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NEUTRON HOLE STATES IN $^{6}_{\Lambda}$Li, $^{7}_{\Lambda}$Li, $^{9}_{\Lambda}$Be, and $^{12}_{\Lambda}$C HYPERNUCLEI

(Heidelberg[†]-Saclay-Strasbourg Collaboration)

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ABSTRACT

Neutron hole states in the 1s shell have been studied in the n(K^-,π^-)Λ strangeness-exchange reaction on ^{6}Li, ^{7}Li, ^{9}Be, and ^{12}C targets at the CERN Proton Synchrotron. The excitation energy and the width of the states as well as the differential cross-section have been determined. The clear similarity with the 1s proton hole states observed in (p,2p) reactions indicates that the presence of the Λ particle can be taken into account within the weak-coupling model. In this way the (K^-,π^-) reaction can be used for the study of Λ states as well as for the investigation of neutron hole states produced at very low momentum transfer.

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1. INTRODUCTION

The deep interior of nuclei has been investigated most successful by knock-out reactions on single nucleons. Proton hole states have been studied in the (p,2p) reaction$^{1-3)}$, and in the (e,e′p) reaction$^{4)}$ with kinematical conditions where the momentum transfer is small (typically $q \simeq$ 0–100 MeV/c). For such small transferred momenta the reaction can very well be considered as quasi-free proton–proton scattering (or quasi-free electron–proton scattering) and the residual nucleus will therefore remain undistorted. Some properties of 1s proton hole states in light nuclei are summarized in Table 1.

Until now knock-out reactions on neutrons, such as (p,p′n) or (e,e′n), have not been reported, as the neutrons cannot be detected with sufficient accuracy. Using neutron pick-up reactions, such as the (p,d) reaction$^{5)}$, neutron hole states have been studied. These reactions are limited by the large momentum transfer to the nucleus (typically $q > 150$ MeV/c).

In the $n(K^-,\pi^-)\Lambda$ strangeness-exchange reaction the momentum transfer can be chosen to be small if the pion is detected in the forward direction$^{6)}$. At a kaon momentum of p_K = 530 MeV/c the momentum transfer q is even zero; in our experiment, at p_K = 720 MeV/c, the momentum transfer is $q \simeq$ 50 MeV/c. The (K^-,π^-) reaction therefore offers a unique possibility to study neutron hole states, provided that the behaviour of the produced Λ particle is well understood.

The properties of Λ particles in nuclei have been the subject of some recent investigations on hypernuclei$^{7-9)}$. In connection with those studies, part of the data have been presented and discussed before$^{7,10-15)}$. In this paper we want to investigate how far we can study the properties of the nuclear core when Λ particles are produced on strongly bound neutrons in light nuclei.

2. EXPERIMENT

The experiment has been performed at the low-momentum separated K^- beam k_{22} at the CERN Proton Synchrotron. At the experimental target 2×10^4 kaons per burst were available with a kaon momentum p_K = 720 MeV/c. The forward-emitted pions were analysed in the magnetic spectrometer SPES2$^{16)}$ with a large angular acceptance (30 msr) and a large momentum acceptance ($dp/p \simeq \pm 0.18$). The energy resolution in the experiment was determined by the straggling in the target material and in the particle-identification counters along the beam line. With the ^{6}Li target (1.1 g/cm^2) the momentum resolution was 2.4 MeV/c FWHM. The experimental set-up is described in more detail elsewhere$^{17)}$.

In Fig. 1 the transformation energy spectra are given for the (K^-,π^-) reaction on ^{6}Li, ^{7}Li, ^{9}Be, and ^{12}C. The transformation energy M(Hy) - M(A) is defined as the mass difference between the excited hypernuclear system and the target nucleus. From the measured kaon and pion momenta and the relative angle of their trajectories, the total energy of the kaon $E_{tot}(K)$ and of the pion $E_{tot}(\pi)$ and the recoil energy of the hypernucleus $E_{kin}(Hy)$ can be calculated. The transformation energy is then given by

$$M(Hy) - M(A) = E_{tot}(K) - E_{tot}(\pi) - E_{kin}(Hy) \ . \qquad (1)$$

In Fig. 1 the different spectra are normalized to the same differential cross-section per energy bin. The highest excited resonances are due to the recoilless Λ production on 1s neutrons. The fits to these resonances are Breit-Wigner distributions folded with the experimental resolution. The results of these fits are given in Table 2. For $^9_\Lambda$Be the fit is rather tentative, as part of the 1p strength is expected at about the same energy as the recoilless Λ production on the 1s neutron.

