plot[9] which has had some success in the study of elastic scattering.

Following this, we have plotted in Fig. 3 our one point at $P_\perp^2=1.33$ (GeV/$c$)$^2$, along with the two points of Baker *et al.*[6] around $P_\perp^2=2.9$ (GeV/$c$)$^2$. In plotting these points, we have used the values of $(d\sigma/d\Omega)_{\theta=0}$ obtained by Overseth *et al.*[5] by interpolation. A third point of Baker *et al.*[6] was not plotted because no zero-degree measurements are available. We have also plotted the line $\exp(-3.5P_\perp^2)$. This was the fit obtained by Ratner *et al.*[7] for the differential cross section for the production of pions in 12.5-GeV/$c$ proton-proton collisions. Clearly this line is in good agreement with these points. The line is also in good agreement with the points of Overseth *et al.*[5] We believe that this is evidence that the process $p+p\to\pi^++d$ is similar to production cross sections rather than to elastic cross sections.[10]

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[10] The distinction between production and elastic processes has been made in terms of the two variables $R$ and $r$ by A. D. Krisch, Phys. Rev. **135**, B1456 (1964); *Lectures in Theoretical Physics* (University of Colorado Press, Boulder, Colo., 1966), Vol. IX.

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# Observation of the Reaction $K^-+\mathrm{He}^4\to\Lambda^0+\pi^-+p+d$[†]

I. R. Kenyon,[*] A. E. Sichirollo,[‡] C. R. Sun[§]
*Helium Bubble Chamber Group, Northwestern University, Evanston, Illinois*

AND

E. M. Harth and S. Zenone
*Syracuse University, Syracuse, New York*

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This paper reports the observation of 164 definite and 20 ambiguous examples of the reaction $K^-+\mathrm{He}^4\to\Lambda^0+\pi^-+p+d$ produced by $K^-$-meson absorptions at rest in the Northwestern University 20-cm liquid-helium bubble chamber. We confirm that the reaction is dominated by the two-step process $K^-+\mathrm{He}^4\to(\Sigma+\text{nucleus})+\pi^-\to\Lambda^0+p+d+\pi^-$. The momentum distributions of the baryonic particles (for events with $\pi^-$-meson momentum below 180 MeV/$c$) are compared with the predictions of an impulse-model calculation. In this calculation the $\Sigma$-hyperon–nucleus interaction in the intermediate state is approximated by an effective potential acting on the $\Sigma$ hyperon. It is found that very good fits are obtained with a potential of central depth around 37 MeV. This value implies that the $\Lambda$- and $\Sigma$-hyperon–nuclear potentials are of similar strengths. We show that such a result is consistent with the data on free $(\Sigma^\pm,p)$ and $(\Lambda,p)$ interactions at low energies, and data on hypernuclear binding energies. This potential depth is also consistent with the meager information on the effective potential felt by $\Sigma$ hyperons in medium-weight nuclei. There is therefore no evidence in the reaction observed for any final-state $(\Lambda,p)$ resonance as postulated by Bugg, Bhatt, and Cohn.

MOMENTUM spectra have been reported by Cohn *et al.*[1] for particles emitted from $\Sigma^-$-hyperon absorptions at rest on helium in the channel

$$\Sigma^-+\mathrm{He}^4\to\Lambda^0+n+t.$$

There is marked disagreement between the prediction of an impulse-model calculation and the observed triton momentum distribution, which the authors attribute to the formation of a dibaryon $Y=1$ resonance in the final state with mass around 2095 MeV. However, $\Lambda^0$-hyperon–proton scattering experiments[2] and searches of the $\Lambda^0$-hyperon plus nucleon mass distributions in final states of other reactions[3] show no structure in this mass region. In this letter, we present the momentum spectra of final-state particles from the reaction:

$$K^-+\mathrm{He}^4\to\Lambda^0+\pi^-+p+d,$$

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[*] Present address: Brookhaven National Laboratory, Upton, N. Y.

[‡] Present address: University of Milan, Milan, Italy.

[§] Present address: Queens College, Flushing, N. Y.

[1] H. O. Cohn, K. H. Bhatt, and W. M. Bugg, Phys. Rev. Letters **13**, 688 (1964).

