

The analysis of the nonmesonic decay of hypernuclei gives us a unique possibility to gain information on the weak $\Lambda N \to NN$ process which determines the lifetime of heavier Λ hypernuclei. In nuclear physics, a similar weak (parity nonconserving) process $NN \to NN$ leads only to subtle effects which are very hard to detect.

3. Double Λ hypernuclei

So far only three double Λ hypernuclei have been identified in emulsions exposed to K^- beams: ${}^{10}_{\Lambda\Lambda}$Be [2], ${}^{6}_{\Lambda\Lambda}$He [12], and ${}^{13}_{\Lambda\Lambda}$B [13]. The observed rare events consist of the following four processes: (1) production of Ξ^- in the double strangeness exchange reaction (K^-, K^+) or (K^-, K^0) according to the respective elementary processes $K^-p \to K^+\Xi^- - 383$ MeV or $K^-n \to K^0\Xi^- - 387$ MeV, in which two units of strangeness $S = -2$ are transferred to the nucleon which converts into Ξ^-; (2) production of a double Λ hypernucleus by the stopped Ξ^- according to the elementary process $\Xi^-p \to \Lambda\Lambda + 28.5$ MeV; (3) mesonic decay of the double Λ hypernucleus into a single Λ hypernucleus; (4) mesonic or nonmesonic decay of the single Λ hypernucleus. To increase the chance of identifying all four processes, a counter assisted emulsion technique was applied in [13]. The analysis of the events allowed a determination of the separation energies $B_{\Lambda\Lambda}$ of the two Λ's from the respective nuclear cores. The difference $\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda} - 2B_\Lambda$, where B_Λ is the separation energy from the single Λ hypernucleus with the same core, is a measure of the $\Lambda\Lambda$ interaction. The result obtained, $\Delta B_{\Lambda\Lambda} \simeq 5$ MeV, indicates that the $\Lambda\Lambda$ interaction is attractive. So far it is the only experimental information on this interaction.

The observation of double Λ hypernuclei is important in connection with the hypothetical stable H dibarion which is a six quark state ($uuddss$) with $J^\pi = 0^+, I = 0$, and $S = -2$, predicted by Jaffe [14]. If its mass M_H was smaller than $2M_\Lambda - B_{\Lambda\Lambda}$, the double Λ hypernucleus would decay "immediately" into a free H dibarion and a residual nucleus, and we would never be able to observe its weak decay. Thus the observation of double Λ hypernuclei (with $B_{\Lambda\Lambda} \simeq 20$ MeV) and of their weak decay implies that if H exists at all, its mass $M_H \gtrsim 2M_\Lambda - 20$ MeV.

To gain more information on double Λ hypernuclei, and to resolve the problem of the H dibarion and of Ξ hypernuclei, projects of counter experiments with the double strangeness exchange reaction (K^-, K^+) are now in progress.

4. Σ hypernuclei

In 1979 at CERN Bertini et al. [3] observed in the (K^-, π^-) reaction on ^{9}Be, in addition to the familiar Λ hypernuclear states, narrow peaks at an excitation energy larger by about $\Delta = M_\Sigma - M_\Lambda \simeq 80$ MeV, consistent with, and attributed to, the formation of Σ hypernuclei (see Fig. 5). The presently existing experimental data on Σ hypernuclear states reveal two characteristic features: *(i)* the states have surprisingly narrow widths $\Gamma_{exp} \sim 5$ MeV, and *(ii)* their energy is positive (up to about 10 MeV), *i.e.*, the Σ binding energy B_Σ is negative.

