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A FULL SET OF NUCLEAR SHELL ORBITALS FOR THE Λ PARTICLE OBSERVED IN $^{32}_{\Lambda}$S AND $^{40}_{\Lambda}$Ca

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ABSTRACT

The strangeness exchange reaction (K^-, π^-) on ^{32}S and ^{40}Ca has been studied. The strongest transitions lead to states having a configuration with the Λ particle in a 1s, 1p, 1d, 2s, and 1f orbit coupled to the nuclear core. These Λ shells are approximately equidistantly spaced, the energy spacings being about 9 MeV. In the first approximation the Λ particle behaves like a "spinless neutron" in a harmonic oscillator potential.

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In a recent experiment [1], p-shell hypernuclei have been studied by means of the strangeness exchange reaction (K^-, π^-). The outstanding result of this experiment was the determination of the spin-orbit interaction in the Λ-nucleus system. Its strength was found to be an order of magnitude weaker than in the nucleon-nucleus system. In this letter we report a study of the hypernuclei ${}^{32}_{\Lambda}S$ and ${}^{40}_{\Lambda}Ca$ which yield new information on the properties of a Λ particle in nuclei.

A systematic study of heavy hypernuclei turned out to be reasonably easy because the (K^-, π^-) reaction is clean of background, provided the measurement is carried out close to 0°. Hypernuclear states with excitation energies up to 50 MeV were found, which are believed to be produced by one-step processes [2]. In the (K^-, π^-) reaction only a single neutron is involved, namely the one which turns into the Λ particle, while the rest of the nucleus is left untouched. In this process the Λ particle may occupy the same orbital as that previously occupied by the neutron; this is called recoilless Λ production. Or it may occupy one of the neighbouring shells; then we speak of quasi-free Λ production. In both cases we are dealing with very simple configurations: the Λ particle in the different orbitals is coupled to the same nuclear core. If a full set of these orbitals is found in a single nucleus, the properties of the Λ particle depending on its binding energy can be studied. Such information should be of great help in understanding the physics of the quasi-particle model of the nucleus.

The reported experiment has been performed on the low momentum separated K^- beam (k_{22}) at the CERN Proton Synchroton (PS). The experimental set-up consisting essentially of two spectrometers, one for measuring the kaon momenta and the other for the pion momenta, has been described previously [1]. The over-all energy resolution of about 2 MeV is determined by the energy-loss difference for kaons and pions in the target and by the straggling in the trigger counters. The target thickness of 2 g/cm^2 was dictated by the compromise between the resolution and yield requirements of the experiment.

The measured spectra are shown in fig. 1. For the qualitative discussion of the spectra it turned out to be advantageous to compare the sulfur spectrum (fig. 1a) with the calcium one (fig. 1b). The sulfur spectrum was taken at a kaon momentum of 720 MeV/c, whereas the calcium spectrum was taken at 790 MeV/c. For both, the pion spectrometer was set to 0°. We also measured a calcium spectrum at 5° (fig. 1c) in order to distinguish between the recoilless and the quasi-free Λ production. In addition, this 5° spectrum is inserted in fig. 1b as a dotted line. In order to compare the three spectra, we plotted them as a function of the transformation energy $M_{HY}-M_A$, which yields the Q value of the strangeness exchange reaction in transforming the nuclear ground state with mass M_A into a hypernuclear state with mass M_{HY}. It is expected that in neighbouring nuclei the transformation energy for the nucleons in the same orbitals will be the same in the first approximation. Therefore the peaks appearing at the same energy in the $M_{HY}-M_A$ scale for calcium and sulfur will be assigned to the same configuration.

