EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

STRANGENESS EXCHANGE REACTION ON NUCLEI

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ABSTRACT

Population of hypernuclear states has been observed in recoilless Λ production of the strangeness exchange reaction (K^-, π^-) on ^9Be, ^{12}C, ^{16}O, ^{32}S and ^{40}Ca.

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The strangeness exchange reaction (K^-, π^-) on nuclear targets has become an excellent tool for studying hypernuclei. In particular, advantage has been taken of the fact that in this reaction the Λ particle can be produced without recoil. This favours the formation of hypernuclear states with configurations closely related to the target nucleus ground state.

The (K^-, π^-) reaction has been carried out on several light nuclei$^{1)}$. The states observed in ${}^{9}_{\Lambda}\mathrm{Be}$ and ${}^{12}_{\Lambda}\mathrm{C}$ have been tentatively assigned to independent particles configurations, where a neutron is replaced by the Λ particle in either the 1s or 1p shell$^{2)}$. The excited states which belong to different configurations seem to be well separated. In ${}^{16}_{\Lambda}\mathrm{O}$, however, the observed states cannot be described as unperturbed configurations and some mixing at least for the $p_{3/2}$ and $p_{1/2}$ has to be taken into account. It is likely that in heavier nuclei this configuration mixing will be stronger and collective phenomena will become dominant. An alternative interpretation of the ${}^{9}_{\Lambda}\mathrm{Be}$, ${}^{12}_{\Lambda}\mathrm{C}$, and ${}^{16}_{\Lambda}\mathrm{O}$ spectra$^{2)}$ has been put forward elsewhere$^{3)}$, identifying the narrow low excited state in ${}^{12}_{\Lambda}\mathrm{C}$ and ${}^{16}_{\Lambda}\mathrm{O}$, and in ${}^{9}_{\Lambda}\mathrm{Be}$ the broad upper bump as a strangeness analogue resonance (see also Fig. 2). The energy of this resonance has been calculated using the method of Kerman and Lipkin$^{4)}$.

In the present experiment, ${}^{16}\mathrm{O}$, ${}^{32}\mathrm{S}$, and ${}^{40}\mathrm{Ca}$ were chosen as targets for the following reasons. The number of configurations excited in the reaction increases from ${}^{16}\mathrm{O}$ (1s, 1p) to ${}^{40}\mathrm{Ca}$ (1s, 1p, 2s, 1d). If some configuration mixing exists, we can expect that collective effects will become more pronounced in the heavier hypernuclei. On the other hand, if excitations belonging to different configurations are energetically separated they could easily be resolved by the apparatus, which has a typical resolution of 1 MeV.

The (K^-, π^-) reaction on ${}^{16}\mathrm{O}$, ${}^{32}\mathrm{S}$, and ${}^{40}\mathrm{Ca}$ was studied at the K^- momentum of 900 MeV/c, using a separated K^- beam at the CERN PS. The outgoing π^- were observed at 0°, so that the momentum transfer to the Λ was always smaller than 100 MeV/c. The energy loss between the incoming K^- and the outgoing π^- was determined using a magnetic double spectrometer (Fig. 1), which is described in detail in Ref. 2. In order to achieve reasonable yields, rather thick targets of 4.8 g/cm^2 H_2O, 9.6 g/cm^2 S and 6.3 g/cm^2 Ca were used. The experimental resolution was entirely determined by the target thickness and amounts to about 3 MeV.

The reaction events were selected by requiring, in three ways, that the interaction take place in the target: i) the events had to have K timing before the target and π timing after the target; ii) the coordinates projected by the magnet optics from the chambers at the two ends had to agree with those measured at the target; iii) finally, a liquid hydrogen Čerenkov counter was placed after the target to discriminate against $K^- \to \pi^-\pi^0$ decay after the target, which was the worst source of background in the previous runs.

The measured energy spectra for the (K^-, π^-) reaction on ^{16}O, ^{32}S and ^{40}Ca are shown in Fig. 2. In addition, re-evaluated $^{9}_{\Lambda}Be$ and $^{12}_{\Lambda}C$ spectra are shown for comparison. The difference of the re-evaluated and old spectra lies in the background rejection. It was shown that stringent requirements for the reconstruction of the trajectories almost completely eliminate the background.

The spectra are plotted as a function of the Λ binding energy B_Λ. B_Λ is the only directly measured quantity in the present experiment and is related to the momentum loss in the spectrometer. $B_\Lambda = 0$ corresponds to a zero relative energy between the Λ particle and the core nucleus ground state. Since the ground states in the hypernuclei heavier than $^{14}_{\Lambda}N$ are not known experimentally, the indicated ground states in $^{16}_{\Lambda}O$, $^{32}_{\Lambda}S$, and $^{40}_{\Lambda}Ca$ are calculated by extrapolating the known binding energies of the very light hypernuclei$^{5)}$. Under the chosen kinematical conditions of the experiment a population of the ground state is not expected.