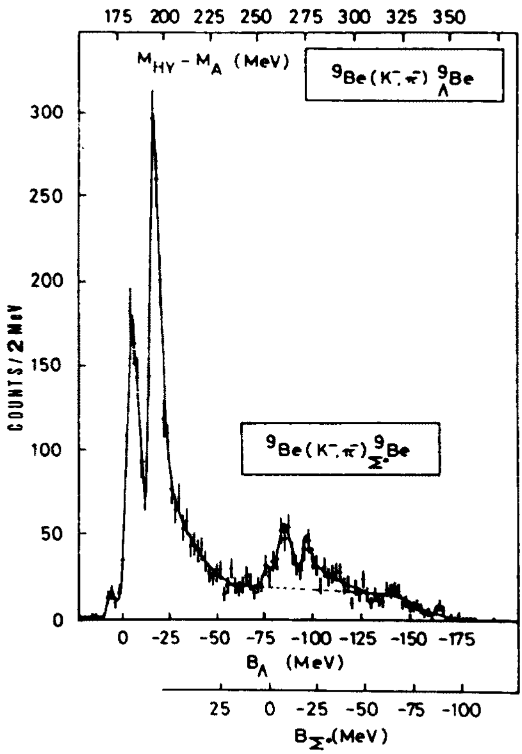

Fig. 5. Pion spectrum from from (K^-, π^-) reaction on a beryllium target at $p_K = 720$ MeV/c [3].

The narrowness of the observed Σ hypernuclear states came as a surprise for the following reason. Whereas a free Σ is in the time scale of nuclear dynamics a very stable particle (see Table I), in nuclear matter (of density ρ) it may undergo the strong $\Sigma\Lambda$ conversion process $\Sigma N \to \Lambda N + 80$ MeV. The semiclassical estimate Γ_0 of the corresponding width of Σ in nuclear is: $\Gamma_0 = (1/2)\hbar\rho\langle v\sigma\rangle$, where σ is the total cross section for the $\Sigma\Lambda$

conversion, v is the relative ΣN velocity, and $\langle\rangle$ indicates averaging over N velocities. Now, if we insert for ρ the equilibrium density $\rho_0 = 0.17$ fm^{-3} and for σ the experimental cross section (~ 60 mb), we get for zero Σ momentum (*i.e.* for the g.s. of Σ in nuclear matter) the result $\Gamma_0 \simeq 24$ MeV, which is about five times larger than Γ_{exp}.

However, the semiclassical estimate disregards important many-body effects: Pauli blocking and binding effects. The importance of these effects is well known in the case of neutron which in free space β decays into a proton within about a quarter of an hour, but is perfectly stable inside nuclei. Namely, because of the Pauli blocking, the proton emerging from the β decay would have to occupy a state of such a high energy, that the decay would be energetically impossible. In the case of Σ, these many-body effects may be taken into account by a simple modification of the expression for Γ_0 [15]. First, we have to multiply σ by the Pauli blocking operator Q which vanishes whenever the momentum p_{N} of the nucleon emerging from the $\Sigma\Lambda$ conversion is smaller than the Fermi momentum p_{F}, and is equal 1 otherwise. Second, in the energy conservation equation for the $\Sigma\Lambda$ conversion, we have to include into the energies of Σ, Λ and N the momentum dependent s.p. potentials. The second modification diminishes final nucleon momenta p_{N} to such a degree that an essential part of them are smaller than p_{F} and are excluded by the Q operator. The result obtained in this way for zero Σ momentum is $\Gamma \simeq 6$ MeV [16].

In finite hypernuclei, the width is expected to be smaller than in nuclear matter, because the Σ wave function spreads out beyond the nuclear core, and its overlap with nuclear density is diminished. This leads to a reduction in Γ, especially for loosely bound Σ states in which Σ spends most of the time outside the nuclear core. (An extreme case is that of Σ^- atoms whose width is of order of eV [16].)

We conclude that Pauli blocking and binding effects suppress $\Sigma\Lambda$ conversion in hypernuclei so that the resulting width Γ does not exceed the width Γ_{exp} found in experiment. The same conclusion has been reached in [17–19]. In some cases additional reduction of Γ may occur as the result of the selectivity mechanism suggested in [20]. Other possible factors like quenching of the one-pion-exchange component of the $\Sigma\Lambda$ conversion in nuclear matter [21] and SU(3) symmetry [22] have been discussed also.

