THE PRODUCTION OF POSSIBLE HYPERNUCLEAR γ-EMITTERS IN THE REACTION $^{A}Z(K^{-}, \pi^{-})\, ^{A}_{\Lambda}Z$ INDUCED BY K^{-} MESONS AT REST

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The transition rates for the (K^{-}, π) two body reactions at rest leading to the production of hypernuclear γ-emitters have been calculated for different light targets. The calculated production rates are in general lower than 5×10^{-5} per captured kaon.

1. *Introduction*

Until recently, most of the hypernuclear data have been coming from the investigations of the production and decay processes of hypernuclei in the nuclear emulsion exposed to a beam of slow K^{-} mesons. Those studies were limited to the ground-state properties of hypernuclei, such as binding energies and, in some cases, spins. These data have been the main source of knowledge about the hyperon–nucleon interaction. It is clear that the development of hypernuclear spectroscopy is of great importance for this field of physics. The best process for the production of hypernuclei is the strangeness-exchange reaction:

$$K^{-}+{}^{A}Z \rightarrow \pi^{-}+{}^{A}_{\Lambda}Z \tag{1}$$

which is related to the elementary interaction:

$$K^{-}+\mathrm{n} \rightarrow \pi^{-}+\Lambda. \tag{2}$$

Experimental investigations of reaction (1) are in progress. Excited states of hypernuclei are usually analysed by means of the pion-spectrometer technique. A survey of the experimental data obtained so far may be found in the article by Povh [1]. The production of hypernuclei in reaction (1) was discussed by several authors [2–4]. Those investigations concern mostly hypernuclear continuum excitations arising when a nucleon is replaced

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by a Λ particle in the same shell. The excited states of the p-shell hypernuclei with moderate excitation energies (usually $E^* \lesssim 10$ MeV) are believed to belong to the shell-model configuration

$$\{(1s)_N^4(1p)_N^{A-5}(1s)_\Lambda\}.$$

Those of the states whose excitation energies do not exceed the separation energy of the most loosely bound particle should decay electromagnetically with the emission of γ-rays. The possibility of hypernuclear γ-spectroscopy was discussed by Pniewski [5]. For each hypernuclear species known at the time, the author evaluated the number of possible γ-emitters, assuming the attachment of the Λ-particle in the $1s$ state to various low-lying excited states of the parent nucleus.

In this paper we consider the possibility of the observation of γ-transitions following reaction (1) at rest for various possible p-shell nuclear targets, namely: ^{7}Li, ^{9}Be, ^{10}B, ^{11}B, ^{12}C, ^{14}N.

We derive a formula for the T-matrix element assuming DWIA and calculate the formation rates for low-lying hypernuclear states per stopping kaon. We allow for the final-state interaction of the pion by the use of the scattering solution of the Klein–Gordon equation with the appropriate optical-model potential.

2. *Calculation of the transition rates*

When a negative kaon is slowed down in a target, the atomic capture takes place and a mesic atom is formed in a highly excited state, with $n \gtrsim (m_{K^-}/m_e)^{1/2}$.

The deexcitation through electromagnetic processes proceeds until the kaon reaches a state for which nuclear capture takes over. The quantum numbers of the states from which the nuclear absorption occurs are not well defined. The selection rules for the X-ray radiation lead to a high population of the states $(n, l = n-1)$ in the lowest Bohr orbits. Hence, a large percentage of K^- mesons are captured from such states. The transition amplitude from a system containing a kaon in a state (n_K, l_K) and a nucleus with spin and isospin denoted by J and T respectively, and other internal quantum numbers denoted by α to a state consisting of a distorted wave of a pion with momentum p, $\psi_{\pi p}$, and a hypernucleus in a state (β, J', T', M') is:

$$\langle \psi_{\pi p}\psi(\beta T'J'M')\,|T|\,\psi_{n_K l_K m_K}\psi(\alpha TJM)\rangle. \tag{3}$$

We shall assume that the process (1) involves a single neutron from a shell model state $n_n l_n$, which is changed into a Λ particle with quantum numbers $n_\Lambda l_\Lambda$. The lowest states of hypernuclei may be reached via the transition:

$$(1p)_n \to (1s)_\Lambda. \tag{4}$$

Since we are interested in the production of possible hypernuclear γ-emitters, we shall confine our attention to the transitions (4).

It is advantageous to write down the wave function of the target nucleus in the form:

$$\psi(\alpha TJM) = \sum_{J_N, T_N, j, m, \mu} \langle J_N T_N; j\,\tfrac{1}{2}\,|\}JT\rangle\,(T_N M_{T_N}\,\tfrac{1}{2}\,m_T|TM_T)\times(J_N m j\mu|JM)$$
$$\times\,\phi(\tilde{\alpha} T_N J_N m) R_n(r)\,|j\mu\rangle. \tag{5}$$