[2] G. Alexander and U. Karshon, paper presented at the Second International Conference on High Energy Physics and Nuclear Structure, Rehovoth, 1967 (unpublished), and references therein.

[3] A. C. Melissinos, N. W. Reay, J. T. Read, T. Yamanouchi, E. Sacharidis, S. J. Lindenbaum, S. Ozaki, and L. C. L. Yuan, Phys. Rev. Letters **14**, 604 (1963); T. Burna, O. Eivindson, O. Skjeggestad, H. Tofte, and I. Vegge, Phys. Letters **20**, 318 (1966).

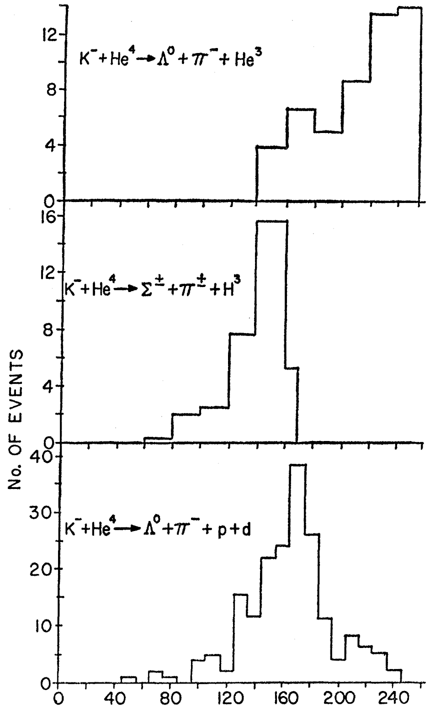

FIG. 1. The $\pi$-meson momentum distributions for reactions involving $K^-$-meson capture at rest in $He^4$ nuclei, (a) for the reaction $K^-+He^4\rightarrow\Lambda^0+\pi^-+He^3$; (b) for the reaction $K^-+He^4\rightarrow\Sigma^\pm+\pi^\mp+H^3$; and (c) for the reaction $K^-+He^4\rightarrow\Lambda^0+\pi^-+p+d$.

which is expected to be dominated by the two-step process[4]

$$\begin{aligned} K^-+\mathrm{He}^4 &\rightarrow (\Sigma+\text{nucleus})+\pi^- \\ &\qquad\qquad \searrow \\ &\qquad\qquad\qquad \Lambda^0+p+d. \end{aligned}$$

The first step involves $\Sigma$-hyperon creation and the second step involves $\Sigma$-hyperon conversion.

We have measured events with the configuration

$$K^-+\mathrm{He}^4\rightarrow\Lambda^0+\pi^-+(1\text{ or }2\text{ heavy tracks})$$

found in 12 000 pictures taken of the 20-cm Northwestern University liquid-helium bubble chamber[5] exposed to a low-momentum-separated $K^-$-meson beam. Many events measured previously for studies[6] of 3-body final states which had been kinematically fitted as such were rejected at this stage.

362 candidates for the channel of interest were found satisfying the following conditions: (1) The $K^-$-meson track must exceed 3 cm in length; (2) the $K^-$ meson must be within one standard deviation of rest at capture as determined by curvature measurement; (3) the $\Lambda^0$-hyperon path length must exceed 2 mm; (4) the $\Lambda^0$-hyperon kinematic fit for emission from the $K^-$-meson capture must be acceptable within the definition of Block *et al.*[7]; (5) the $\pi^-$-meson track projected length must exceed 5 cm.

Kinematic analysis of the primary vertex was performed with the HEGUTS program. The hypotheses considered are:

$$K^-+\mathrm{He}^4\rightarrow\Lambda^0+\pi^-+p+d\,, \qquad (1)$$

$$K^-+\mathrm{He}^4\rightarrow\Lambda^0+\pi^-+p+p+n\,, \qquad (2)$$

and

$$K^-+\mathrm{He}^4\rightarrow\Lambda^0+\pi^-+\mathrm{He}^3. \qquad (3)$$

Tables I and II show the assignments of the 362 candidates between the channels. Table I exhibits the data for events with 2 visible heavy tracks. The assignment "$\Lambda^0\pi^-pd$(unique)" corresponds to a fit for reaction (1) with a $\chi^2$ less than 5.0: The "$\Lambda^0\pi pd$(ambiguous)" assignment corresponds to two fits for reaction (1) with $\chi^2$ less than 5.0. It should be noted that most events including those assigned to reaction (1) give a fit to reaction (2). In the latter cases the fitted neutron direction lies within a few degrees of that of one of the protons, so we regard these fits to (2) as spurious. No attempt was made to fit with $\Sigma^0$-hyperon emission since for the reaction of interest [Eq. (1)] the visible energy release is 152 MeV while for the analogous reaction with $\Sigma^0$-hyperon emission the visible energy release is much lower (75 to 119 MeV). The bracketed numbers refer to events with no unmeasured quantities on the visible tracks, the remaining events have one momentum unmeasured. Table II exhibits the data on events with only one visible heavy track. As before, the numbers in brackets refer to events with all parameters of the visible tracks measured. These events are 1-constraint fits: We are also able to use the fact that the fitted "invisible" recoil must have projected range less than 0.5 mm. The number of "$\Lambda^0\pi^-pd$" assignments in Table II is not highly reliable but must be viewed as

TABLE I. Final-state assignments for 311 events with 2 dark outgoing prongs. The expressions "unique" and "ambiguous" are explained in the text.

| Final-state assignment | No. of events |
|---|---|
| $\Lambda^0\pi^-pd$ (unique) | 138 (105) |
| $\Lambda^0\pi^-pd$ (ambiguous) | 20 (15) |
| $\Lambda^0\pi^-ppn$ | 149 (108) |
| No fit | 4 (4) |

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[4] Helium Bubble Chamber Collaboration Group, in *Proceedings of the 1960 International Conference on High Energy Physics* (Interscience Publishers, Inc., New York, 1960), p. 426.

[5] M. M. Block, W. A. Fairbank, E. M. Harth, T. Kikuchi, C. M. Meltzer, and J. Leitner, in *Proceedings of the International Conference on High-Energy Accelerators and Instruments* (CERN Scientific Information Service, Geneva, 1959), p. 461.

[6] Helium Bubble Chamber Collaboration Group, Nuovo Cimento **20**, 724 (1961).

[7] M. M. Block, R. Gessaroli, S. Ratti, L. Grimellini, T. Kikuchi, L. Lendinara, L. Monari, E. Harth, W. Becker, W. M. Bugg, and H. O. Cohn, Phys. Rev. **130**, 766 (1963).

an estimate which is probably too large.[8] In what follows we consider the examples of reaction (1) *only*.

Figure 1 shows the fitted $\pi^-$-meson momentum distribution for our events and for comparison the momentum distributions observed in the 3-body reactions. Reaction (1) shows a peak at the kinematic limit for $\Sigma$-hyperon reaction. This is consistent with a calculation by Sawicki[9] for reaction (3) when it is dominated by $\Sigma$-hyperon creation and conversion. We feel confident that the reaction channel goes through an intermediate state containing a $\Sigma$ hyperon. To eliminate almost all examples of direct $\Lambda^0$-hyperon production we can reject events with $\pi^-$-meson momenta above 180 MeV/*c*. There remain 143 events. For these we plot in Fig. 2 the momentum spectra of the final-state baryonic particles transformed to the $\Sigma$-hyperon–nucleus rest frame[10] and also the $\Lambda^0$-hyperon–proton effective-mass distribution.

The comparison curves in Fig. 2 are the predictions of impulse-model calculations[11] made assuming that the reaction can be separated into the two steps of $\Sigma$-hyperon creation followed by $\Sigma$-hyperon conversion. This calculation is made for the conversion process only. In such a treatment the observed $\pi^-$-meson momentum distribution becomes the input for the calculation since the $\Sigma^+$-hyperon momentum $k$ in the rest frame of the $\Sigma^+$-hyperon–triton system is directly determined by the $\pi^-$-meson momentum:

$$k^2=\frac{m_t m_\Sigma}{(m_t+m_\Sigma)}\left[2(m_K+m_{\mathrm{He}}-m_\Sigma-m_t-E_\pi+V_\Sigma)-k_\pi^2/(m_t+m_\Sigma)\right],$$

