Cross Sections for Λ^0 Production by π^- Interactions in Nuclei*

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(Received 19 September 1968)

The total cross sections for Λ^0 production by 925-MeV π^- mesons in Be, C, Al, Cu, and W have been measured. The data suggest a simple production model with cross sections for medium-to-heavy nuclei varying as $(Z/A)A^{1/3}$. For Be, the energy dependence of the Λ^0 yield has been obtained in the region 750–1100 MeV.

I. INTRODUCTION

PHYSICISTS planning experiments on the decays of Λ^0 or K^0 particles and wishing to produce them copiously in $\pi^- p$ collisions are often faced with the choice of employing hydrogen targets or higher-yield nuclear targets (but with the kinematic complication of nucleon internal motion). Unfortunately, there exist no systematic data on the yields of Λ^0 and K^0 particles from nuclear targets. Accordingly, at the close of an experiment studying associated production in hydrogen we inserted a variety of samples (Be, C, Al, Cu, and W) into our apparatus with a desire to obtain yields of Λ^0's in nuclei relative to yields from hydrogen.

Λ^0 particles are produced in π^- interactions with protons by the following processes:

$$\pi^- + p \rightarrow \Lambda^0 + K^0, \quad (1)$$

$$\pi^- + p \rightarrow \Sigma^0 + K^0, \quad \Sigma^0 \rightarrow \Lambda^0 + \gamma. \quad (2)$$

The geometry traditionally employed is that of a target followed closely by an anticoincidence counter. (See Fig. 1.) This geometry selects neutral products such as those of Eqs. (1) and (2) and inhibits reactions with charged secondaries such as $\pi^- + p \rightarrow \pi^- + p$ which have very much larger cross sections.

In the study of Λ^0 production in nuclear targets, this geometry also acts to inhibit the observation of Λ^0's in a variety of ways:

(a) If Λ^0 production is accompanied by fast protons ejected from the nucleus, the protons may enter the anticoincidence counter and veto the event.

(b) Energy loss of the Λ^0 or K^0 by inelastic nuclear collisions produces lower-velocity Λ^0 or K^0 particles. This would result in a larger fraction of these particles decaying before the anticoincidence counter than would be expected for a hydrogen target.

A strong indication that most of the events are heavily inelastic and hence are, indeed, removed by this geometry appears in the work of Kim, Burleson, Kalmus, Roberts, and Romanowski,[1] who studied Λ^0 production in carbon at 1.17 BeV/c. This group measured the energy and momenta of the π, Λ^0, and K^0 and reconstructed the missing mass of the target nucleon. They found that all their events matched the proton rest mass within their measurement accuracy of 50 MeV. The momentum distribution of the protons in the nucleus was roughly what one would expect for carbon. Thus the interaction appears to be with "quasifree" protons.

It is also well known that Λ^0's are produced in $\pi^- p$ collisions in a highly polarized state. Experimenters have also used targets such as carbon and Be to produce Λ^0's and have established that the Λ^0's so produced, again in the typical anticoincidence geometry, are highly polarized.[2]

In this paper we shall show that the cross sections for Λ^0 production are well fitted by a model which leads naturally to the hydrogenlike nature of Λ^0 production in medium and heavy nuclei.

II. APPARATUS

The targets were placed in a triple-focused π^- beam at the Princeton-Pennsylvania accelerator. Figure 2 shows a diagram of the apparatus used to detect the charged-particle decays of the neutral particles Λ^0 and K^0.

Counters C1 and C2 and spark chambers A, B, and C detected the incoming π^- beam. C4, a $\frac{1}{8}$-in.-thick scintillation counter in anticoincidence, selected events which have only neutral reaction products in the target. Spark chambers $WXYZ$ were used to view the charged-particle decays of the reaction products. C3 was a $\frac{1}{16}$-

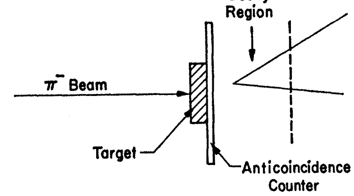

FIG. 1. Typical anticoincidence geometry used for Λ^0K^0 production.