The differential cross-sections have been analysed over a small range within the angular acceptance of the SPES2 spectrometer. In Table 3 these values with the statistical errors in the fits are given. The absolute accuracy of those numbers is however only 30%.

3. DISCUSSION

In the (K^-,π^-) strangeness-exchange reaction the average transformation energy is around 190 MeV, as can be seen in Fig. 1. The largest part of the transformation energy can be understood from the heavier mass of the Λ particle, $m_\Lambda - m_n = 176$ MeV/c^2.

The rest is determined by the binding energy of the neutron in the target nucleus (B_n) and by the binding energy of the produced Λ particle in the hypernucleus (B_Λ), see Fig. 2.

$$M(Hy) - M(A) = B_n - B_\Lambda + 176 \text{ MeV} . \qquad (2)$$

As can be seen from Eq. (2), the transformation energy gives us the combined information on the neutron binding energy and the Λ binding energy. The combination of these energies complicates the interpretation of the spectra. Therefore it is important to select recoilless Λ production, which gives maximal overlap of the neutron and Λ wave functions and thus a strong selectivity in the produced states.

The transformation energies of the hypernuclear resonances fitted in Fig. 1 are given in Table 2. The 1s neutron binding energies (B_n) are derived using the known Λ binding energies of the hypernuclear ground states (B_Λ). In the ground state of a hypernucleus the Λ particle occupies the lowest possible state, the 1s state. The recoilless Λ production on a 1s neutron will also leave the Λ particle in the 1s state. In first approximation the binding energy of the 1s Λ particle to an excited nuclear core will be the same as the Λ binding energy to a nuclear core in its ground state.

When we compare the neutron hole states in Table 2 with the proton data of Table 1, we see quite good agreement with the increase in excitation energies and widths. In general the neutron hole states observed in the (K^-,π^-) reaction have somewhat larger excitation energies of about 2-5 MeV.

3.1 ${}^{6}_{\Lambda}\text{Li}$

The ground state of ${}^{6}_{\Lambda}\text{Li}$ has not been observed in emulsion experiments. In our spectra we observe a weak transition at 177.2 MeV, which corresponds to a Λ binding energy of $B_\Lambda = 4.5$ MeV. This transition may correspond to the $(\lambda s_{1/2}, \nu p_{3/2}^{-1})1^-$ ground state of ${}^{6}_{\Lambda}\text{Li}$. The Λ binding energy also shows that the hypernucleus is unstable against proton emission, since the (${}^{5}_{\Lambda}\text{He} + p$) mass is smaller by 600 keV. The decay properties of the excited states of ${}^{6}_{\Lambda}\text{Li}$ have been discussed extensively by Majling et al.[15]. Most of the strangeness-exchange strength $\simeq 2.5$ mb/sr goes to the broad resonance at 185.5 MeV, which presumably is due to the recoilless

Λ production on the $p_{3/2}$ neutron. As argued by Auerbach et al.[14], the Λ escape from the unbound p state can explain the width of the resonance. Consequently, the strong narrow resonance at 195.5 MeV is the $(\lambda s_{1/2}, \nu s_{1/2}^{-1})0^{+}$ recoilless Λ production on the 1s neutron in ^{6}Li. Its differential cross-section of about 1 mb/sr is slightly decreasing with transferred momentum, as is expected for recoilless Λ production. The derived 1s neutron binding energy in the ^{6}Li nucleus is 24.0 ± ± 0.5 MeV. This we can compare with the 1s proton binding energy of 21.4 MeV observed[2] in ^{6}Li(p,2p) and the 1s neutron binding energy of 22.3 MeV observed[5] in ^{6}Li(p,d). The difference in proton and neutron binding energy of 0.9 MeV is due to Coulomb effects. The difference in 1s neutron binding energy of 1.7 MeV, observed in (p,d) and (K^{-},π^{-}), may be due to the difference in binding energy of the 1s Λ particle to an excited nuclear core and to a nuclear core in its relative ground state, which we neglected. The observed width of the 195.5 MeV resonance is about 3 MeV. Taking into account the experimental resolution, a width of 0.7 ± ± 1.0 MeV is derived. Narrow widths have also been observed in (p,2p) and (p,d) reactions.