where $m_t$, $m_\Sigma$, $m_K$, $m_{\mathrm{He}}$ are the masses of the triton, $\Sigma^+$ hyperon, $K^-$ meson, He$^4$ nucleus, respectively; $E_\pi$ and $k_\pi$ are laboratory total energy and 3-momentum of the $\pi^-$ meson. $V_\Sigma$ is an effective nuclear potential acting on the $\Sigma$-hyperon when it is formed. This is an important term since estimates of $V_\Sigma$ in medium-weight nuclei are comparable with the energy release in $\Sigma$-hyperon conversion. Following Bhatt *et al.*,[12] the $\Sigma$-hyperon conversion is taken to occur on a single nucleon and the $\Sigma$ hyperon is assumed to be in an *s* state relative to the triton. The comparison curves shown in Fig. 2 are obtained with a square-well potential of radius 2 F. Zero potential is equivalent to the calculation made by Cohn *et al.*,[1] for $\Sigma^-$-hyperon absorption at rest on helium. We can see that even $V_\Sigma=10$ MeV gives a poor fit to the data and, in particular, leads to an unexplained excess of events with $\Lambda^0$-hyperon–proton effective masses in the region 2060 to 2100 MeV.[13] However, the choice of a 37-MeV potential gives a very good fit to the data. The fit is equally good for potential depths several MeV different from this value. The predicted spectra are unaffected by variations in $R$, provided $R$ is greater than about 1.2 F, but the potential required for a fit increases rapidly as $R$ is reduced below 1.2 F. Thus the calculation is insensitive to the shape of the potential tail, and the value of 37 MeV must be looked on as a mean depth for the potential inside a radius of 1.2 F. The volume

TABLE II. Final-state assignments for 51 events with one dark outgoing track.

| Final-state assignment | No. of events |
|---|---|
| $\Lambda^0\pi^-pd$ | 26 (20) |
| Other | 25 (19) |

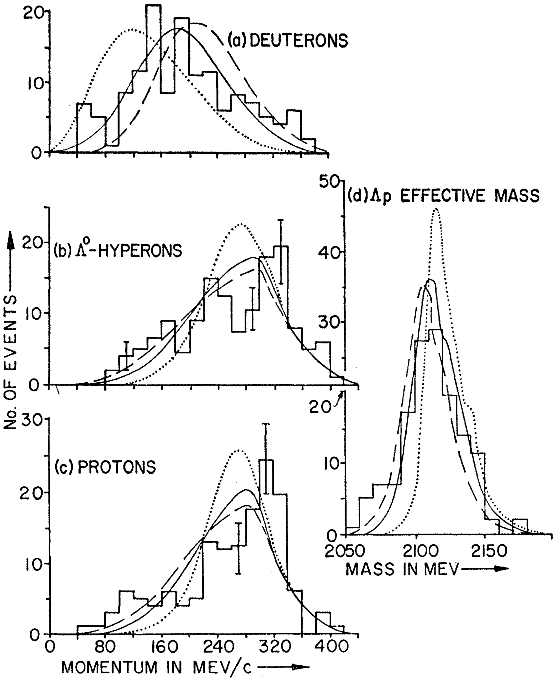

FIG. 2. Final-state momentum and effective-mass distributions for the reaction $K^-+\mathrm{He}^4\rightarrow\Lambda^0+\pi^-+p+d$ where the $\pi$-meson momentum is below 180 MeV/*c*, together with comparison curves from the impulse-model calculation of Ref. 9. The momenta are given in the c.m. frame of the $\Sigma$ hyperon plus nucleus in the intermediate state. Figures 2(a)–(c) show the deuteron, $\Lambda^0$-hyperon, and proton momentum distributions, respectively. (d) shows the $\Lambda^0$-hyperon plus proton effective-mass distribution. The comparison curves are for $\Sigma$-hyperon potentials of 10 MeV (dotted line), 37 MeV (solid line), and 60 MeV (dashed line).

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[8] The entries in Table II are derived from the sample measured at Northwestern University. They need to be scaled by 1.2 when compared to the data of Table I. This correction has been used whenever appropriate.

[9] J. Sawicki, Nucl. Phys. **B1**, 183 (1967).

[10] For the events which are ambiguous between the $\Lambda^0\pi^-pd$ final-state hypotheses the hypothesis giving the lowest value of the deuteron momentum has been used in Fig. 2.

[11] I. R. Kenyon (to be published).