* Experimental work carried out at the Princeton-Pennsylvania accelerator and supported in part by the U. S. Atomic Energy Commission.

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[1] Y. S. Kim, G. R. Burleson, P. I. P. Kalmus, A. Roberts, and T. A. Romanowski, Phys. Rev. **140**, B1655 (1965).

[2] See, for example, D. A. Hill, K. K. Li, E. W. Jenkins, T. F. Kycia, and H. Ruderman, Phys. Rev. Letters **15**, 85 (1965).

TABLE I. Summary of results for various nuclei and beam kinetic energies.

1 Target (cm)	2 Beam kinetic energy (MeV)	3 No. of pictures scanned	4 No. of V's found	5 Pictures/ 10^6 beam particles	6 (No. of V's)/ (10^6 beam particles)	7 R=(No. of V's)/ (10^6 beam particles) −background	8 T	9 f_Σ	10 $K(E)$	11 σ/σ_H (925 MeV)
1.27 Be	750	459	46	10.5±0.6	1.05±0.17	0.97±0.18	0.137	0.0	0.914	0.16±0.03
1.27 Be	850	493	144	17.3±0.5	5.05±0.45	4.63±0.46	0.137	0.0	0.955	0.71±0.08
1.27 Be	925	332	131	28.4±0.5	11.2 ±1.0	10.3 ±1.0	0.137	0.0	1.00	1.51±0.15
0.635 Be	925	309	148	15.0±0.5	7.2 ±0.6	6.3 ±0.6	0.073	0.0	1.00	1.73±0.17
1.27 Be	1025	258	146	39.2±0.7	22.2 ±1.9	20.3 ±1.9	0.137	0.0	1.022	2.89±0.27
1.27 Be	1100	499	176	43.1±0.9	15.3 ±1.2	14.0 ±1.2	0.137	0.0	1.036	1.98±0.17
0.95 C	925	315	136	15.8±0.3	6.83±0.62	5.89±0.63	0.071	0.0	1.00	1.66±0.17
1.27 Al	925	332	140	22.6±0.4	9.52±0.82	8.58±0.63	0.067	0.01	1.00	2.59±0.25
0.71 Cu	925	347	157	28.1±0.6	12.8 ±1.1	11.9 ±1.1	0.0564	0.04	1.00	4.39±0.38
0.476 W	925	340	151	20.6±0.3	9.13±0.75	8.19±0.76	0.0284	0.09	1.00	6.34±0.53
5.08 H_2	925	862	369	16.2±0.4	6.91±0.50	5.97±0.51	0.1195	0.00	1.00	
Target removed	925	373	75	4.7±0.5	0.94±0.12					

in.-thick scintillation counter placed between chambers W and X to detect charged-particle decays and define the decay region. H was a 10-counter hodoscope placed between the spark chamber Z and the 27-gap (70 g cm^{-2}), $\frac{3}{8}$-in. aluminum-plate range chamber. H selected those reaction products which produced two or more charged particles (defined as 2/10). Events which triggered C1, C2, C4, C3, 2/10 were accepted electronically and the spark chambers were pulsed. Chambers *ABC WXYZ* were photographed in two 90° stereoscopic views. In addition, the range chamber was photographed in one of these views with a small-angle stereoscopic view.

III. SCANNING PROCEDURE

The film was rich in V events (~35% of the pictures contained a V). A single scan was made of 3700 pictures (approximately 400 for each measurement) for single-V events. Events were selected with vertices in chamber W (the decay region between counters C4 and C3) and both particles of the V intersecting the hodoscope. The beam direction was nearly parallel to the Z axis, which is the common coordinate between views. Events were accepted as V's if the two tracks met at the same depth along the Z axis in both views within the decay region (chamber W).