Now, let us turn to the problem of the positive energy of the observed Σ hypernuclear states, and discuss whether these states can be explained within the Σ s.p. model. In this model the motion of Σ in the hypernucleus is described by the wave function $\psi_\Sigma(\boldsymbol{r})$ which is the solution of the s.p. Schrödinger equation with the s.p. potential $\mathcal{V}_\Sigma(\boldsymbol{r}) = V_\Sigma(\boldsymbol{r}) + iW_\Sigma(\boldsymbol{r})$, where W_Σ represents the absorption due to the $\Sigma\Lambda$ conversion. If we calculate in the impulse approximation the cross section $d^2\sigma/d\hat{k}_\pi dE_\pi$ for the

(K^-, π) reaction, we obtain peaks in the spectrum of pions, whose widths are approximately equal to the widths of resonances in the final Σ states ψ_Σ. Now, resonances at an energy $\sim 5-10$ MeV in $\mathcal{V}_\Sigma$ of the generally assumed Woods–Saxon or square-well shape have widths (even without any absorptive part W_Σ) much larger than $\Gamma_{\rm exp}$. What we need to have narrow resonances at high energy is $\mathcal{V}_\Sigma$ with a sufficiently high barrier at the surface of the hypernucleus (for low l_Σ orbits in the light observed Σ hypernuclei, the centrifugal barrier is too small).

Recently Myint, Tadokoro and Akaishi [23] (see also [24]) have suggested that indeed $V_\Sigma(r)$ has a repulsive bump $U_B(r)$ near the nuclear surface. First they determine the effective ΣN potential in nuclear matter, $V^{\rm eff}_{\Sigma N}(r_{\Sigma N})$, which is repulsive at short and attractive at large ΣN distance (see Fig. 6). Next, by folding $V^{\rm eff}_{\Sigma N}$ with nuclear density, they obtain their $V_\Sigma(r)$. The mechanism of the appearance of the repulsive bump in V_Σ is shown in Fig. 6. Nucleons inside the dotted area contribute to V_Σ a repulsive interaction while those in the shaded area an attractive interaction. When Σ is deep inside the nucleus (at point A), it feels from the surrounding nucleons both the full repulsion and the full attraction which overweighs the repulsion, and the net result is an attractive V_Σ. When Σ is near the nuclear surface (at point B), it still feels the full repulsion, but only a diminished attraction which is overweighed by the full attraction, and the net result is a repulsive V_Σ.

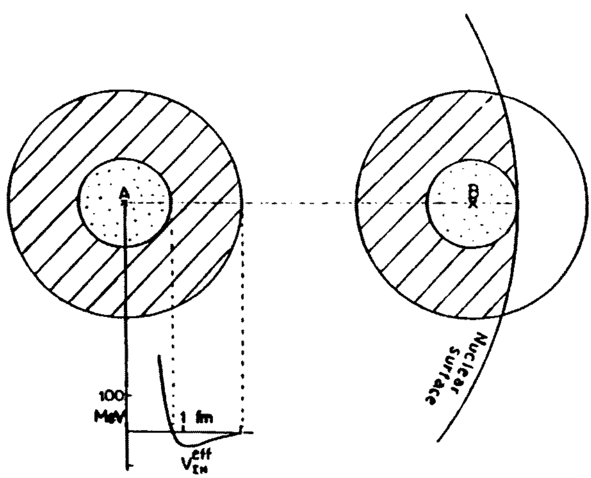

Fig. 6. Repulsive and attractive interaction felt by Σ in a hypernucleus [23].