[12] K. H. Bhatt, W. M. Bugg, and H. O. Cohn, Nuovo Cimento **38**, 317 (1965).

[13] The choice of 10 MeV potential and not 0 MeV is dictated by the inclusion of events with $\pi^-$-meson momentum of 170 to 180 MeV/*c* which is above the kinematic limit for free $\Sigma$-hyperon production. With $V_\Sigma=0$ MeV we would have $k^2$ negative for these events.

integral of the potential inside this radius is 265 MeV $\mathrm{F}^3$. For the $_{\Lambda}\mathrm{H}^4$ hypernucleus the corresponding partial volume integral is found to be 232 MeV $\mathrm{F}^3$, using the potential described by Dalitz.[14] Comparison of these two volume integrals shows that our result implies that the $\Sigma$- and $\Lambda$-hyperon–nuclear potentials should have similar strengths. This requirement is now critically examined.

Analyses in terms of simple spin-dependent potentials of elastic $(\Sigma^+,p)$ scattering[15] and of hypernuclear binding energies[16] show that $(\Sigma^+,p)$ well-depth parameters as large as $(\Lambda,p)$ well-depth parameters cannot be excluded. Direct comparison of the elastic cross sections [$\sigma(\Sigma^+p\rightarrow\Sigma^+p)$ is $109\pm23$ mb[17] and $\sigma(\Lambda p\rightarrow\Lambda p)$ is $135\pm20$ mb (Ref. 2) at $\sim$160-MeV/$c$ incident laboratory momentum] indicates the potentials are quite similar, both with weak spin triplet parts. The low-energy $(\Sigma^-,p)$ interaction is strong and dominated by absorption.[2] Helder and de Swart[18] find that in order to fit the parameters of the low-energy $(\Sigma^-,p)$ interactions by a potential model, $g_{\pi\Lambda\Sigma}$ must be comparable to $g_{\pi NN}$. The main contribution to the real part of the effective $(\Sigma,N)$ potential for the isospin-$\frac{1}{2}$ configuration inside a nucleus will come from (a) single-$\pi$-meson exchange without conversion, (b) two-$\pi$-meson exchange via an intermediate virtual $\Lambda$ hyperon plus nucleon state, and (c) $K$-meson exchange. The two-$\pi$-meson and $K$-meson exchanges are generally taken to be the main contributors to the $\Lambda$-hyperon–nucleus potential.[14] We note that the coupling constants involved for two-$\pi$-meson exchange are identical for $\Lambda$ hyperons or $\Sigma$ hyperons [case (b)]: for $K$-meson exchange $g_{K\Lambda N}^2$ is $4.8\pm1.0$, but $g_{K\Sigma N}^2$ is less well known and could be as large as 3.2.[19] It seems likely then that the real part of the $(\Sigma,N)$ effective potential for the isospin-$\frac{1}{2}$ configuration is stronger than the $(\Lambda,N)$ potential and is of longer range while equality of strengths for the isospin-$\frac{3}{2}$ $(\Sigma,N)$ and the $(\Lambda,N)$ effective potentials cannot be excluded. A further consistency check is provided by estimates of the potential felt by $\Sigma$ hyperons inside heavy nuclei. We recall that the value of 37 MeV is a mean central value of the potential depth. By assuming that the $\Sigma^+$-hyperon–triton potential has the same shape as the $_{\Lambda}\mathrm{H}^4$ potential,[14] we obtain an equivalent square-well potential depth ($W_\Sigma$) of around 24 MeV. Oppenheimer and Davis[20] find a value of 15 MeV for the minimum *binding* energy of $\Sigma^-$ hyperons in the nuclei of a heavy-liquid bubble chamber and Capps[21] has estimated, using nuclear-emulsion data, that the $\Sigma$-hyperon–nuclear potential is between 10 and 35 MeV attractive. The value of $W_\Sigma$ found here is quite consistent with these results. Our conclusion is therefore that the departure of the momentum spectra for reaction (1) from the simple impulse-model prediction is due to the initial-state $\Sigma$-hyperon–nucleus interactions which can be represented by a potential well of central depth 37 MeV, and not to a resonance between the final-state $\Lambda^0$ hyperon and proton.

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[21] R. H. Capps, Phys. Rev. **107**, 239 (1957).