Table I shows the results for the various nuclei and beam kinetic energies. Column 3 shows the number of pictures scanned for each sample and column 4 shows the number of V's found. Column 5 shows the trigger rate, i.e., number of pictures per 10^6 beam particles as counted from a coincidence between counters C1 and C2. Column 6, the number of V's per 10^6 beam particles, is obtained from columns 3–5.

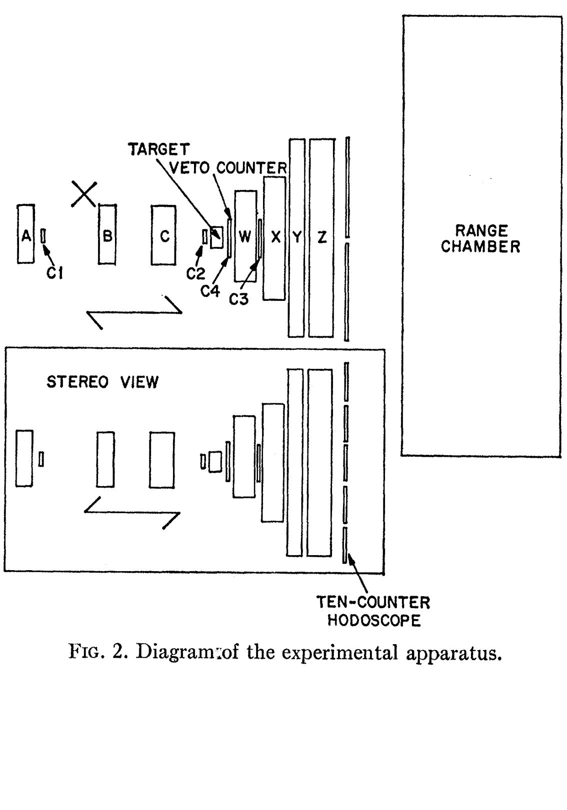

FIG. 2. Diagram of the experimental apparatus.

IV. BACKGROUND SUBTRACTION

A. Rate with Target Removed

Column 7, Table I, shows the correction of the measured rates for the background observed with the target removed. This background was assumed to be due to Λ^0 particles produced in counter C2 or near the upstream edge of the anticoincidence counter, resulting in insufficient light to provide an anticoincidence trigger. The background rate was measured at 925 MeV. (At other beam energies for the Be target, the background rate was assumed to be proportional to Λ^0 production in Be and the correction made by multiplication by a fraction; these corrections were at most 15% at 925 MeV.)

B. K^0 Decays

If the V's were derived from processes (1) and (2), the majority of them would be Λ^0 decays. The detection efficiency for single-V K^0's from the decay $K^0 \rightarrow \pi^+ + \pi^-$ is small because of the short lifetime of the K^0 and the large minimum opening angle between the two pions in this decay. A Monte Carlo calculation showed that the ratio of the detection efficiencies of the decay

$\Lambda^0 \to p+\pi^-$ to the decay $K^0 \to \pi^+ + \pi^-$ was 21:1. In the analysis procedure the V's were assumed all to be Λ^0 decays.

C. Non-Λ^0 V's Produced in the Target

Another possible source of background exists if the amount of non-Λ^0 background is different in the nuclear samples from that in the hydrogen sample. This background was measured as follows: 482 of the V's from the nuclear targets and 157 from the hydrogen target were measured on an MPSΘ digitized measuring machine[3] and reconstructed in the computer program SCRAP.[4] The tracks of the V were assumed to be a proton and a π^-, the proton being identified as the track with the smaller decay angle. (This is true for all Λ^0 momenta produced in this experiment.) The ranges of both particles of the V were measured in the range chamber. Using the particle momenta deduced from their ranges and the measured V opening angle, the mass of the parent particle of the V was calculated from two-body kinematics. Not all of these events are expected to reconstruct so as to yield the Λ^0 mass. If the pion (or proton) interacts in the range chamber before coming to rest, the range, and hence the energy, will be underestimated. Thus we expect a low-energy tail to the mass distribution.

