*Work performed under the auspices of the U. S. Atomic Energy Commission.

†On leave from Technische Universität München, München, Germany.

[1]L. A. Charlton and D. Robson, Phys. Rev. Lett. 32, 946 (1974).

[2]P. Braun-Munzinger, W. Bohne, C. K. Gelbke, W. Grochulski, H. L. Harney, and H. Oeschler, Phys. Rev. Lett. 31, 1423 (1973).

[3]D. A. Sink, J. V. Maher, and J. C. Peng, to be published.

[4]M. F. Werby and W. Tobocman, Bull. Amer. Phys. Soc. 19, 504 (1974), and Phys. Rev. C 10, 1022 (1974).

[5]For a list of references see, for instance, D. G. Kovar, in *Proceedings of the International Conference on Reactions Between Complex Nuclei, Nashville, Tennessee, 1974*, edited by R. L. Robinson *et al.* (North-Holland, Amsterdam, 1974), Vol. I.

[6]W. Henning, D. G. Kovar, B. Zeidman, and J. R. Erskine, Phys. Rev. Lett. 32, 1015 (1974).

[7]M. C. Lemaire, M. C. Mermaz, H. Sztark, and A. Consolo, in *Proceedings of the International Conference on Reactions Between Complex Nuclei, Nashville, Tennessee, 1974*, edited by R. L. Robinson *et al.* (North-Holland, Amsterdam, 1974), Vol. II; P. D. Bond, J. D. Garrett, S. Kahana, M. J. LeVine, and A. Z. Schwarzschild, *ibid.*; M. S. Zisman, R. M. DeVries, J. G. Cramer, K-L Liu, Y-D Chan, and B. Cuengio, to be published.

[8]R. M. DeVries, to be published.

[9]G. Hauser, R. Löhken, H. Rebel, G. Schatz, G. W. Schweimer, and J. Specht, Phys. Lett. 27B, 220 (1968), and Nucl. Phys. A128, 81 (1969); I. Brissaud, M. K. Brussel, M. Sowinski, and B. Tatischeff, Phys. Lett. 30B, 324 (1969); B. Tatischeff and I. Brissaud, Nucl. Phys. A155, 89 (1970).

[10]G. Gaul, H. Lüdecke, R. Santo, H. Schmeing, and R. Stock, Nucl. Phys. A137, 177 (1969).

[11]R. M. DeVries, H. W. Fulbright, and R. G. Markham, Bull. Amer. Phys. Soc. 19, 523 (1974).

[12]R. M. DeVries, Phys. Rev. C 8, 951 (1973).

[13]J. Blair, R. M. DeVries, K. G. Nair, A. J. Baltz, and W. Reisdorf, Phys. Rev. C 10, 1856 (1974).

[14]J. P. Draayer, to be published.

[15]J. P. Draayer, H. E. Gove, J. P. Trentelman, N. Anantaraman, and H. Collins, in Proceedings of the International Conference on Nuclear Structure and Spectroscopy, Amsterdam, The Netherlands, 9–13 September 1974 (to be published).

[16]I. Rotter, Fortschr. Phys. 16, 195 (1968); D. Kurath, Phys. Rev. C 7, 1390 (1973).

[17]R. M. DeVries, Nucl. Phys. A212, 207 (1973). Note that a reanalysis of this data with a bound-state radius $=1.25\times 12^{1/3}$ fm yields a ratio $\mathcal{S}(^{12}C^*)/\mathcal{S}(^{12}C_{g.s.})\approx 2$.

[18]I. Badawy, B. Berthier, P. Charles, B. Fernandez, and J. Gastebois, in *Proceedings of the International Conference on Reactions Between Complex Nuclei, Nashville, Tennessee, 1974*, edited by R. L. Robinson *et al.* (North-Holland, Amsterdam, 1974), Vol. I, Suppl.

[19]H. H. Gutbrod, H. Yoshida, and R. Bock, in *Proceedings of the International Conference on Nuclear Reactions Induced by Heavy Ions, Heidelberg, Germany, 1969*, edited by R. Bock and W. R. Hering (North-Holland, Amsterdam, 1970), p. 311.

Observation of the Hypernuclei $^{16}_{\Lambda}O$ and $^{27}_{\Lambda}Al$

G. C. Bonazzola,* T. Bressani,* E. Chiavassa,* G. Dellacasa,* A. Fainberg,*† M. Gallio,* N. Mirfakhrai,*‡ A. Musso,* and G. Rinaudo*

Istituto di Fisica Superiore dell'Università, Torino, Italy, and Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Italy

(Received 28 January 1975)

The (K^-,π^-) reaction on ^{16}O and ^{27}Al at $p_{K^-}=390$ MeV/c with forward emitted π^- (Feshbach-Kerman kinematics) was studied. Formation of $^{16}_{\Lambda}O$ and $^{27}_{\Lambda}Al$ was observed. Experimental energy spectra are compared with some theoretical predictions.