The most prominent recoilless transitions are expected to stem from the (K^-, π^-) reaction on the neutrons of the last shells. In the case of the calcium target these transitions lead to states built on neutron holes in the $1d_{5/2}$, $2s_{1/2}$, and $1d_{3/2}$ orbits. In the case of sulfur, with the $1d_{3/2}$ orbital not yet filled up, only particle-hole excitations with $1d_{5/2}$ and $2s_{1/2}$ orbitals can be expected. As the transition strength will be roughly proportional to the number of neutrons in an orbital, the strongest transition in calcium and sulfur at $B_\Lambda = 5$ MeV is assigned to have the $\left(1d_{5/2}, 1d^{-1}_{5/2}\right)_{\Lambda n}$ configuration. At $B_\Lambda = 0$ MeV in the calcium spectrum, a second recoilless peak is observed. It does not show up in the sulfur spectrum and is therefore assigned to the $\left(1d_{3/2}, 1d^{-1}_{3/2}\right)_{\Lambda n}$ configuration. The recoilless peaks have a strong angular dependence, the intensity being proportional to $\exp\left[-(qR)^2\right]$, where q is the recoil momentum of the hypernucleus and R the nuclear radius [1]. To demonstrate this angular dependence for the recoilless peaks, the spectra at 0° and 5° are compared in fig. 1b. The spacing between the two recoilless peaks is about 5 MeV, which is as much as the spacing between the $1d_{5/2}$ and $1d_{3/2}$ neutron hole in ^{40}Ca [3]. In agreement with the conclusion already obtained from the data on the p-shell hypernuclei [1], one does not observe any appreciable spin-orbit splitting in Λ-nucleus system. The state with the $\left(2s_{1/2}, 2s^{-1}_{1/2}\right)_{\Lambda n}$ configuration is expected to be weak as compared to the state belonging to the 1d configuration, as only two neutrons contribute to this transition and it does not show up clearly in the spectra.

Let us now turn to the peaks with intensities showing only a weak angular dependence: these peaks cannot be due to the recoilless transitions. Of particular interest is the peak in ${}^{32}_{\Lambda}S$ at B_{Λ} = 17.5 ± 0.5 MeV, which is close to the binding energy expected for the ground state. The ground state of ${}^{32}_{\Lambda}S$ has the configuration $\left(1s_{1/2},\ 2s^{-1}_{1/2}\right)_{\Lambda n}$ and it is therefore not surprising to observe it in the present experiment. At small recoil momenta of the Λ particle the strength of the $\Delta\ell = 0$ transitions such as 2s → 1s is comparable [4] to the strength of $\Delta\ell = 1$ transitions to the neighbouring shells. At 0° the spin-flip amplitude of the (K^-, π^-) reaction is zero, and we expect to observe only those $\Delta\ell = 1$ transitions that can be obtained from the target nucleus without spin-flip. We therefore interpret the peak at B_{Λ} = 7 MeV as a $\Delta\ell = 1$ transition to the state with $\left(1p_{3/2},\ 1d^{-1}_{5/2}\right)_{\Lambda n}$ configuration.

In calcium, additional states produced on the neutrons of the $1d_{3/2}$ shell should be observed. Without spin-flip the $\left(1p_{1/2},\ 1d^{-1}_{3/2}\right)_{\Lambda n}$ configuration can be reached. The pronounced peak at B_{Λ} = 11 MeV is believed to belong to this configuration. Unfortunately, in calcium the transition to the $\left(1s_{1/2},\ 2s^{-1}_{1/2}\right)_{\Lambda n}$ state could not be identified because this part of the spectrum is obscured by K → 2π decay for kaons of 790 MeV/c momentum. The ground state of ${}^{40}_{\Lambda}Ca$ with $\left(1s_{1/2},\ 1d^{-1}_{3/2}\right)_{\Lambda n}$ configuration is not expected to be populated under the kinematical conditions of the present experiment; a change of the angular momentum $\Delta\ell = 2$ is required for this transition.

According to calculations of Bouyssy [5], the broad structure partially underlying the recoilless peaks and extending to high excitations is accounted for by the strangeness exchange reaction on the neutrons in the 1p and 1s shells. The hypernuclear states built on deep-lying neutron holes are several MeV broad and will not show up as discrete narrow resonances. But there is an additional state at high excitation with the configuration $\left(1f_{7/2},\ 1d^{-1}_{5/2}\right)_{\Lambda n}$ which is expected to be sufficiently narrow. At B_{Λ} = −13 MeV there is an indication of a peak both in the sulfur and in the calcium spectrum, and we will tentatively assign it to the state with that configuration.