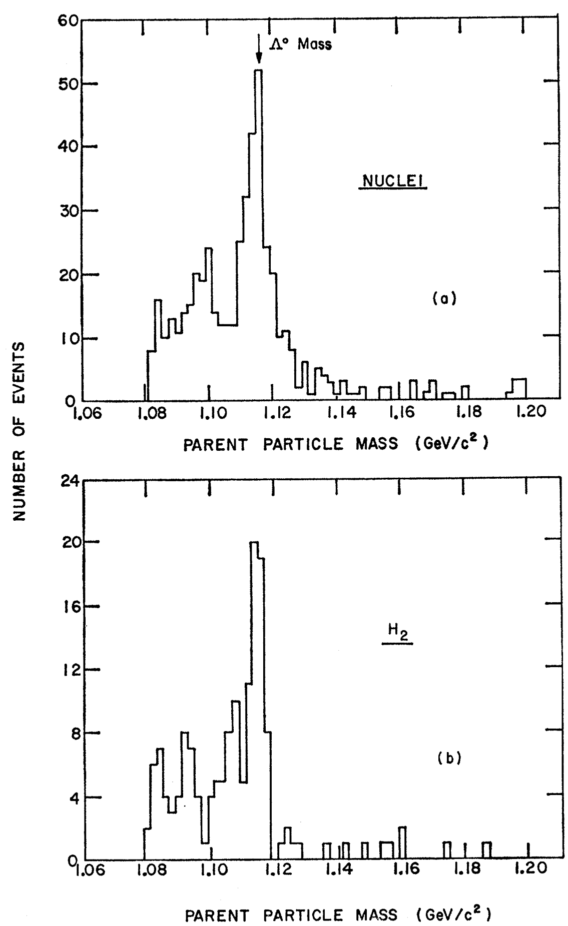

FIG. 3. Distribution of Λ^0 rest mass obtained from event reconstruction using the proton and pion energies measured in the range chamber. (a) Nuclear events; (b) hydrogen events.

[3] Manufactured by Nuclear Research Instruments, Berkeley, Calif.

[4] D. M. Wolfe, University of Pennsylvania Internal Report (unpublished).

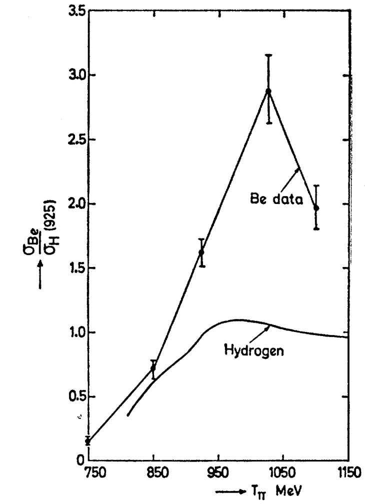

FIG. 4. $\sigma_{\text{Be}}/\sigma_{\text{H}}$ (925 MeV) as a function of pion energy. For comparison the hydrogen cross section (Ref. 7), normalized to 1 at 925 MeV, is plotted.

Figures 3(a) and 3(b) show the distribution of masses for 482 nuclear events and 157 hydrogen events, respectively. The fractions of events in the Λ^0 mass region $1109 < M < 1121$ MeV/c^2 for Figs. 3(a) and 3(b) were $(40\pm2)\%$ and $(41\pm4)\%$, respectively. These two quantities, and the general shape of the distribution, indicate little non-Λ^0 background.

The average Λ^0 asymmetry of the 482 nuclear events in Be was measured and found to be -0.36 ± 0.09. Using the known asymmetry parameter,[5] the average polarization in the energy region studied was found to be 0.56 ± 0.14.

V. CALCULATION OF CROSS SECTIONS FROM Λ^0 YIELDS

The rate of production R of single-V Λ^0's per incident pion from the nuclear target is given by

$$R = N_0 M g T(1-f_\Sigma)\sigma K(E), \tag{3}$$

where N_0 is Avogadro's number, M is a correction factor common to the hydrogen and nuclear yields, i.e., Λ^0-decay branching ratios, beam contamination, g is the solid-angle factor for $\Lambda^0 \to p+\pi^-$ detection, T is the effective thickness of the target times the

[5] O. E. Overseth and R. F. Rothe, Phys. Rev. Letters 19, 391 (1967).