The symbol $\langle J_N T_N; j\;1/2|\}JT\rangle$ denotes the coefficients of fractional parentage (c.f.p.) relating the states of the parent nucleus, ${}^{A-1}Z$, and the ground state of the target nucleus, ${}^{A}Z$, $R_n(r)$ and $|j\mu\rangle$ denote the space and spin wave functions of the neutron, respectively. Similarly, we may treat the states of the produced hypernucleus as superpositions of products of the core wave functions, $\phi_{J_N m}({}^{A-1}Z)$ and the wave function of the Λ particle:

$$\psi(\beta T'J'M') = \sum_{\tilde{\alpha}, J_N, m, \mu'} a(\tilde{\alpha} T_N J_N;\,\beta T'J')\,(J_N m\,\tfrac{1}{2}\,\mu'|J'M')\phi(\tilde{\alpha} T_N J_N m) R_\Lambda(r)\,|s\mu'\rangle. \tag{6}$$

The hypernuclear coefficients of fractional parentage, $a(\tilde{\alpha} T_N J_N;\;\beta T'J')$ depend on the properties of the Λ-N interaction. Gal et al. [6, 7] presented an extensive analysis of all available hypernuclear data in order to determine parameters of the nuclear interaction of the Λ particle and to make some predictions concerning level schemes and wave functions of the p-shell hypernuclei. Although no definite answers could be achieved and various sets of parameters describing the Λ-N interactions in hypernuclei turned out to be admissible, the hypernuclear wave functions were found to be strongly dominated by the coupling to a single state of the core nucleus. This is a consequence of the fact that the states with spins $J'-\tfrac{1}{2}$ and $J'+\tfrac{1}{2}$, which may be parents of a hypernuclear state of spin J' are usually well separated in energy. Therefore, we shall apply a single-parent approximation for the hypernuclear states (6), i.e. we shall put all but one of the coefficients $a(\tilde{\alpha} T_N J_N;\,\beta T'J')$ equal to zero. Assuming that the reaction (1) proceeds through the single particle transition (4) we may factorize the transition amplitude (3) in the following way:

$$\langle \psi_{\pi p}\psi(\beta T'J'M'T)\,|T|\,\psi_{n_K l_K m_K}\psi(\alpha TJM)\rangle = \langle p|t|k\rangle \cdot F \tag{7}$$

where the first factor is the amplitude of the elementary process (2) and the latter is a form-factor depending on the quantum numbers describing initial and final states. It may be interpreted as the square root of the "effective number of neutrons". A simple calculation leads to the following formula for F^2:

$$F^2 = n(T_N M_{T_N}\,\tfrac{1}{2}\,m_T|TM_T)\,(2j_\Lambda+1)\,(2J'+1)\sum_{l'}(2l'+1)$$
$$\times\sum_{l}(2l+1)\begin{pmatrix} l & l_K & l' \\ 0 & 0 & 0\end{pmatrix}\times\tfrac{1}{4}\,[1+(-1)^{l_n+l_\Lambda+l'}]^2$$
$$\times\left[\sum_{j}(-1)^j\sqrt{2j+1}\begin{pmatrix} j & l' & j_\Lambda \\ \tfrac{1}{2} & 0 & \tfrac{1}{2}\end{pmatrix}\langle J_N T_N; j\,\tfrac{1}{2}\,|\}JT\rangle\begin{Bmatrix} J' & l' & J \\ j & J_N & j\end{Bmatrix}\right]^2. \tag{8}$$

For the transition (4) the only value of l' for which the expression (8) does not vanish is $l' = 1$. The summation is extended over l — the angular momentum of the emitted pion and j — the total angular momentum of the p-shell nucleon, which may be equal to $\frac{1}{2}$ and $\frac{3}{2}$. In this formula j_Λ denotes the total angular momentum of the Λ particle, which in our case is equal to $\frac{1}{2}$; n is the number of the p-shell nucleons in the target nucleus. The symbol R_l denotes the radial overlap integrals which, in the absence of final state interaction, are:

$$R_l = \int R_\Lambda(r)R_n(r)j_l(pr)R_{n_K l_K}(r)r^2dr. \tag{9}$$

We are interested in the probability of production of particular hypernuclear states per one stopping K^- meson. Following Hüfner et al. [2] we shall write it in the form:

$$R = 0.8\,\frac{\sigma(K^-\mathrm{n}\to\pi^-\Lambda)F^2}{\sigma_{\mathrm{tot}}(K^-\mathrm{n})\int\varrho_{\mathrm{n}}|R_{n_K l_K}(r)|^2r^2dr+\sigma_{\mathrm{tot}}(K^-\mathrm{p})\int\varrho_{\mathrm{p}}(r)\,|R_{n_K l_K}(r)|^2r^2dr}. \tag{10}$$

The integrals in the denominator are the overlap of the kaon wave function squared with neutron and proton densities which are normalized as follows:

$$\int\varrho_{\mathrm{p}}(r)r^2dr = Z, \qquad \int\varrho_{\mathrm{n}}(r)r^2dr = A-Z. \tag{11}$$

The nuclear density distributions are taken from Ref. [25]. The first factor in Eq.(19) is a correction to account for the two-nucleon absorption processes which occur in about 20% of all K^--nucleon interactions.