In all spectra with the exception of $^{40}_{\Lambda}Ca$, a strong transition to a narrow state with a width comparable to the resolution (∿ 3 MeV) is seen. In addition, at higher excitations a broad bump with a width of the order of 10 MeV is observed. The cross-section for the (K^-, π^-) reactions at 0° decreases at higher excitations and integrated over the whole spectrum is always about 1 mb/sr (see Table 1). This is a strong argument for the assumption that we observe only the contribution of the one-step process in the (K^-, π^-) reaction. A simple calculation, assuming a one-step process and strong absorption of K^- and π^-, shows that the 0° yield of the (K^-, π^-) reaction is independent of the target nucleus.

The $^{40}_{\Lambda}Ca$ shows only one broad peak, but the sharp rise of this peak at lower excitations may indicate that in $^{40}_{\Lambda}Ca$ the narrow and the broad peak overlap in energy. Relevant quantities for the spectra are summarized in Table 1.

Let us begin a qualitative interpretation of the spectra in the particle-hole picture$^{6)}$. The energetically lowest excitation is expected to be a particle-hole excitation in the last shell. In the $^{16}_{\Lambda}O$ spectrum even a splitting between the $p_{3/2}$ and $p_{1/2}$ configurations is indicated. A mixing between these two configurations would enhance the intensity of the upper state$^{7)}$. Following this line of argument, the sharp peak in $^{32}_{\Lambda}S$ would be assigned to the $d_{5/2}$ particle-hole excitation. Similary to $^{16}_{\Lambda}O$, also in $^{40}_{\Lambda}Ca$ the major strength of the 2s, 1d shell would be concentrated in the $d_{5/2}$ particle-hole excitation, which is embedded in the broad bump. The problem is, however, to explain the excitation energies of the observed peaks. Simple calculations assuming a Saxon-Woods potential, which reproduces the hypernuclear ground states$^{7)}$, yield for the energies of the last shell contribution in $^{16}_{\Lambda}O$, $^{32}_{\Lambda}S$, and $^{40}_{\Lambda}Ca$, $E_x = 11$, 19 and 19 MeV, respectively. The disagreement between these values and the observed ones is obvious and increases systematically with A. Such disagreement between the experiment and the simple model is not astonishing, but it is certainly an important observation which bears the information on the many-body system.

The broad structure in the high-energy part of the spectrum is attributed to the contributions of the (K^-, π^-) reaction on neutrons in the inner shells. The intensities of these bumps, however, are higher than the expected contribution, assuming a direct population in the (K^-, π^-) reaction that should be proportional to the number of nucleons in the bound shells. This may also indicate mixing of different shells in heavier nuclei. The most obvious case is ${}^{40}_{\Lambda}\mathrm{Ca}$, where the different shells are not separated.

An alternative interpretation of the spectra in a collective picture was proposed about 10 years ago by Lipkin$^{8)}$. In this case, one assumes that, in the first approximation, all the particle-hole states are degenerate and form a strangeness analogue resonance, which splits due to the difference in the ΛN and NN interactions. The criticisms of this model have been based on the assumption that the spacing of the Λ and N shells differs so much$^{6)}$ that the particle-hole states are well separated energetically and do not mix. The present experiment shows, however, that the difference in spacing between the Λ shells and the N shells, at least in ${}^{40}\mathrm{Ca}$, is small enough so that mixing between the particle-hole states in different shells must be included. In Table 1, the relevant parameter, $V_{n\Lambda} = B_n - B_\Lambda$, that measures the energy needed to transform a neutron into a lambda, and should be independent of the target nucleus in the model of Lipkin, is listed for different bumps. But it does not seem reasonable to us to pick out some bumps in the spectrum and assign them to strangeness analogue resonance, as has been done in Ref. 3. Starting with a strangeness analogue state, that splits due to the symmetry-breaking effects, one has to take an average $\langle V_{n\Lambda}\rangle$ which considers the whole resonance. Since a detailed theory is lacking, we assumed as a first approximation that the energy of the resonance $\langle B_\Lambda\rangle$ is given by the centre of gravity of the peaks. The $\langle V_{n\Lambda}\rangle$ in Table 1 is obtained using this value of the excitation. The value of $\langle V_{n\Lambda}\rangle$ is very constant for all measured targets, with the exception of ${}^{9}\mathrm{Be}$. But the sample of targets studied is too small to decide if the agreement in $\langle V_{n\Lambda}\rangle$ is accidental or not. In the present sample, the neutron binding energies B_n are practically the same with the exception of ${}^{9}\mathrm{Be}$. It is premature to decide if the disagreement in the case of ${}^{9}\mathrm{Be}$ is due to different B_n or that this target is too light to show collective effects. It should be the aim of the next generation of experiments to find out if $V_{n\Lambda}$ adequately describes the $n \rightarrow \Lambda$ transformation in the nucleus.