Let us see whether such repulsive bump may lead to the two peaks at $\Delta M = 277.5 \pm 1$ and 284 ± 1 MeV ($B_\Sigma = -5.9 \pm 1$ and -12.4 ± 1 MeV) observed [25] in the (K^-, π^+) reaction on ^{16}O at $p_{K^-} = 450$ MeV/c (at $\theta \simeq 0°$). We assume for $\mathcal{V}_\Sigma$ the simplified form $\mathcal{V}_\Sigma = -(V_0 + W_0)\theta(R - r) + V_B\delta(r - R)$ with $R = 3$ fm, $V_B = 20$ Mev fm $[\simeq \int drU_B(r)]$, $V_0 = 20$ MeV (which is compatible with the Nijmegen interaction, see [15], [26]), and $W_0 = 2.5$ MeV (calculated in [27]). To determine the target proton wave function in the $p_{1/2}$ and $p_{3/2}$ states, we use a square well potential (with a delta spin-orbit coupling) adjusted to the respective empirical proton energies. The result [28] obtained in the plane wave impulse approximation for $d^2\sigma/d\hat{k}_\pi dE_\pi$ at $\theta = 0°$ is shown in Fig. 7, together with the data of [25] (as the data represent counting rates only, the calculated curves include an arbitrary normalization to match the overall magnitude of the data). Considering the simplified way of calculating the pion spectrum (without any adjustable parameters), the result indicates that it appears possible to explain the observed Σ hypernuclear states within the Σ s.p. model, provided there is a surface bump in V_Σ.

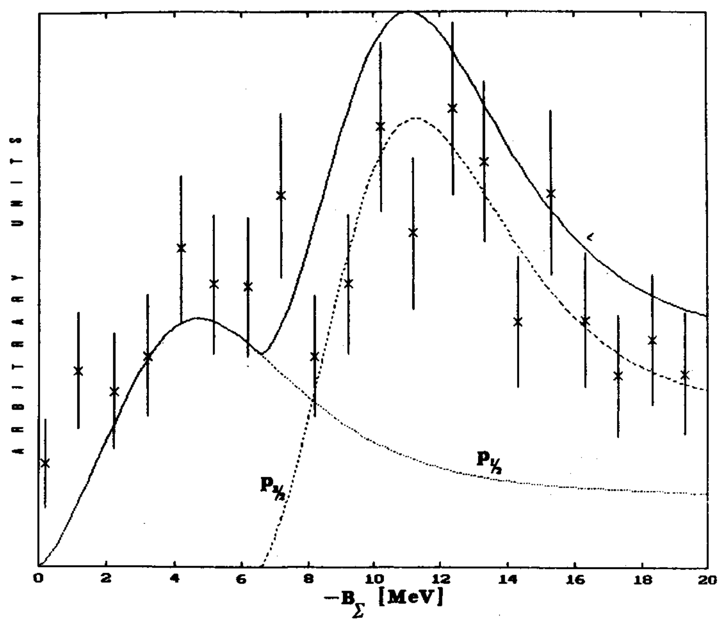

Fig. 7. Pion spectrum from from (K^-, π^-) reaction on ^{16}O at $\theta = 0°$ at $p_K = 450$ MeV/c. The solid curve is the total spectrum, the dotted curves are contributions of the K^- interaction with $p_{1/2}$ and $p_{3/2}$ protons in ^{16}O.

Whereas in our calculation the lower peak corresponds to the $(p^{-1}_{1/2})_p$ state and the upper peak to the $(p^{-1}_{3/2})_p$ state of the nuclear core, the authors of [25] interpret their results in the reversed way. According to our calculation, the situation is similar to that in ${}^{16}_{\Lambda}$O (see Fig. 3) and is compatible with a very weak spin-orbit coupling in V_{Σ}, whereas the inerpretation of the authors of [25] leads them to the conclusion that the spin-orbit coupling in V_{Σ} is twice that of the nucleon-nucleus spin-orbit coupling. On the other hand, theoretical predictions [29–31] suggest a Σ spin-orbit coupling comparable to the nucleon spin-orbit coupling.

To resolve the problem of the nature of the Σ hypernuclear states and of the Σ spin-orbit coupling, we obviously need more experimental date of an improved accuracy, including data on heavy Σ hypernuclei which might be obtained with the (π, K^{+}) reactions (see [32]).