The relative values of the cross section for the process (2) and for other elementary K^--N interactions are vital for the correct determination of the transition rates (10). They are strongly energy dependent because of the $Y_0(1405)$ resonance located 27 MeV below threshold. The threshold values of the cross section are not appropriate for the interaction of the kaon with bound nucleons. Furthermore, the parameters of the Y^* resonance are expected to be altered in the nuclear medium. This problem was considered by Wycech [8] in his work on the kaon-nucleus interactions. The author has calculated two parameters characterising the K^--N interaction, namely:

$$E_1 = \sigma(K^-\mathrm{p}\to\Sigma^+\pi^-)/\sigma(K^-\mathrm{p}\to\Sigma^-\pi^+) \tag{12}$$

and

$$E_2 = [\sigma(K^-\mathrm{p}\to\Sigma^+\pi^-)+\sigma(K^-\mathrm{p}\to\Sigma^-\pi^+)]/\sigma(K^-\mathrm{n}\to\Sigma^-\pi^0) \tag{13}$$

as functions of the nuclear density. Assuming that the nuclear capture takes place at the nuclear surface at the point where the nuclear density amounts to about 6% of the central value and taking the nonresonant amplitudes of $T = 1$ channels from Martin and Sakitt (see Ref. [8]) we obtain the following relationship among the cross sections entering Eq. (10):

$$\sigma(K^-\mathrm{n}\to\pi^-\Lambda) : \sigma_{\mathrm{tot}}(K^-\mathrm{n}) : \sigma_{\mathrm{tot}}(K^-\mathrm{p}) = 0.051 : 0.154 : 1. \tag{14}$$

For the nuclei with $Z = A/2$ the rate R depends on the ratio:

$$\frac{\sigma(K^-\mathrm{n}\to\pi^-\Lambda)}{\sigma_{\mathrm{tot}}(K^-\mathrm{n})+\sigma_{\mathrm{tot}}(K^-\mathrm{p})}, \tag{15}$$

which, according to Eq. (14), is equal to 0.044. This number is determined with a large theoretical uncertainty, nevertheless we expect it to be more adequate than the value 1/7 used by Hüfner et al. [2].

3. *The distortion of the pion wave*

Since the outgoing pion interacts strongly with the hypernucleus, we should use the actual wave function of the particle moving in the potential well rather than a plane wave.

In the Born approximation the optical potential for pions is:

$$V(r) = \int e^{-iqr} f(q) F(q) dq, \tag{16}$$

where $F(q)$ is the nuclear formfactor and $f(q)$ is the π^--nucleon scattering amplitude. If only s and p waves are taken into account, the π-nucleon amplitude which enters Eq. (16) has a form:

$$f = a_0 + a_1 \vec{q}_2 \cdot \vec{q}\,'_2 \tag{17}$$

where $\vec{q}_2$ and $\vec{q}\,'_2$ denote the initial and final pion momenta in the pion-nucleon CM system. Substituting (17) into (16) gives a nonlocal potential which may be written in the form (the well-known Kisslinger-type potential [9]):

$$U_K \equiv 2E_\pi V_K = -A[b_0 k^2 \varrho(r) - b_1 \nabla(\varrho(r)\nabla)], \tag{18}$$

where E_π is the total pion energy, ϱ is the density of nuclear matter normalised to unity, k is the pion momentum and b_i are the coefficients related to the amplitudes a_0 and a_1. If the pion amplitude is taken on the mass-shell, a local laplacian form is obtained:

$$U_L = -A[(b_0 + b_1)k^2 \varrho(r) + \tfrac{1}{2} b_1 \nabla^2 \varrho(r)]. \tag{19}$$

If the p-wave is neglected, a simple local potential proportional to ϱ is obtained:

$$U = -A(b_0 + b_1)k^2 \varrho(r). \tag{20}$$

There is a number of attempts to construct an optical potential for pions. Most authors agree that in the energy interval 0—300 MeV only the S and P waves are important. Sternheim and Auerbach [10] have taken into account the Fermi motion of the nucleons within nuclei. The authors obtained a satisfactory agreement with the π-nucleus scattering data. They claim also that the pion wave functions obtained by solving the Klein–Gordon wave equation with their optical potential should be reliable. The choice of one of the two forms (18) and (19) of the potential is difficult. Silbar and Sternheim [11] suggest to use a combination:

$$U = \lambda U_L + (1-\lambda) U_K, \tag{21}$$

with a free parameter λ whose value should be between 0 and 1.

In order to examine the influence of the distortion of the pion wave on the matrix element (3) we solved the Klein–Gordon equation for $A = 12$ using the optical potential taken from reference [11]. The optical potential, written in the form (21) with $\lambda = 0$ or 1, was treated as a fourth component of a four-vector potential, in anology to the Coulomb potential, and the V^2 term was dropped, as it is usually done. We also neglected Coulomb interaction of the π^- meson with the nucleus. The results and discussion are given in the following section.