From the above discussion we can conclude that it is very likely that ${}^{32}_{\Lambda}S$ and ${}^{40}_{\Lambda}Ca$ states have been observed for which the Λ particle is in the 1s, 1p, 1d, 2s, and 1f orbits, coupled, however, to the nuclear core which corresponds either to the 1d or to the 2s neutron hole in the ${}^{32}S$ or ${}^{40}Ca$ nuclei. From these states the energy ladder of the Λ particle in ${}^{32}_{\Lambda}S$ and ${}^{40}_{\Lambda}Ca$ can easily be deduced. It is found that the orbitals 1s, 1p, (1d2s) and 1f are approximately equidistantly spaced with an energy splitting of about 9 MeV. This result is not surprising. The energy spacing between the shells does not get distorted by spin-orbit or spin-spin interaction. As we learnt recently, the spin-orbit [1] as well as the spin-spin [6] energy splitting in the Λ-nucleus system is at least an order of magnitude smaller than the energy splitting between the shells.

The equidistant spacing between the shells indicates that the potential seen by the Λ in sulfur and calcium is well approximated by the harmonic oscillator shape. Emphasizing the difference between hypernuclei and nuclei in an oversimplifying manner, we can say that the Λ particle in nuclei behaves like a "spinless neutron".

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REFERENCES

[1] W. Brückner, M.A. Faessler, T.J. Ketel, K. Kilian, J. Niewisch, B. Pietrzyk, B. Povh, H.G. Ritter, M. Uhrmacher, P. Birien, H. Catz, A. Chaumeaux, J.M. Durand, B. Mayer, J. Thirion, R. Bertini and O. Bing, Phys. Lett. 79B (1978) 157.

[2] B. Povh, Annu. Rev. Nucl. Phys. 28 (1978) 1, and references quoted therein.

[3] G. Jacob and Th.A.J. Maris, Rev. Mod. Phys. 45 (1973) 6.
P. Doll, G.J. Wagner, K.T. Knöpfle and G. Mairle, Nucl. Phys. A263 (1976) 210.