In this Letter we report the first observation and measurement of the differential cross sections for the reactions

$$K^- + {}^{16}O \rightarrow {}^{16}_{\Lambda}O + \pi^-, \tag{1}$$

$$K^- + {}^{27}Al \rightarrow {}^{27}_{\Lambda}Al + \pi^-. \tag{2}$$

The experiment was carried out with K^- in flight (390 ± 8 MeV/c) and π^- detected in the forward direction ($\theta_{\pi,\mathrm{lab}}\leq 15°$), that is, a Feshbach-Kerman kinematical situation,[1] which favors the production of hypernuclei in two-body reactions leaving the $\Lambda°$ almost at rest (≤ 80 MeV/c for our arrangement). Partial results of preliminary analyses were already presented.[2,3]

A detailed description of the experimental techniques will be published elsewhere[4]; the apparatus was located at the K_{12a} beam on the external target in the slow-extracted proton beam of the CERN proton synchrotron. Four slices of water (or aluminum) targets sandwiched between three thin scintillators (2 mm) were used. This arrangement allowed a rough determination of the interaction point by a $\Delta E/\Delta x$ measurement of the particles traversing the scintillators. The total thickness of the sliced target was 5 g/cm^2.

Figure 1 shows the raw-data spectra; the binding energies B_Λ of the Λ hyperon in $^{16}_{\Lambda}$O and $^{27}_{\Lambda}$Al are plotted on the abscissa. Neither of the two hypernuclei have been reported in the literature. From the B_Λ values of ground states of known hypernuclei[5] we expect that bound states should fall between 0 and about -20 MeV. We also expect peaks at positive B_Λ (i.e., unbound Λ states), due to the formation of resonances in the continuum.

In order to extract the events corresponding to hypernuclei production from the spectra of Fig. 1 it was essential to measure the background with great accuracy. Principal sources of background were π^- and K^- circulating in the spectrometer and missed by the trigger (responsible for the large accumulation of events around 15 and 40 MeV); $K_{\pi 2}$ decays in the target region (producing the broad bump around -30 MeV); and other spurious events such as K^- and π^- scattered by the magnet poles, decays outside the target region, etc. The first two sources of background were determined by triggering on (π^-,π^-) and (K^-,K^-) events, and the other by analyzing (K^+,π^+) events at the same incident momentum and in the same triggering conditions as for (K^-,π^-): A detailed description of the analysis of the background was given in our previous study of $^{12}_{\Lambda}$C production.[6]

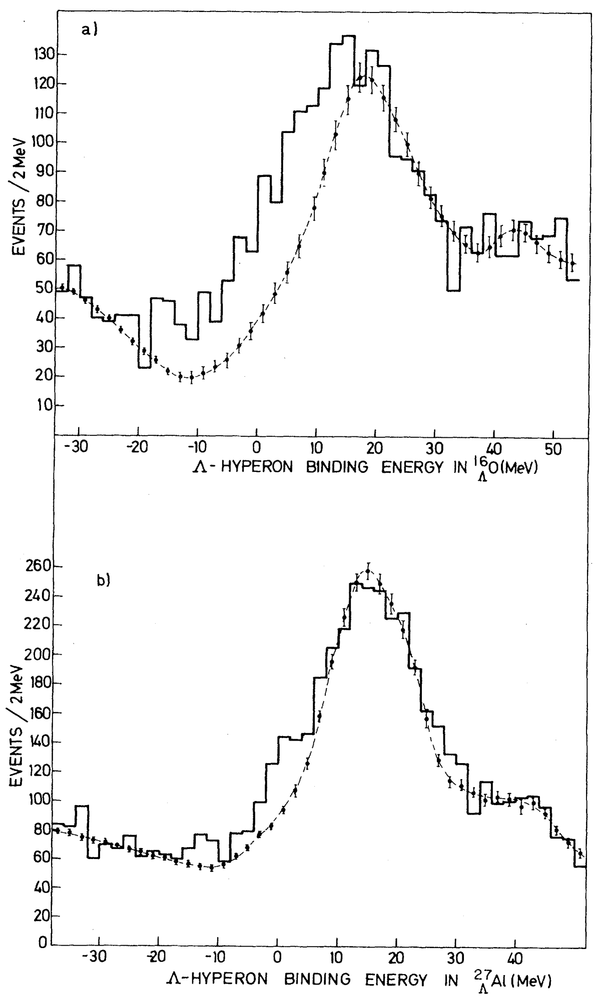

FIG. 1. Raw-data spectra for the (K^-,π^-) events on (a) ^{16}O and (b) ^{27}Al targets. The dashed lines connect points representing the total background. Errors on the histograms are not indicated since they are the statistical ones.