4. *The reaction* $^{12}C(K^-, \pi^-)^{12}_{\Lambda}C^*$

The formation of $^{12}_{\Lambda}C^*$ by the kaon capture in carbon has been analysed by Hüfner et al. [2]. The authors described the ground state of the nucleus ^{12}C as a doubly closed--shell state. This is the extreme limit of $j-j$ coupling. Actually, the intermediate-coupling model is more adequate. The wave function of ^{12}C g.s. has been calculated in the frame of intermediate-coupling model by Cohen and Kurath [12]. We give here the c.f.p. for ^{12}C g.s.:

parent state J_N, E^* (MeV)	c.f.p.
$\frac{3}{2}$ 0	$\frac{3}{2}\,\frac{1}{2};\,\frac{3}{2}\,\frac{1}{2}\,00 = -0.8440$
$\frac{1}{2}$ 2	$\frac{1}{2}\,\frac{1}{2};\,\frac{1}{2}\,\frac{1}{2}\,00 = 0.4339$
$\frac{3}{2}$ 4.3	$\frac{3}{2}\,\frac{1}{2};\,\frac{3}{2}\,\frac{1}{2}\,00 = 0.3072$

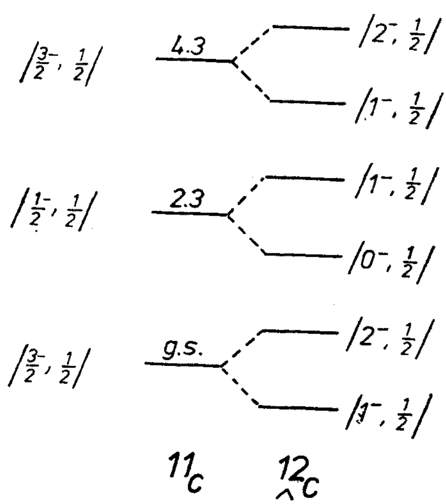

Fig. 1. Energy levels of ^{11}C and $^{12}_{\Lambda}C$

According to our remarks of Chapter 2, the lower part of the spectrum of ^{12}C hypernuclei consists of the states built of the parent states of the $A = 11$ nucleus to which a Λ-particle is attached. For each parent state there are two hypernuclear levels with spins $J' = J_N - \frac{1}{2}$ and $J' = J_N + \frac{1}{2}$ (see Fig. 1).

In the single-particle transition $(1p)_N \to (1s)_\Lambda$ only those states may be formed for which the following selection rules are satisfied: $|J - J'| = 0$ or 1 with $0 \to 0$ forbidden. Since $J = 0$ for ^{12}C g.s. only the states with $J'^{P'} = 1^-$ among possible γ-emitting states of the hypernucleus $^{12}_\Lambda C$ may be formed in the reaction $^{12}C(K^-, \pi^-)^{12}_\Lambda C^*$. The relative rates obtained for the three 1^- states are proportional to the appropriate c.f.p. squared (cf. Table I). The transition to the ground state dominates but the transitions to the states derived from the excited parent states should also be registered in the spectrum of the accompanying pions. However, this would require better instrumental energy resolution. In the experiments performed so far [13] the resolution was about 5 MeV and there was no way to single out possible excited states from the peak ascribed to the ground state of $^{12}_\Lambda C$.

TABLE I

	$^{12}C(K^-, \pi^-)^{12}_\Lambda C$ rates (times 10^{-4} per stopped K^-)								
	$V_\pi = 0$, $V_K = 0$			V_π from Ref. [10], $\lambda = 1$, $V_K = 0$			V_π from Ref. [10], $\lambda = 1$, $l_K = 1$, ψ_{2p} from Ref. [14]		
$n_K l_K$ \ J_N, E^*_N(MeV)	$\frac{3}{2}$, 0	$\frac{1}{2}$, 2	$\frac{3}{2}$, 4.4	$\frac{3}{2}$, 0	$\frac{1}{2}$, 2	$\frac{3}{2}$, 4.4	$\frac{3}{2}$, 0	$\frac{1}{2}$, 2	$\frac{3}{4}$, 4.4
3s	11.3	2.9	1.5	1.13	0.29	0.15			
3d	2.46	0.64	0.32	0.79	0.21	0.10			
2p	4.18	1.09	0.54	0.97	0.25	0.13	0.48	0.12	0.06

While the relative formation rates of the particular hypernuclear states are fairly well defined, the values of the rates normalized to the number of stopped kaons are charged with a large theoretical uncertainty. They depend on both the initial state of kaon and the distortion of the pion wave. For the sake of orientation we performed the calculation for the kaon capture from the states 3s, 3d and 2p. The results are shown in Table I. The experimental value of the formation rate of the $^{12}_\Lambda C$ "ground state" which is expected to include also the transition rates to the two excited states is $(2 \pm 1) \times 10^{-4}$ per stopped kaon. The sum over the formation rates of the three states of $^{12}_\Lambda C$ calculated for the case of no final-state interaction and $l_K = 0$ exceeds this number considerably, whereas it is comparable with the experimental value when $l_K = 2$ is assumed. The inclusion of the pion distortion effect leads to a strong reduction of the expected formation rates. When we take the potential of Sternheim and Auerbach [10], the sum of the expected formation rates of the three states of $^{12}_\Lambda C$ is about 1.6×10^{-4} for $n_K = 3$, $l_K = 0$, 1.1×10^{-4} for $n_K = 3$, $l_K = 2$ and 1.4×10^{-4} for $n_K = 2$, $l_K = 1$. Using a distorted wave function of kaon in 2p state, taken from Alberg et al. [14], reduces the last figure to the value about 0.7×10^{-4}.