3.2 $^{7}_{\Lambda}$Li

The ground state of $^{7}_{\Lambda}$Li has a known[18] Λ binding energy of 5.6 MeV. Weak and unresolved transitions in the region of 177 to 180 MeV, corresponding to B_{Λ} around 3.3 to 6.3 MeV, are observed. We ascribe those transitions as leading to $(\lambda s_{1/2}, \nu p_{3/2}^{-1})$ configurations, as the $p_{3/2}$ strength is split over the $J = 1^{+}$ ground state and $J = 3^{+}$ state at 2.2 MeV excitation energy of the ^{6}Li core. The broad resonance at 186 MeV contains the bulk of the strangeness-exchange strength ≃ 3.5 mb/sr for the recoilless Λ production on the $p_{3/2}$ neutrons. Again the width of the resonance can be explained by the Λ escape from the p state[14]. The rather narrow resonance at 197.9 MeV is therefore the recoilless Λ production on a 1s neutron of ^{7}Li. The differential cross-section is slightly decreasing with increased transferred momentum, as expected for recoilless Λ production. Surprisingly, the cross-section for this transition is almost a factor of two smaller than for $^{6}_{\Lambda}$Li. This might be due to a more efficient screening by the two $p_{3/2}$ neutrons in ^{7}Li. However, it must be realized that the cross-section depends on the assumption of the background below the peak and on the normalization. The 1s neutron binding energy of 26.6 ± 0.5 MeV in ${}^{7}_{\Lambda}\mathrm{Li}$ can be compared with the 1s proton binding energy of 25.5 MeV observed$^{1)}$ in ${}^{7}\mathrm{Li}(p,2p)$. The width derived for the 197.9 MeV resonance is 1.6 ± 1.5 MeV. The larger value of 5.9 MeV for the width observed$^{1)}$ in ${}^{7}\mathrm{Li}(p,2p)$ is mainly due to the experimental resolution. In the (p,d) reaction no 1s neutron hole excitation has been observed. This excitation region is completely masked by the ${}^{3}\mathrm{He} + {}^{3}\mathrm{H}$ fragmentation, which is considerable at a momentum transfer larger than 150 MeV/c $^{5)}$.

3.3 ${}^{9}_{\Lambda}\mathrm{Be}$

The ground state of ${}^{9}_{\Lambda}\mathrm{Be}$ has a binding energy of 6.7 MeV $^{18)}$. In our spectra we see weak transitions from 171 to 176 MeV, corresponding to a Λ binding energy between 1.7 and 6.7 MeV. From (p,d) reactions$^{1)}$ the $p_{3/2}$ neutron strength is known to be distributed over several states. The 0^{+} ground state and 2^{+} state at 3 MeV excitation energy of ${}^{8}\mathrm{Be}$ have isospin T = 0. Around 17 MeV excitation energy a large part of the $p_{3/2}$ strength is found in states with both isospin T = 0 and T = 1 $^{19)}$. The apparent double structure of the strong resonance at 185 MeV may correspond to the ground state and 3 MeV excitation of the ${}^{8}\mathrm{Be}$ core in the transition to isospin T = 0 states. These resonances are broadened by the large Λ escape width $^{14)}$. The strong resonance at 196 MeV contains the recoilless transitions to isospin T = 0 and T = 1 states. As pointed out by Dalitz and Gal$^{13)}$, the excited states with the permutation symmetry $[3,1]$ of the ${}^{8}\mathrm{Be}$ core with T = 0 and T = 1 are almost degenerate in the 196 MeV resonance of ${}^{9}_{\Lambda}\mathrm{Be}$, the separation between the 185 MeV and 196 MeV resonances being primarily determined by the central NΛ potential. In ${}^{9}_{\Lambda}\mathrm{Be}$ the differences in neutron binding energies and Λ binding energies of the 1p and 1s states are expected almost to cancel in the transformation energy. A tentative fit is done, see Fig. 1, to unravel the 1p and 1s contributions.