If we try to fit the spectra of Fig. 1 under the hypothesis that they are only due to the above mentioned sources of background, we obtain a χ^2 probability smaller than 5×10^{-3}, with 72 degrees of freedom (df) for the ^{16}O spectrum and 87 df for the ^{27}Al spectrum. The poorness of these fits is obviously due to the excess of events in the B_Λ region where hypernuclei production is expected. To describe hypernuclei we allowed in the fitting procedure, besides the background, two peaks of Gaussian shape whose centers and widths were left as free parameters. The χ^2 probabilities for the best fits to the entire spectra under these hypotheses were 60% for $^{16}_{\Lambda}$O with 70 df and 50% for $^{27}_{\Lambda}$Al with 85 df. The dashed lines of Fig. 1 represent the total background spectra with their errors, which include all the statistical uncertainties due to the fitting procedure and due to the statistical errors affecting the (π^-,π^-) and (K^-, K^-) spectra.

The energy spectra after subtraction of the background are shown in Fig. 2. While the $^{27}_{\Lambda}$Al spectrum presents a quite clear structure of two peaks, the $^{16}_{\Lambda}$O spectrum is more complicated. In fact the subtracted spectrum of Fig. 2(a) can be fitted with an equally good χ^2 probability of 87.5% by using either two or three Gaussian curves with centers and widths left as free parameters (indicated in the following as fits I and II, respectively). The best-fit parameters and the differential cross sections for the production of the peaks are collected in Table I together with the data for the unique fit to the $^{27}_{\Lambda}$Al spectrum.

There are no precise and detailed predictions of the energy spectra of $^{16}_{\Lambda}$O and $^{27}_{\Lambda}$Al as well as none of the differential cross sections in the strangeness-exchange reactions (1) and (2). Be-

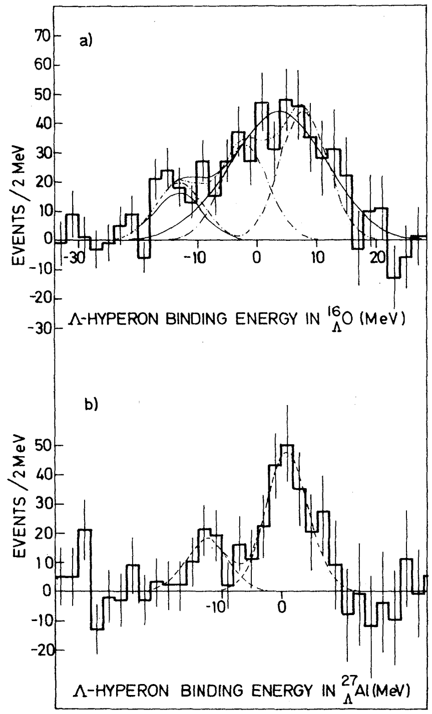

FIG. 2. Spectra of (a) $^{16}_{\Lambda}$O and (b) $^{27}_{\Lambda}$Al after subtraction of the background. The continuous lines in (a) represent fit I; the dot-dashed lines, fit II. The dashed lines in (b) represent the unique fit.

cause of the limited energy resolution (6 MeV full width at half-maximum) we cannot determine the real width of the observed states or even establish whether one or more hypernuclear states contribute to the observed peaks.

In the $^{16}_{\Lambda}$O spectrum there is the ambiguity between fits I and II, though in our opinion fit II should be preferred since the widths of the higher-energy peaks are close to the experimental resolution. Fit I would require the existence of a broad band of excited states, not observed in $^{12}_{\Lambda}$C and $^{12}_{\Lambda}$Al. Both fits give a peak at $B_\Lambda = -13.0 \pm 2.0$ MeV, which might contain the ground state. A B_Λ value around this energy is in fact expected from the trend of the B_Λ values for lighter hypernuclei.[5] It agrees also with the 1^- configuration predicted by the first set of selected parameters used by Gal, Soper, and Dalitz[7] for the Λ-N and Λ-N-N interactions in their phenomenological shell-model analysis of the Λ binding energies for the ground states of the p-shell hypernuclei. The 1^- spin and parity assignment of this state is also fully consistent with that expected in our kinematical situation, where only natural-parity states can be reached from the ^{16}O target nucleus.