5. *The reaction* $^7Li(K^-, \pi)^7_\Lambda Z$, $Z = 2, 3$

The level schemes of the $A = 6$ core nucleus and of hypernuclei $^7_\Lambda$Li and $^7_\Lambda$He are shown in Fig. 2. The doublets of states corresponding to particular parent states are split due to the spin dependent forces and (or) spin-orbit forces. In the limit of LS coupling

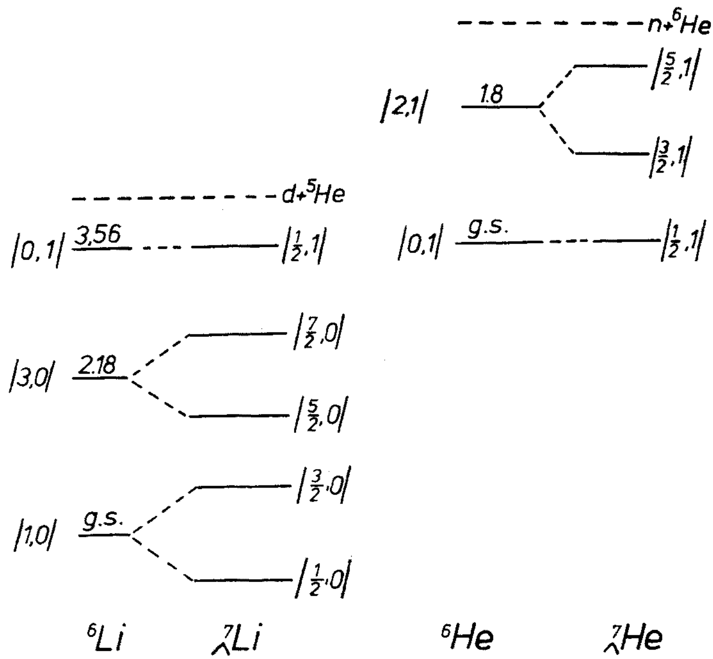

Fig. 2. Energy levels of $A = 6$ nucleus and of hypernuclei $^7_\Lambda$Li and $^7_\Lambda$He

the splitting energies are expressed in a simple way in terms of the parameters characterising spin-spin and spin-orbit forces, Δ and $S^{\pm}$, introduced by Gal et al. [6, 7].

As it was pointed out by Gal [15], the formation of excited states of $A = 7$ systems

TABLE II

	$^7Li(K^-, \pi)\,^7_\Lambda Z$, $Z = 2,3$ rates (times 10^{-4} per stopped K^-) $n_K = 2$, $l_K = 1$						
J_N, T_N; E^*_N(MeV)	1, 0; 0		3, 0; 2.18		0, 1; 3.56	2, 1; 6	
J'	$\frac{1}{2}$	$\frac{3}{2}$	$\frac{5}{2}$	$\frac{7}{2}$	$\frac{1}{2}$	$\frac{3}{2}$	$\frac{5}{2}$
LS	0.96	—	0.54	—	0.32	0.03	0.23
Cohen and Kurath [12]	0.80	0.00	0.62	—	0.33	0.03	0.19
Barker [16]	0.88	0.02	0.67	—	0.31	0.02	0.17

in the strangeness exchange reaction is not favoured as compared to the formation of $^{7}_{\Lambda}$Li g.s. Gal [15] has presented the corresponding branching ratios calculated both for the case of pure LS and intermediate coupling nuclear wave functions. We repeated the calculation assuming three sets of nuclear wave functions: LS limit and two intermediate coupling fits by Cohen and Kurath [12] and Barker [16]. In the calculation of the pion distortion effect the local potential ($\lambda = 1$) with the parameters taken from Sternheim and Auerbach [10] was assumed. The results are given in Table II.

5.1. $^{7}_{\Lambda}$Li

The production of the state ($\frac{7}{2}^+$) is forbidden for the single particle transition $(1p)_N \to (1s)_\Lambda$ since the spin of the initial nucleus, ^{7}Li, is $\frac{3}{2}$. Also, the transition to the ($\frac{3}{2}^+$) number of the ground-state doublet is suppressed. In the LS limit this state is $^4S_{3/2}$ and it cannot be reached from $^2p_{3/2}$ (^{7}Li g.s.) without spin-flip. The transition rate to the ($\frac{5}{2}^+$) state built on the (3,0); 2.18 MeV parent is expected to be approximately 6×10^{-5} per stopped kaon. This state is of special interest since it was suggested by Pniewski et al. [17] that hypernuclear weak decay may compete with γ-emission. The effect depends on the parameters Δ and S. If S is positive and sufficiently strong, the ($\frac{5}{2}^+$) level is driven sufficiently close to the ground state to slow down the E2 transition to the values of the order 10^{10} s^{-1}, which is typical for the hypernuclear decay. Gal et al. [7] estimated that the state ($\frac{5}{2}^+$) should be isomeric if its excitation energy is less than about 0.8 MeV. This condition is satisfied for most of the fits obtained by Gal et al. [7], for which $S > 0$. On the other hand the present emulsion data [18] do not give any evidence for the existence of an isomeric state of $^{7}_{\Lambda}$Li. In this situation observation of γ-rays from $^{7}_{\Lambda}$Li* would be of great importance.