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Table 1

The main parameters of observed resonances in the (K^-, π^-) reaction on different nuclei. B_Λ is the only directly measured quantity. $B_\Lambda = 0$ corresponds to zero relative energy between the Λ particle and the core nucleus ground state. The ground state energies with an asterisk are theoretical estimations. $V_{n\Lambda}$ is the difference in binding energy between the last neutron in the target nucleus and B_Λ: $V_{n\Lambda} = B_n - B_\Lambda$. The error in the relative yields amounts to about 30%. The numbers in parentheses represent a tentative description of the low-energy shoulder as weak narrow peaks. The decomposition is not significant statistically.

	Target nucleus	Ground state	Narrow peak				Broad bump				Whole spectrum		
	B_n (MeV)	B_Λ (MeV)	B_Λ (MeV)	Γ_{exp} (MeV)	$V_{n\Lambda}$ (MeV)	$\sigma(0°)$ (mb)	B_Λ (MeV)	Γ_{exp} (MeV)	$V_{n\Lambda}$ (MeV)	$\sigma(0°)$ mb	$\langle B_\Lambda \rangle$ (MeV)	$\langle V_{n\Lambda} \rangle$ (MeV)	$\sigma(0°)$ (mb)
${}^{9}_{\Lambda}Be$	2	7	-9	5	11	0.3	-21	11	23	0.8	-16	18	1.1
${}^{12}_{\Lambda}C$	19	10	0	4	19	0.4	-12	13	31	0.8	-8	27	1.2
${}^{16}_{\Lambda}O$	16	14*	(-1 -7	7 4	17 23	0.2) 0.4	-17	14	33	0.7	-11	27	1.3
${}^{32}_{\Lambda}S$	15	20*	-6	5	21	0.4	-16 -27	10 12	31 42	0.5 0.3	-15	30	1.2
${}^{40}_{\Lambda}Ca$	16	21*	(1 (-9	2*5 5	15 25	0.2) 0.2)	(-22	17	38	0.7)	-14	30	1.1

Figure captions

Fig. 1 : Magnetic double spectrometer BM - bending magnets, Q - quadrupoles, p - plastic scintillators, W - multiwire drift chambers, T - target, Č - liquid hydrogen Čerenkov counter.

Fig. 2 : Spectra of the (K^-, π^-) reaction on ^{9}Be, ^{12}C, ^{16}O, ^{32}S, and ^{40}Ca, as a function of the Λ binding energy B_Λ. $B_\Lambda = 0$ corresponds to a zero relative energy between the Λ particle and the core nucleus ground state.