3.4 ${}^{12}_{\Lambda}\mathrm{C}$

The ground state of ${}^{12}_{\Lambda}\mathrm{C}$ is known from earlier work$^{18)}$ to have a Λ binding energy of B_{Λ} = 10.8 MeV. At 183.5 MeV a weak transition is observed, corresponding to a B_{Λ} of 11.2 ± 1.0 MeV. Some weaker transitions up to 188 MeV may be observed, which contain about 30% of the 183.5 MeV intensity. They may correspond to the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ core excitations at 2 and 4.8 MeV in the ^{11}C core, which are also excited in the $^{12}C(p,d)$ reaction[20]. The strong and narrow resonance at 194.5 MeV has been attributed to the recoilless Λ production on $p_{3/2}$ neutrons[7,9]. The broad structure at 204.5 MeV is presumably the recoilless Λ production on the 1s neutron. In the fit we did not take into account that a relatively large contribution of the quasi-free $(\lambda d_{5/2}, \nu p_{3/2}^{-1})$ transitions is also expected in this region. So the cross-section of the recoilless Λ production on the 1s neutron may be considerably less. This contamination shows especially the importance of low-momentum transfer in obtaining a clear signal of the recoilless Λ production on strongly bound neutrons in heavier hypernuclei.

3.5 Neutron binding energies in hypernuclei

So far we have discussed hypernuclear spectra and the 1s neutron binding energies of the target neuclei ^6Li, ^7Li, ^9Be, and ^{12}C. We can also learn about neutron binding energies in hypernuclei from our measurements in a simple way, using the known Λ and neutron binding energies[21] of Table 4 in the following relation.

$$B_n(_\Lambda A + 1) + B_\Lambda(_\Lambda A) = B_\Lambda(_\Lambda A + 1) + B_n(A) \; . \tag{3}$$

This gives the neutron binding in the hypernucleus $^7_\Lambda Li$ as follows:

$$\begin{aligned} B_n(^7_\Lambda Li) &= B_\Lambda(^7_\Lambda Li) - B_\Lambda(^6_\Lambda Li) + B_n(^6Li) = \\ &= (5.58 - 4.50 + 5.66) \text{ MeV} = 6.74 \text{ MeV} \; . \end{aligned}$$

With 6.74 MeV we thus can separate the valence neutron of $^7_\Lambda Li$. If we would knock-out a 1s neutron from $^7_\Lambda Li$, we would produce the same 1s neutron hole excited state of $^6_\Lambda Li$ as obtained in the recoilless Λ production on a 1s neutron of ^6Li. Therefore the 1s neutron binding energy in the hypernucleus $^7_\Lambda Li$ is given by

$$B_n^{1s}(^7_\Lambda Li) = B_n^{1p}(^7_\Lambda Li) + M_{exc}(^6_\Lambda Li) - M_{gs}(^6_\Lambda Li) \; . \tag{4}$$

In Table 5 the 1s neutron binding energies in $^7_\Lambda Li$, $^8_\Lambda Li$, $^{10}_\Lambda Be$, and $^{13}_\Lambda C$ are given. Indeed, the added Λ particle provides a small extra binding to the neutrons in the nuclear core.

4. CONCLUSIONS

Neutron hole states have been produced in the (K^-,π^-) strangeness-exchange reaction by the transformation of a neutron into a Λ particle, predominantly by recoilless Λ production. The transformation energy for such a process can be described in terms of the neutron binding energy of the target nucleus (B_n) and the binding energy of the produced Λ particle in the hypernucleus (B_Λ). Using the known Λ binding energies of the hypernuclear ground states, 1s neutron binding energies have been derived. The widths of the states and the differential cross-sections have been analysed, however using certain assumptions for the shape of the background.

The clear similarity of these 1s neutron hole states to the 1s proton hole states observed in (p,2p) reactions and the good agreement with the (p,d) results obtained at higher transferred momentum indicate that in the (K^-,π^-) reaction the presence of the Λ particle does not appreciably disturb the nucleus and can be taken into account in a simple way by applying the weak-coupling model.

The (K^-,π^-) strangeness-exchange reaction is thus a promising tool in the investigation at very low momentum transfer of neutron hole states. When new beam lines with kaon momentum of $p_K \simeq 530$ MeV/c are built[22)], also deeply-lying neutron hole states of heavier hypernuclei will become accessible. A clear signature of those neutron hole states can be expected at the lowest momentum transfer.

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Table 1

1s proton binding energies B_p observed in (p,2p) reactions. The widths are not corrected for the experimental resolutions.