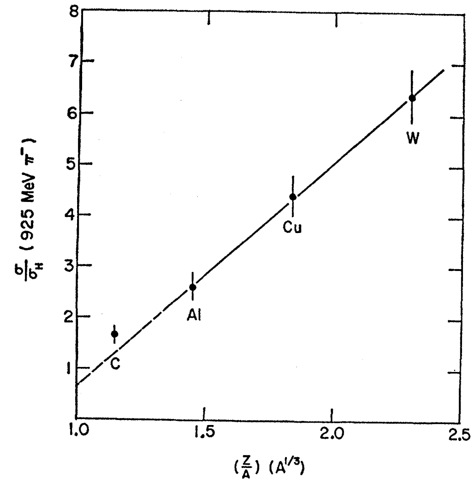

FIG. 5. Cross sections for Λ^0 production in various nuclei at 925-MeV pion energy relative to cross section in hydrogen as a function of $(Z/A)A^{1/3}$.

probability of the Λ^0 decaying in chamber W, f_Σ is the calculated fraction of events in which the γ ray from Σ_0 decay converts in the heavy target, resulting in a veto signal in C4, σ is the cross section for Λ^0 production in the nucleus of atomic mass A by the processes given in Eqs. (1) and (2) and $K(E)=1$ at 925 MeV and is an energy-dependent factor required to normalize the Be cross sections at other energies to the hydrogen cross section at 925 MeV. T in turn may be approximated by

$$T=(\rho\lambda/A)(e^{-x_0/\lambda}-e^{-x/\lambda})(1-e^{-t/\lambda}), \qquad (4)$$

where ρ is the density of the target material of atomic weight A, λ is the mean decay length projected on to the beam direction, x_0 is the distance from the downstream end of the target to the first plate of chamber W, x is the distance from the downstream end of the target to counter C3, and t is the target thickness. For our experiment, $x=(9.67+x_0)$ cm; $x_0=1.75$ cm for all targets except hydrogen and carbon, which were 2.06 and 3.02 cm, respectively.

There are three ratios of cross sections that are of interest in this work: (a) the ratio of cross sections for the various nuclei studied, (b) the ratio of nuclear cross sections to those in hydrogen, and (c) the energy variation of the Be cross section to that in hydrogen at 925 MeV.

In principle, a treatment of "quasielastic" production requires proper incorporation of the Fermi motion of the proton with which the pion interacts in the various nuclei. The following subsections describe how g, T, and $K(E)$ are calculated and to what extent they would be affected by Fermi motion.

A. 925-MeV Data

The solid-angle factor g was investigated at 925 MeV by a Monte Carlo calculation of Λ^0 production from "quasifree" protons of 15-MeV Fermi energy. The Fermi motion decreased g by 5% and it is likely (see Sec. VI) that 15 MeV is an overestimate for the Fermi energy.

T at 925 MeV was calculated from a Monte Carlo calculation for stationary target nucleons. It agreed with the analytic expression (4) to within 1%. Since the approximate expression for T turns out to be insensitive to the mean decay length, varying by less than 10% from $\lambda=4.0$ to 5.5 cm, the effect of Fermi motion on T at 925 MeV should be negligible and was not calculated.

The largest value of f_Σ occurred for tungsten and was 9% for stationary nucleons. This was sufficiently small so that Fermi-motion calculations were not carried out for f_Σ.

B. Be Cross-Section Energy Dependence

$K(E)$ takes into account the variation of g and T with energy. The g energy variation was obtained using a Monte Carlo program for Λ^0's obeying an isotropic decay distribution below 925 MeV and distribution of Ref. 6 at and above 925 MeV. $K(E)$ as seen in Table I, column 10, varied from 0.91 to 1.04 over the whole range of Be data.