REFERENCES

[1] M. Danysz, J.Pniewski, *Phil. Mag.* **44**, 348 (1953).
[2] M. Danysz *et al., Phys. Rev. Lett.* **11**, 29 (1963); *Nucl.Phys.* **49**, 121 (1963).
[3] R. Bertini *et al., Phys. Lett.* **90B**, 375 (1980).
[4] H.T. Bandō, T.Matoba, J. Žofka, in *Perspectives in Meson Science*, Eds T.Yamazaki, K.Nakai, K.Nagamine, in press.
[5] A.R. Bodmer, *Phys. Rev.* **141**, 1387 (1966); in Proc. Second Int. Conf. on High-Energy Physics and Nucl. Structure, Rehovoth, 1967, North-Holland 1967, p. 60.
[6] N.M. Nagels, T.A. Rijken, J.J. de Swart, *Phys. Rev.* **D15**, 2547 (1977).
[7] N.M. Nagels, T.A. Rijken, J.J. de Swart, *Phys. Rev.* **D20**, 1633 (1979).
[8] J. Rożynek, J. Dąbrowski, *Phys. Rev.* **C20**, 1612 (1979).
[9] A.G. Reuber, Diplomarbeit, Universität Bonn, 1992; A. Reuber, K. Holinde, J.Speth, in Proc. of the Workshop on Strangeness in Nuclei, Cracow, 1992, Eds St. Kistryk, O.W.B. Schult, World Scientific, 1992, p. 97.
[10] W. Brückner *et. al., Phys. Lett.* **79B**, 157 (1978).
[11] D.J. Millener, C.B. Dover, A. Gal, *Phys. Rev.* **C38**, 2700 (1988).
[12] D. Prowse, *Phys. Lett.* **17**, 782 (1966).
[13] A. Aoki *et al. Progr. Theor. Phys.* **85**, 951, 1287 (1991).
[14] R.L. Jaffe, *Phys. Rev. Lett.* **38**, 195 (1977).
[15] J. Dąbrowski, J. Rożynek, *Phys. Rev.* **C23**, 1706 (1981).
[16] J. Dąbrowski, J. Rożynek, *Acta Phys. Pol.* **B14**, 439 (1983).
[17] W. Stępień-Rudzka, S. Wycech, *Nucl. Phys.* **A236**, 349 (1981).
[18] J.A. Johnston, A.W. Thomas, *J. Phys. G: Nucl. Phys.* **8**, L105 (1982); *Nucl. Phys.* **A392**, 409 (1983).
[19] Y. Yamamoto, H. Bandō, *Progr. Theor. Phys.* **69**, 1312 (1983).
[20] A. Gal, C.B. Dover, *Phys. Rev. Lett.* **44**, 379 (1980); A. Gal, *Nukleonika* **25**, 447 (1980).
[21] R. Brockman, E. Oset, *Phys. Lett.* **118B**, 33 (1982); E. Oset, P. Fernández de Cordoba, L.L. Salcedo, R. Brockman, *Phys. Rep.* **188**, 79 (1990).
[22] C.B. Dover, H. Feshbach, *Phys. Rev. Lett.* **59**, 2539 (1987).

[23] K.S. Myint, S. Tadokoro, Y. Akaishi, *Progr. Theor. Phys.* **82**, 112 (1989).
[24] S. Tadokoro, Y. Akaishi, *Phys. Rev.* **C42**, 2591 (1990).
[25] R. Bertini *et al., Phys. Lett.* **158B**, 19 (1985).
[26] C.B. Dover, D.J. Millener, A. Gal, *Phys. Rep.* **184**, 1 (1989).
[27] J. Dąbrowski, *Phys. Lett.* **139B**, 7 (1984).
[28] J. Dąbrowski, J. Rożynek, *Phys. Lett.* **B**, in press.
[29] H.J. Pirner, *Phys. Lett.* **85B**, 190 (1979); H.J. Pirner, B. Povh, *Phys. Lett.* **114B**, 308 (1982).
[30] C.B. Dover, A. Gal, *Progr. Part. Nucl. Phys.* **12**, 171 (1984).
[31] C.B. Dover, in Proc. Intern. Nucl. Phys. Conf., Harrogate, 1986, Eds J. L. Durell, *et al.*, Inst. Phys. Conf. Ser. 86, IOP Publishing, Bristol, 1987, p. 99.
[32] S. Tadokoro, Y. Akaishi, *Phys. Lett.* **282B**, 19 (1992).