Target nucleus	B_p (MeV)	Width (MeV)	Reference
^{4}He	20.4 ± 0.3	2.4	1
^{6}Li	22.7 ± 0.3	4.0	1
	21.4	1.2	2
^{7}Li	25.5 ± 0.4	5.9	1
^{9}Be	25.4 ± 0.5	6.3	1
^{12}C	34.0 ± 2.0	9.2	1

Table 2

Results of the 1s neutron binding energies B_n and the widths of 1s neutron hole states observed in (K^-,π^-) reactions.

Target nucleus	Transformation energy (MeV)	B_n (MeV)	Width (MeV)
^{4}He		20.6	
^{6}Li	195.5 ± 0.5	24.0 ± 0.5	0.7 ± 1.0
^{7}Li	197.9 ± 0.5	26.6 ± 0.5	1.6 ± 1.5
^{9}Be	(199.0 ± 1.0)	(29.7 ± 1.0)	(5.0 ± 2.0)
^{12}C	204.5 ± 1.5	39.3 ± 1.5	9.0 ± 2.0

Table 3

Results of the differential cross-sections for the recoilless Λ production on 1s neutrons. Only statistical errors are given. The observed reaction angles fall inside the acceptance of the pion spectrometer, which is centred at zero degree.

Hyper-nucleus	Kaon momentum (MeV/c)	Reaction angle (mrad)	Momentum transfer (MeV/c)	Differential cross-section (mb/sr)
${}^{6}_{\Lambda}\mathrm{Li}$	790	10-50	48-61	1.04 ± 0.13
		50-80	61-78	0.92 ± 0.12
		80-120	78-106	0.75 ± 0.11
${}^{7}_{\Lambda}\mathrm{Li}$	720	10-50	35-48	0.63 ± 0.13
		50-80	48-66	0.59 ± 0.08
		80-120	66-91	0.56 ± 0.07
${}^{12}_{\Lambda}\mathrm{C}$	720	16-50	38-48	< 1.67 ± 0.20
		50-80	48-66	< 1.81 ± 0.17
		80-120	66-91	< 1.26 ± 0.15

Table 4

Some neutron binding energies B_n (from Ref. 21) and Λ particle binding energies B used in the calculations. Except for ${}^{6}_{\Lambda}\mathrm{Li}$, the B_Λ values are taken from Ref. 18.

Hypernucleus	B_Λ (MeV)	Nucleus	B_n (MeV)
${}^{6}_{\Lambda}\mathrm{Li}$	4.5 ± 0.5	${}^{6}\mathrm{Li}$	5.66
${}^{7}_{\Lambda}\mathrm{Li}$	5.58 ± 0.03	${}^{7}\mathrm{Li}$	7.25
${}^{8}_{\Lambda}\mathrm{Li}$	6.80 ± 0.03	${}^{9}\mathrm{Be}$	1.67
${}^{9}_{\Lambda}\mathrm{Be}$	6.71 ± 0.04	${}^{12}\mathrm{C}$	18.72
${}^{10}_{\Lambda}\mathrm{Be}$	9.11 ± 0.22		
${}^{12}_{\Lambda}\mathrm{C}$	10.76 ± 0.19		
${}^{13}_{\Lambda}\mathrm{C}$	11.69 ± 0.12		