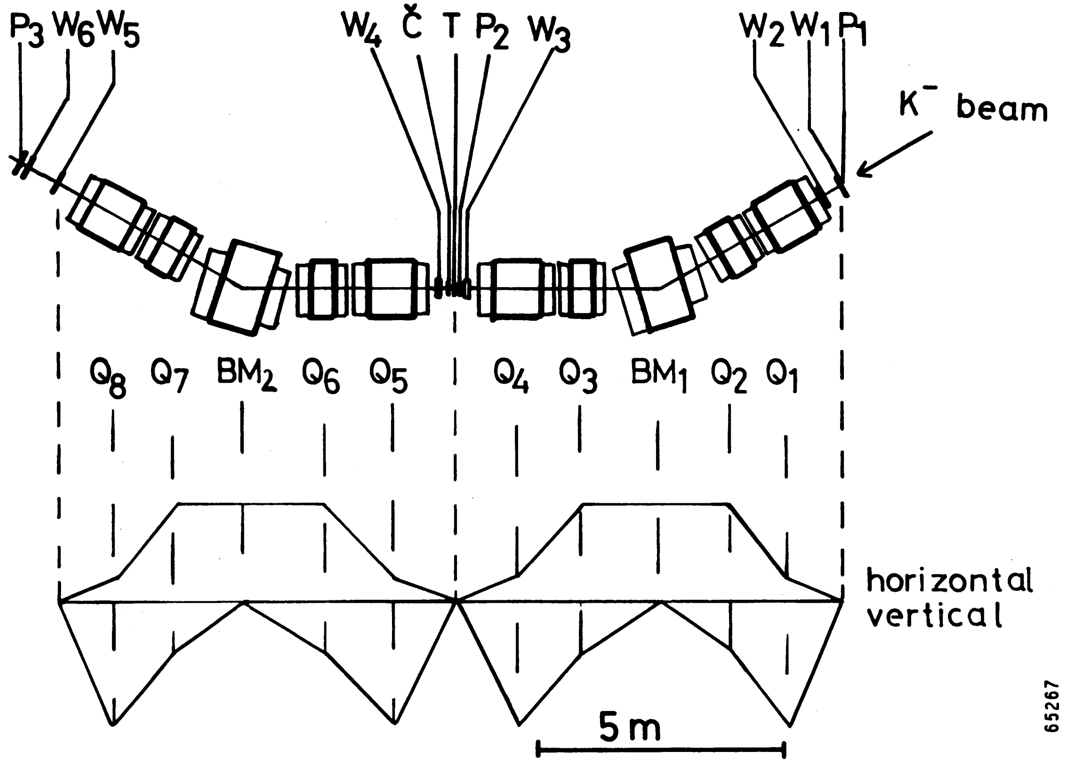
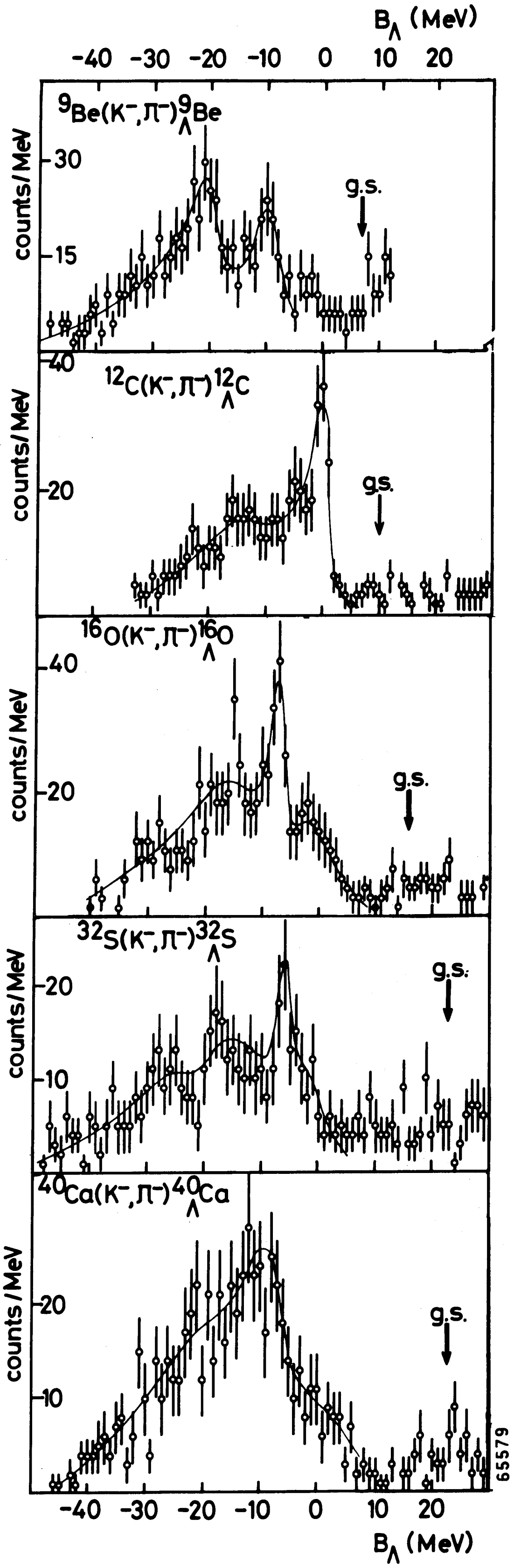

P3 W6 W5
W4 Č T P2 W3
W2 W1 P1
K⁻ beam
Q8 Q7 BM2 Q6 Q5
Q4 Q3 BM1 Q2 Q1
horizontal
vertical
5 m
65267

Fig. 1



B_Λ (MeV)
-40
-30
-20
-10
0
10
20
$^{9}Be(K^-,\pi^-)^{9}_{\Lambda}Be$
counts/MeV
30
15
g.s.
$^{12}C(K^-,\pi^-)^{12}_{\Lambda}C$
40
20
g.s.
$^{16}O(K^-,\pi^-)^{16}_{\Lambda}O$
40
20
g.s.
$^{32}S(K^-,\pi^-)^{32}_{\Lambda}S$
20
10
g.s.
$^{40}Ca(K^-,\pi^-)^{40}_{\Lambda}Ca$
20
10
g.s.
65579

Fig. 2