TABLE I. Best-fit parameters [value of B_Λ for the center of the peaks and widths of the peaks (standard deviation)] χ^2 probabilities, and differential cross sections in the lab frame for the peaks found in the fits to the subtracted spectra.

		B_Λ (MeV)	Peak width (MeV)	χ^2 (%)	$\left(\frac{d\sigma}{d\Omega}\right)_{\rm lab}$ (mb/sr)
^{16}O	Fit I	-13.0 ± 2.0	4.0 ± 0.5	87.5	1.0 ± 0.4
		$+4.0 \pm 1.5$	8.0 ± 1.0		5.1 ± 0.8
	Fit II	-13.0 ± 2.0	4.0 ± 0.5		1.3 ± 0.4
		-2.0 ± 1.5	4.0 ± 0.5	87.5	2.1 ± 0.5
		$+8.0 \pm 1.5$	4.0 ± 0.5		2.7 ± 0.6
^{27}Al		-12.5 ± 2.0	3.5 ± 0.5	50	1.3 ± 0.6
		$+1.0 \pm 1.5$	3.5 ± 0.5		3.5 ± 0.7

The other peak(s), independently of the particular fit chosen (I or II), can be interpreted as due to the formation of $^{16}_{\Lambda}$O excited states in which a Λ^0 or a neutron is raised to an upper shell. Esch[8] carried out a calculation of the differential cross section for the strangeness-exchange reaction (1), without taking into account initial- and final-state interactions. We made a rough evaluation of these effects by using the simple formula[6]

$$\left(\frac{d\sigma}{d\Omega}\right)_{^{16}_{\Lambda}\mathrm{O}} = \left(\frac{d\sigma}{d\Omega}\right)_{\rm free} \mathfrak{N}(A,N)|F(q_\Lambda)|^2, \qquad (3)$$

where $(d\sigma/d\Omega)_{\rm free}$ is the differential cross section for the free reaction

$$K^- + n \to \Lambda + \pi^- \qquad (4)$$

in the laboratory frame, taken from the recent work of Berley *et al.*,[9] $\mathfrak{N}(A,N)$ is the effective neutron number as defined by Kölbig and Margolis,[10] and $F(q_\Lambda)$ is a form factor accounting for the probability that a Λ^0 is trapped in an s or a p state, taken from Esch.[8] In the calculation we used a Woods-Saxon density distribution:

$$\rho = \frac{\rho_{\rm norm}}{1 + \exp[(r-c)/a]}, \qquad (5)$$

with $a = 0.545$ fm and $c = 1.14A^{1/3}$ fm. With correction for the angular acceptance of our spectrometer, formula (3) gives values of 0.41 and 2.5 mb/sr for the $^{16}_{\Lambda}$O configurations corresponding to Λ^0 trapping in an s or p state; these are about half of the experimental values.

In the $^{27}_{\Lambda}$Al spectrum, the peak at $B_\Lambda = -12.5 \pm 2$ MeV can hardly be interpreted as due to the formation of the ground state, which could be reasonably expected around $B_\Lambda = -20$ MeV. The lack of formation of ${}^{27}_{\Lambda}$Al in the ground state can be explained by the fact that in the transition from the ground state of ^{27}Al ($\frac{5}{2}^+$) to the ground state of ${}^{27}_{\Lambda}$Al ($\frac{9}{2}^+$ or $\frac{11}{2}^+$) the change in angular momentum must be at least two units (for the p-shell hypernuclei ${}^{12}_{\Lambda}$C and ${}^{16}_{\Lambda}$O where ground states were observed, a change of one unit was sufficient). A possible interpretation of the ${}^{27}_{\Lambda}$Al spectrum can be based on the predictions of the general trend of hypernuclear excited states formed in strangeness-exchange reactions of the type (1) and (2). The first prediction is the strangeness-analog-states hypothesis of Kerman and Lipkin,[11,12] and the second one is that put forward by Auerbach and Gal.[13] The main difference between the two hypotheses is the shape of the self-consistent single-particle potentials witnessed by a Λ^0 and a nucleon, which are supposed to be the same according to the first authors and different according to the second authors. As a consequence, Kerman and Lipkin expect that the great part of the transition strength in strangeness-exchange reactions with Feshbach-Kerman kinematics would be concentrated in the strangeness analog state, whose excitation energy is increasing with A. On the contrary Auerbach and Gal expect that most of the transition strength would be concentrated in a state located around 10 MeV of excitation energy, independent of A. If we assume $B_\Lambda \approx -20$ MeV for the ground state, the excitation energies of the experimental states are around 10 and 20 MeV. The latter state is more abundantly produced and its position agrees with that predicted by Kerman and Lipkin. Auerbach and Gal predict the possibility of exciting both states, but with a relative intensity higher for the 10-MeV state, which is not seen in the experimental spectrum.