Table 5

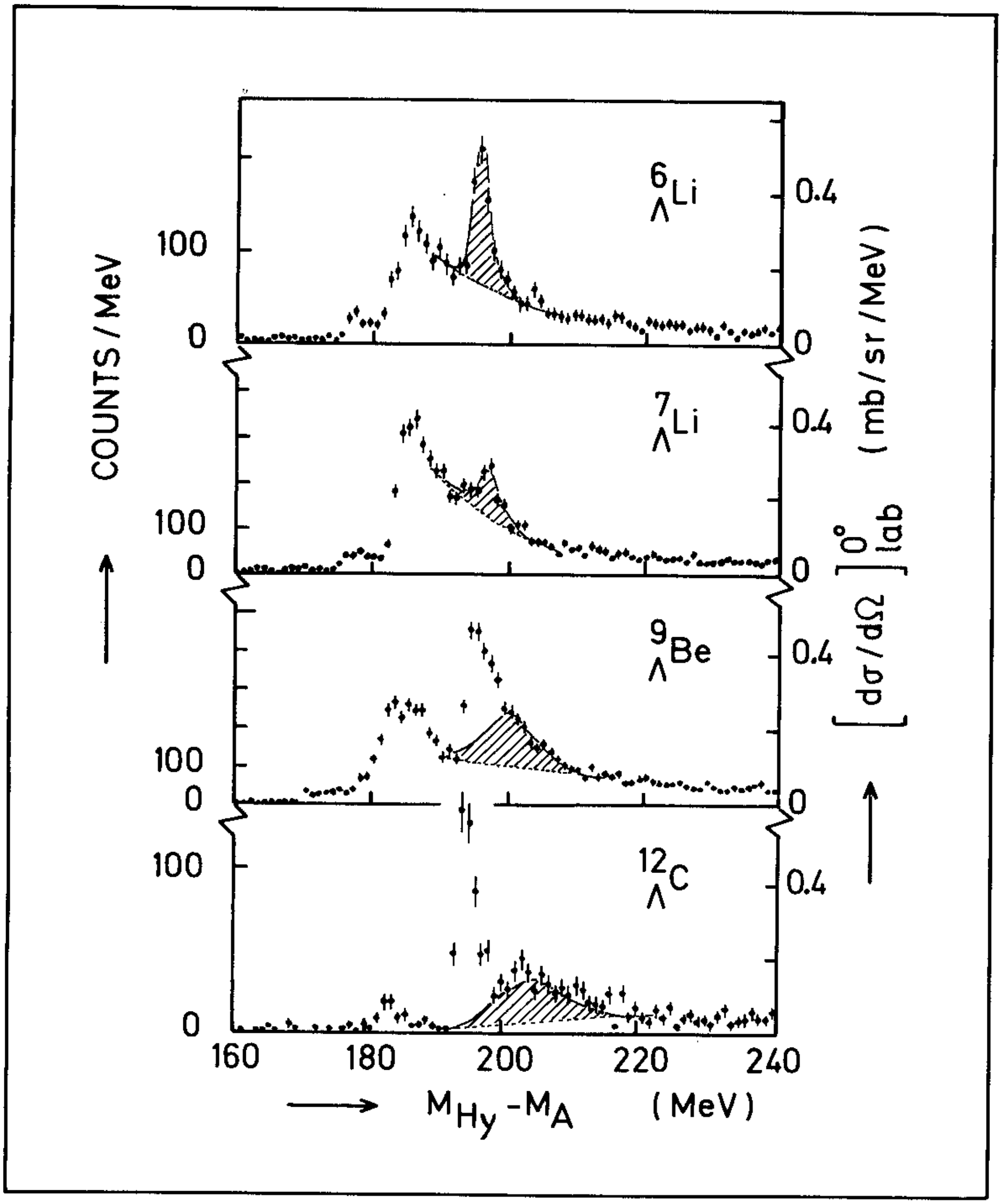
Binding energies of valence neutrons and 1s neutrons in hypernuclei calculated using, from Table 4, the known neutron and Λ particle binding energies in the relations (3) and (4).

Hypernucleus	B_n^{1p} (MeV)	B_n^{1s} (MeV)
${}^{7}_{\Lambda}\mathrm{Li}$	6.74 ± 0.5	25.1 ± 0.5
${}^{8}_{\Lambda}\mathrm{Li}$	8.47 ± 0.04	28.7 ± 0.5
${}^{10}_{\Lambda}\mathrm{Be}$	4.07 ± 0.22	(32.1 ± 1.0)
${}^{13}_{\Lambda}\mathrm{C}$	19.65 ± 0.22	40.2 ± 1.5

Figure captions:

Fig. 1 : Hypernuclear excitation spectra in the (K^-,π^-) strangeness-exchange reactions at kaon momenta of 720-790 MeV/c on ^{6}Li, ^{7}Li, ^{9}Be, and ^{12}C. The pions have been detected in the forward direction. The shaded areas are the results of the fits, which are discussed in the text.

Fig. 2 : Schematic example of the recoilless Λ production on a 1s neutron of a light nucleus. Indicated are the 1s neutron binding energy B_n and the Λ binding energy B_Λ.