The CERN–Heidelberg–Warsaw Collaboration [19] studied the possible production of $^{7}_{\Lambda}$Li* in reaction (K^-, π^-) on ^{7}Li at rest. However, no hypernuclear γ-line was found in coincidence with high energy pion ($E_\pi > 170$ MeV). The upper limit for the production rates of $^{7}_{\Lambda}$Li* was settled as 5×10^{-4} per stopped kaon. It is clear that an increase of the statistics by an order of magnitude would be necessary to solve the problem of the isomeric state of $^{7}_{\Lambda}$Li.

5.2. $^{7}_{\Lambda}$He

There are two $T_N = 1$ states of $A = 6$ nucleus, (0^+) and (2^+), which give important contribution to the decomposition (5) of the wave function of ^{7}Li. Hence, in principle, three states of $^{7}_{\Lambda}$He may be produced in reaction (K^-, π^0) on ^{7}Li. They are shown in Fig. 2. The problem of hyperisomerism has also been discussed for $^{7}_{\Lambda}$He [20]. For the most acceptable fits obtained by Gal et al. [7] the ($\frac{3}{2}^+$) state is expected to be isomeric. The emulsion data on B_Λ distribution [18] for $^{7}_{\Lambda}$He are insufficient to support this result although the distribution seems to be broader than for other species. Again, the direct measurement of the hypernuclear γ-rays would be interesting, but it is even less hopeful than in the case of $^{7}_{\Lambda}$Li*, the calculated rates per stopping kaon being about 2×10^{-6} and 2×10^{-5} for the ($\frac{3}{2}^+$) and ($\frac{5}{2}^+$) states, respectively.

6. *The reaction* $^9Be(K^-, \pi)\,^9_\Lambda Z$, $Z = 3, 4$

Numerous states of ^{8}Be with isospins 0 and 1 and excitation energies up to about 20 MeV contribute to the decomposition (5) of the ^{9}Be g.s. wave function. Since the threshold for the α decay of the ^{9}Be is 3.5 MeV, the only excited states which undergo γ-deexcitation are the two members of the doublet built on the 2^+, 0, E = 2.9 MeV parent

TABLE III

	^{9}Be$(K^-, \pi)\,^9_\Lambda Z$, Z = 3,4 rates (times 10^{-4} per stopped K^-), $n_K = 2$, $l_K = 1$							
J_N, T_N; E_N^*(MeV)	0, 0; 0	2, 0; 2.9		2, 1; 17		1, 1; 17.67		3, 1; 19.07
J'	$\frac{1}{2}$	$\frac{3}{2}$	$\frac{5}{2}$	$\frac{3}{2}$	$\frac{5}{2}$	$\frac{1}{2}$	$\frac{3}{2}$	$\frac{5}{2}$
LS	0.39	0.04	0.31	0.20	—	0.11	0.12	0.11
Cohen and Kurath [12]	0.34	0.23	0.19	0.28	0.00	0.01	0.35	0.11
Barker [16]	0.30	0.26	0.15	0.27	0.00	0.05	0.38	0.04

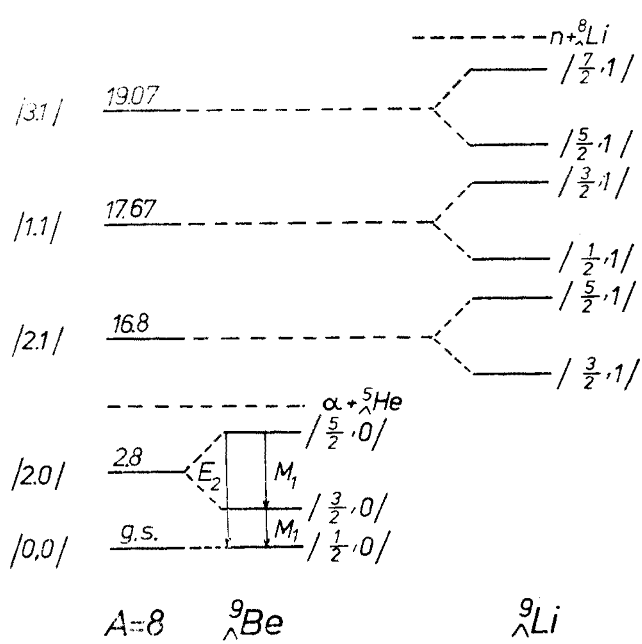

Fig. 3. Energy levels of ^{8}Be and $^9_\Lambda$Be and $^9_\Lambda$Li

state. These states should be produced with comparable rates, of the order of 10^{-5} (see Table III). The lower part of the ^{9}Be spectrum is shown in Fig. 3, where possible γ-transitions are also marked. The energy splitting of the $J' = \frac{3}{2}$ and $J' = \frac{5}{2}$, $T' = 0$ doublet is of particular interest. In the limit of LS coupling the splitting is caused by the spin-orbit interaction and it amounts to:

$$E = \tfrac{5}{2}(S_+ + S_-), \tag{22}$$

where S_+, S_- are the N interaction parameters introduced in Ref. [6]. In reaction (K^-, π) on ^{9}Be hypernuclear states with isospin 1 should also be produced. The $T' = 1$ states of $^9_\Lambda$Be are highly excited and can be registered only by means of the pion spectroscopy. On the other hand, the corresponding states with $T'_3 = -1$ form the ground and lowest excited states of $^9_\Lambda$Li. The threshold energy for a strong decay of $^9_\Lambda$Li is 3.76 MeV. There are several states of this species which are expected to lie below this value. However, as it is seen in Table III, not all of them are expected to be produced with equal abundance. In particular, the formation of the $J' = \frac{5}{2}$ member of the doublet built on the 2^+, 0 state is forbidden in the LS limit and is unlikely in the intermediate coupling scheme.

7. *The reaction* $^{20}B(K^-, \pi^-)^{10}_\Lambda B$

There are four states of $^{10}_\Lambda$B which are expected to lie below the threshold for proton emission, $E = 1.99$ MeV. These are: the ground-state doublet, $J' = 1$ and $J' = 2$ and a doublet of states with spins 2 and 3 built on $J_N = \frac{5}{2}$, $E = 2.43$ MeV state of ^{9}Be. The expected production rates for these states are given in Table IV. The $J' = 1$ state cannot be formed in the transition $(1p)_N \to (1s)_\Lambda$ because of the selection rule $|J-J'| \leqslant 1$. The splitting of the ground-state doublet in the single-parent approximation was given by Gal et al. [6] in Table VI of their paper (we neglect here the contribution of the tensor forces):

TABLE IV

	^{10}B(K^-, π^-) $^{10}_\Lambda$B rates (times 10^{-4} per stopped K^-), $n_K = 2$, $l_K = 1$			
J_N, T_N; E^*_N(MeV)	$\frac{3}{2}$, $\frac{1}{2}$; 0		$\frac{5}{2}$, $\frac{1}{2}$; 2.43	
J'	1	2	2	3
rates:	—	0.29	0.04	0.18

$$B_\Lambda(A = 10, J' = 2) - B_\Lambda(A = 10, J' = 3) = 0.538\Delta + 1.461(S_+ + S_-). \tag{23}$$

The analysis of the hypernuclear data available so far indicates that the values of the parameters Δ as well as S_+ and S_- are positive [21–23]. In this case the $J' = 2$ level should lie lower. The spin of $^{10}_\Lambda$B in the ground state has not been measured. However, it is worthwhile to notice that the situation is similar to that of $A = 12$ hypernuclei, $^{12}_\Lambda$B and $^{12}_\Lambda$C, where the excitation energy of the $J' = 2$ component of the ground-state doublet is given by:

$$B_\Lambda(A = 12, J' = 1) - B_\Lambda(A = 12, J' = 2) = 0.405\Delta + 1.595(S_+ + S_-). \tag{24}$$

The spin of ${}^{12}_{\Lambda}$B was found to be equal to 1 [22], which leads to the conclusion that the right-hand side of Eq. (24) is positive. For the better knowledge of the ΛN interaction parameters a measurement of the excitation energy (23) or (24) would be of great interest. According to our discussion in Section 4 the $J' = 2$ state of ${}^{12}_{\Lambda}$C cannot be produced in the (K^-, π^-) reaction and the observation of γ-rays from the upper component of the ground-state doublet of ${}^{10}_{\Lambda}$B is more hopeful.

8. *The reaction* ${}^{11}B(K^-, \pi^-){}^{11}_{\Lambda}B$

There are many excited states of ${}^{11}_{\Lambda}$B which are expected to lie below the lowest fast-decay threshold, 7.53 MeV. Since the spin of the target nucleus is 3/2, only the states with spin $J' = \frac{1}{2}, \frac{3}{2}$ and $\frac{5}{2}$ may be produced in the $(1p)_N \to (1s)_\Lambda$ transition. The states of the parent nucleus ^{10}B and the c.f.p. describing their role in the decomposition of ^{11}B g.s. wave function are listed in Table V.