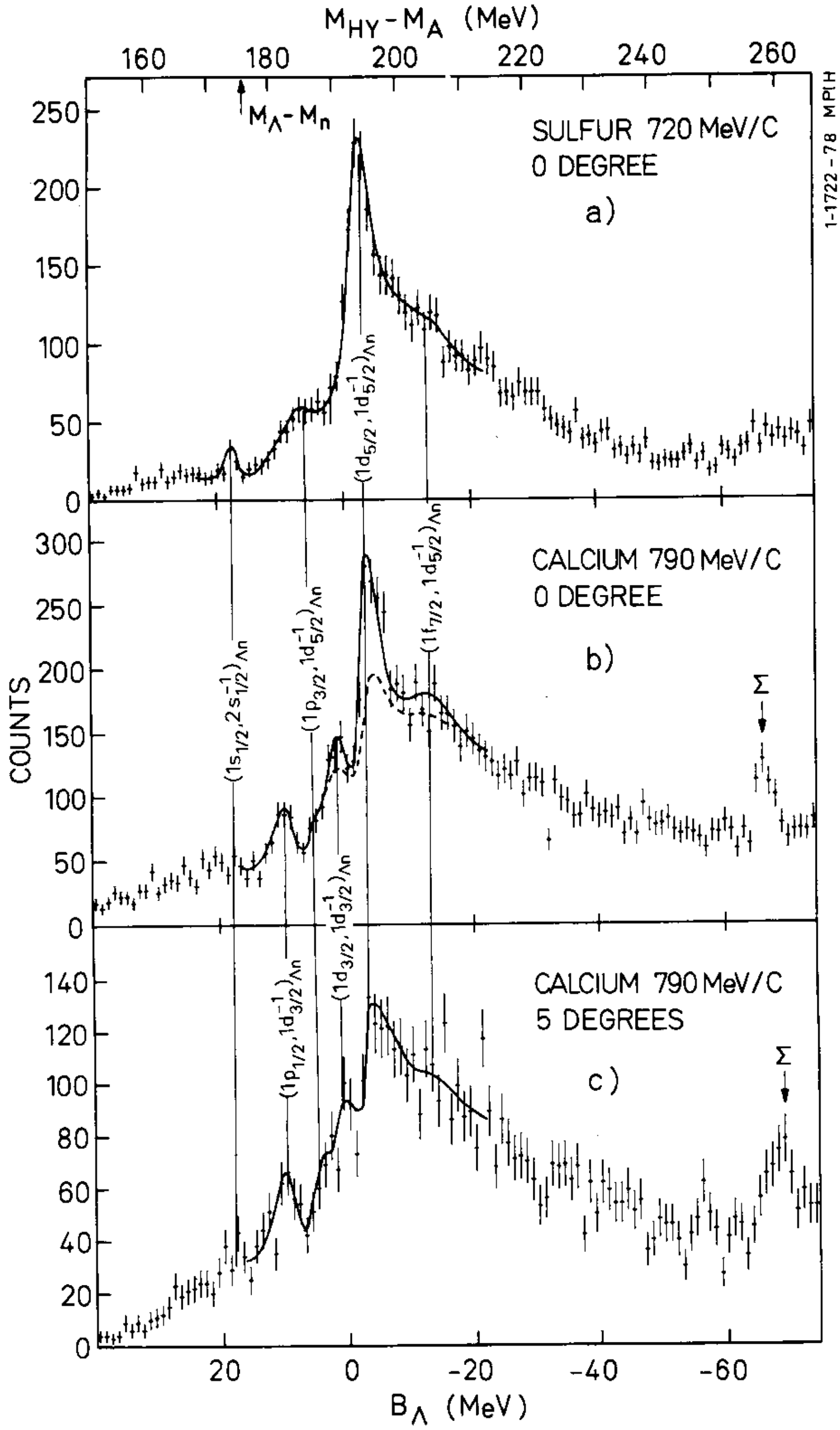
[4] H.J. Lipkin, Proc. Summer Study Meeting on Nuclear and Hypernuclear Physics with Kaon Beams, Brookhaven, 1973 (Brookhaven National Laboratory, Upton, New York, 1973), p. 148.

[5] A. Bouyssy, Nucl. Phys. A290 (1977) 324.

[6] A. Bamberger, M.A. Faessler, U. Lynen, H. Piekarz, J. Piekarz, J. Pniewski, B. Povh, H.G. Ritter and V. Soergel, Nucl. Phys. B60 (1973) 1.

Figure caption

Fig. 1 : Spectra obtained from the (K^-, π^-) reaction: a) on ^{32}S at a kaon momentum of 720 MeV/c, and b,c) on ^{40}Ca at a kaon momentum of 790 MeV/c. The spectra are plotted as a function of the transformation energy $M_{HY}-M_A$ in the strangeness exchange reaction. Also indicated is the energy which is necessary to transform a free neutron into a Λ particle ($M_\Lambda-M_n$). In addition, the Λ binding energy B_Λ is given for each spectrum. For calcium a spectrum is shown at 0° pion spectrometer setting (fig. 1b) and another at 5° (fig. 1c). The 5° spectrum is also inserted in fig. 1b as a dotted line. Both calcium spectra show the peak of the free Σ^+ production in the p(K^-, π^-)Σ^+ reaction which occurs on the protons of our liquid-hydrogen Čerenkov counters. The peak does not appear in the sulfur spectrum because of the much lower cross-section for this process at a kaon momentum of 720 MeV/c. The lines are only given to guide the eye.



M_HY - M_A (MeV)
160
180
200
220
240
260
M_Λ-M_n
SULFUR 720 MeV/C
0 DEGREE
a)
1-1722-78 MPIH
CALCIUM 790 MeV/C
0 DEGREE
b)
Σ
CALCIUM 790 MeV/C
5 DEGREES
c)
Σ
COUNTS
B_Λ (MeV)

Fig. 1