COUNTS / MeV
100
0
100
0
100
0
100
0
$^{6}_{\Lambda}$Li
$^{7}_{\Lambda}$Li
$^{9}_{\Lambda}$Be
$^{12}_{\Lambda}$C
0.4
0
0.4
0
0.4
0
0.4
$\left[d\sigma / d\Omega \right]^{0°}_{lab}$ (mb / sr / MeV)
160
180
200
220
240
$M_{Hy} - M_A$ (MeV)

Fig. 1

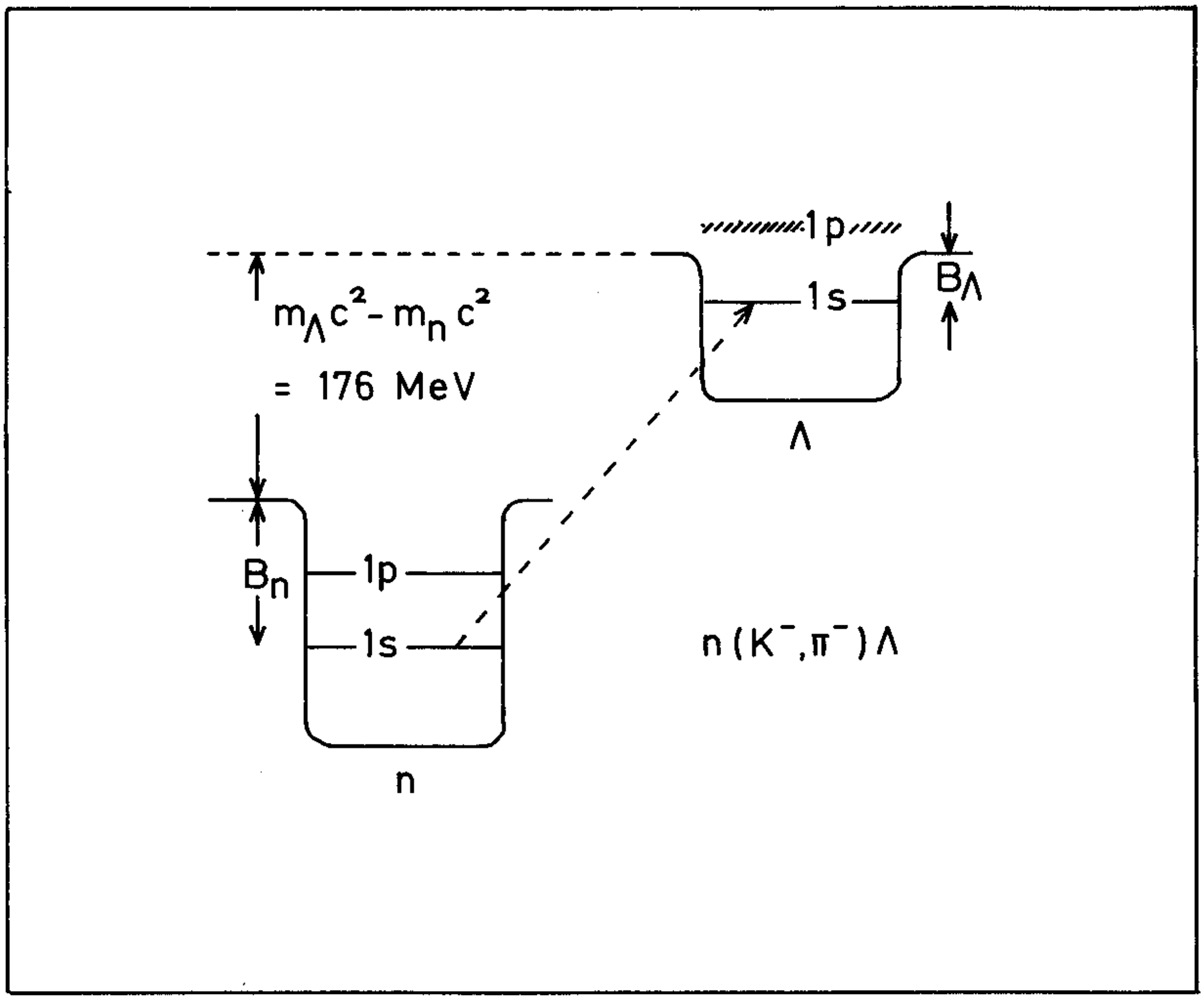

1p
B_Λ
$m_\Lambda c^2 - m_n c^2$
= 176 MeV
1s
Λ
B_n
1p
1s
$n(K^-,\pi^-)\Lambda$
n

Fig. 2