The above discussion is rather speculative, and more precise experiments are needed in order to extract definitive conclusions. We think that with this experiment we have demonstrated the feasibility of spectroscopic studies on hypernuclei using K^- in flight and counter techniques. Our major experimental limitation was the energy resolution, which was sacrificed in favor of the acceptance because of the low intensity of the beam. With the future intense low-energy K^- beams,[14] high-resolution spectrometers could be built and a very rich field of information would emerge.

We are very grateful to Professor C. Rubbia, who drew our attention to the interest in this experiment and helped us in the design of the apparatus. Particular thanks are due to Professor T. E. O. Ericson, Professor O. Kofoed-Hansen, Professor E. Picasso, and Professor D. M. Wilkinson for their continuous encouragement. We are indebted to Professor C. M. Garelli and Professor E. Predazzi for their interest. Dr. R. Cester was involved in part of the experiment. Dr. H. Palevsky is thanked for a critical reading of the manuscript.

*Visitors at CERN, Geneva, Switzerland.

†Present address: Physics Department, University of Syracuse, Syracuse, N. Y. 13210.

‡Fellow of the Italian Government, now at Iran National University, Teheran, Iran.

[1]H. Feshbach and A. K. Kerman, in *Preludes in Theoretical Physics,* edited by A. De-Shalit, H. Feshbach, and L. Van Hove (North-Holland, Amsterdam, 1966), p. 260.

[2]G. C. Bonazzola, T. Bressani, R. Cester, E. Chiavassa, G. Dellacasa, A. Fainberg, D. Freschi, N. Mirfakhrai, A. Musso, and G. Rinaudo, in Proceedings of the Summer Study Meeting on Nuclear and Hypernuclear Physics with Kaon Beams, Upton, New York, 1973, edited by H. Palevsky, BNL Report No. 18335, 1973, (unpublished), p. 106.

[3]T. Bressani, in Proceedings of the Topical Meeting on High Energy Collisions Involving Nuclei, Trieste, Italy, 1974 (to be published).

[4]G. C. Bonazzola, T. Bressani, R. Cester, E. Chiavassa, G. Dellacasa, A. Fainberg, M. Gallio, N. Mirfakhrai, A. Musso, and G. Rinaudo, "A Double Magnetic Spectrometer for the Study of Hypernuclei Production by K^- in Flight" (to be published).

[5]M. Juric, G. Bohm, J. Klabuhn, U. Krecker, F. Wysotski, G. Coremans-Bertrand, J. Sacton, G. Wilquet, T. Cantwell, F. Esmael, A. Montwill, D. H. Davis, D. Kietczewska, T. Pniewski, T. Tymieniecka, and J. Zakrzewski, Nucl. Phys. B52, 1 (1973).

[6]G. C. Bonazzola, T. Bressani, R. Cester, E. Chiavassa, G. Dellacasa, A. Fainberg, N. Mirfakhrai, A. Musso, and G. Rinaudo, Phys. Lett. 53B, 297 (1974).

[7]A. Gal, J. M. Soper, and R. H. Dalitz, Ann. Phys. (New York) 72, 445 (1972).

[8]R. J. Esch, Can. J. Phys. 51, 1524 (1973).

[9]D. Berley, S. P. Yamin, R. R. Kofler, A. Hann, G. W. Meisner, S. S. Yamamoto, J. Thompson, and W. Willis, Phys. Rev. D 1, 1996 (1970).

[10]K. S. Kölbig and B. Margolis, Nucl. Phys. B6, 85 (1968).

[11]H. J. Lipkin, Phys. Rev. Lett. 14, 18 (1965).

[12]A. K. Kerman and H. J. Lipkin, Ann. Phys. (New York) 66, 738 (1971).

[13]N. Auerbach and A. Gal, Phys. Lett. 48B, 22 (1974).

[14]H. Palevsky, in Proceedings of the Summer Study Meeting on Nuclear and Hypernuclear Physics with Kaon Beams, Upton, New York, 1973, edited by H. Palevsky, BNL Report No. 18335, 1973 (unpublished), p. 132.