TABLE V

	^{11}B$(K^-, \pi^-){}^{11}_{\Lambda}$B rates (times 10^{-4} per stopped K^-), $n_K = 2$, $l_K = 1$								
$J_N, T_N,$	3, 0,	1, 0,	1, 0,	2, 0,	3, 0,	2, 0,	2, 1,	1, 0,	0, 1,
rates: $J' = J_N - \frac{1}{2}$	0.57	0.12	0.06	0.07	0.07	0.00	0.28	0.00	0.06
$J' = J_N + \frac{1}{2}$	—	0.01	0.19	0.04	—	0.03	0.01	0.02	0.09

In the single-parent approximation the ground state of ^{10}B, with spin $J_N = 3$, is a parent state of the ground-state doublet $J' = \frac{5}{2}$ and $\frac{7}{2}$. The splitting of this doublet calculated by Gal et al. [6] is:

$$B_\Lambda(A = 11, J' = \tfrac{5}{2}) - B_\Lambda(A = 11, J' = \tfrac{7}{2}) = 0.979\Delta + 2.52(S_+ + S_-). \qquad (25)$$

If the right-hand side of Eq. (25) is positive, the $J' = \frac{5}{2}$ is ground state of ${}^{11}_{\Lambda}$B. Some arguments supporting this possibility based on the analysis of the two-body decay of this species was given in Ref. [23]. It would be also consistent with the ground-state spin assignment for ${}^{12}_{\Lambda}$B (cf. our remarks in Section 7).

The production rates of other possible γ-emitting states of ${}^{11}_{\Lambda}$B are also small compared to the probability of the transition to the ground state (see Table V).

9. *The reaction* ${}^{14}N(K^-, \pi^-){}^{14}_{\Lambda}N$

We assume that the kaon capture in nitrogen takes place from the $3d$ state. The wave function of ^{14}N g.s. is a superposition of a number of terms involving various states of ^{13}N (see Ref. [12]).

The calculated production rates for ${}^{14}_{\Lambda}$N* are given in Table VI. Since the threshold for the proton emission amounts only to 2 MeV, most of these states should be subjects to strong decay. Their production should appear in the spectrum of accompanying pions.

Some data concerning the production of ${}^{14}_{\Lambda}N^*$ in the strangeness exchange process are available from the study of hypernuclei by negative kaons at rest in nuclear emulsion [24].

TABLE VI

	${}^{14}N\ (K^-, \pi^-){}^{14}_{\Lambda}N$ rates (times 10^{-4} per stopped K^-), $n_K = 3$, $l_K = 2$													
J_N; E^*_N(MeV)	$\frac{1}{2}$; 0		$\frac{3}{2}$; 3.5		$\frac{5}{2}$; 7.4		$\frac{1}{2}$; 8.9		$\frac{3}{2}$; 9.5		$\frac{1}{2}$; 10.78		$\frac{3}{2}$; 11.87	
J'	0	1	1	2	2	3	0	1	1	2	0	1	1	2
rates:	0.05	0.07	0.03	0.00	0.36	—	0.05	0.08	0.19	0.03	0.02	0.01	0.01	0.00

The authors of Ref. [24] have collected 25 events which may be ascribed to reaction:

$$K^- + {}^{14}N \to \pi^- + p + {}^{13}_{\Lambda}C. \tag{26}$$

Although the available kinetic energy range of pions is from 0 to 174 MeV, 80% of events are gathered in the upper 20 MeV interval. This observation suggests that the reaction (26) is dominated by the two-step processes:

$$K^- + {}^{14}N \to \pi^- + {}^{14}_{\Lambda}N^*,$$
$${}^{14}_{\Lambda}N^* \to p + {}^{13}_{\Lambda}C. \tag{27}$$

The consideration of the excitation energy suggests that the 9 events for which $T_\pi > 170$ MeV may be those examples of process (27) for which the states ${}^{14}_{\Lambda}N^*$ belong to the configuration $\{(1s)^4_N(1p)^{10}_N(1s)_\Lambda\}$. The total number of K^- mesons stopped in emulsion was 3×10^6. Since the nitrogen content in emulsion is about 4% we assume that there were 12×10^4 kaons stopped in nitrogen. Hence, 9 events correspond to the rate close to 10^{-4} per one K^- meson captured by a nitrogen atom.

Although the energy resolution is very good the statistics are too poor for an attempt to compare this spectrum with the entries of Table VI. The combined rate per stopped K^- meson for all the states listed in Table VI amounts to about 0.9×10^{-4} which is in fair agreement with the experimental rate evaluated above.

10. Summary and conclusion

The strangeness-exchange two-body reaction

$$K^- + {}^AZ \to \pi^{-(0)} + {}^A_{\Lambda}Z'(Z' = Z, Z-1)$$

of stopped K^- mesons with light nuclei has been analysed from the point of view of its usefulness for the hypernuclear γ-spectroscopy. This reaction seemed to be particularly appropriate since one could separate the hypernuclear γ-rays from the background by requiring a coincidence with π^- or π^0 mesons of well-defined energy. However, according to our calculation, the production rates of possible γ-emitting states of various p-shell hypernuclei are rather low, of the order of 10^{-5} per stopped kaon, whereas the rates of the order of 10^{-4} are measurable in the present experiments at CERN.

One factor which determines the production rate of hypernuclei in a single-nucleon interaction is the low branching ratio for the Λ production in the interaction of stopped kaons with nuclei.

Secondly, the radial matrix elements entering the formfactor F (Eq. (8)) are sensitive to the kaon and pion wave functions. Both particles feel some optical potentials whose effect is to attenuate the wave functions inside the nucleus.

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