Monte Carlo calculation also showed that Λ^0's produced by Σ_0 decays at 925 MeV are detected with approximately 20% higher efficiency than those from direct Λ^0 production. At the highest energy for Be the Σ_0 cross section in hydrogen has increased sufficiently so that this effect could raise the 1110-MeV data by 8%.

We estimate the uncertainty in the *ratios of nuclear cross sections* due to uncertainties in g, T, and f_Σ to be $\pm 6\%$. The ratios of nuclear cross sections to that in hydrogen are less certain, partly because of the effects of Fermi motion, but more because of the large difference in the hydrogen target and nuclear target geometries. We estimate that the ratios σ/σ_H are probably accurate to 10%. The shape of the Be curve depends mainly on the factor $K(E)$ and may have variations of 15% due to the unknown variation of the Λ^0 angular distribution and to effects of Σ_0 production.

Our data for σ_{Be}/σ_H as a function of energy appear in Fig. 4.[7]

The values of T, f_Σ, and $K(E)$ appear in columns 8, 9, and 10 of Table I. The cross sections relative to hydrogen at 925 MeV appear in column 11.

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[6] J. A. Anderson, F. S. Crawford, B. B. Crawford, R. L. Golden, L. J. Lloyd, G. W. Meisner, and L. R. Price, in *Proceedings of the International Conference on High-Energy Physics, Geneva, 1962*, edited by J. Prentki, (CERN Scientific Information Service, Geneva, 1962), p. 270.

[7] See J. E. Rush and W. G. Holladay [Phys. Rev. **148**, 1444 (1966)] for a compliation of Λ^0 production cross sections from hydrogen; R. L. Crolius, V. Cook, B. Cork, D. Keefe, L. T. Kerth, W. M. Layson, and W. A. Wentzel [*ibid.* **155**, 1455 (1967)] for the Σ° cross section from hydrogen. Figure 4 shows the sum of the Σ° and Λ° production cross sections versus pion kinetic energy normalized to the value at 925 MeV.

VI. DISCUSSION OF RESULTS

The most outstanding feature of our data is the small variation in the cross section over a very large range of the mass number A.

We have chosen to display our 925-MeV data as a plot of σ/σ_H versus $(Z/A)A^{1/3}$. This graph is shown in Fig. 5 and shows a linear behavior from aluminum to tungsten, with carbon and Be lying above this curve. For comparison, we have plotted in Fig. 6 some of the 900 total π^- absorption cross sections, σ_{abs}, obtained by Miller[8] in a recent study at the Princeton-Pennsylvania accelerator. We have chosen to display these data as a plot of σ_{abs} versus $A^{2/3}$. Again the data are fitted quite well by a straight line for medium to heavy nuclei, lighter nuclei lying above this curve.

The simplest model yielding $A^{2/3}$ for the total absorption cross sections is one of very strong pion absorption, so that only the goemetric cross-sectional area of the target nucleon would be effective, i.e., $\sigma_{abs}=\pi R^2 =\pi r_0^2 A^{2/3}$, with $R=r_0A^{1/3}$.

One might then expect that hydrogenlike Λ^0 production would only occur in interactions at the periphery of the nucleus, so that the incoming pions or product particles have small probability of strong interactions with the remaining nucleons. This suggests $\sigma/\sigma_H = (Z/A)\delta 2\pi R= (Z/A)\delta 2\pi r_0 A^{1/3}$, where δ is an "effective skin depth" independent of A. The Z/A factor represents the fraction of protons at the nuclear surface (within the accuracy of this crude model the preponderance of neutrons at the surface is not important).

We can evaluate r_0 from the slope of Fig. 6 and extract δ using the slope of Fig. 5. We find $\delta=0.25$ F.

Another feature of our results is the observation that the maximum Be cross section occurs at 1025 MeV, about 50 MeV higher than the energy of the maximum cross section in hydrogen.

We conclude with the following remarks:

(a) The increase in Λ^0 or K^0 yield with A is much slower than hitherto believed (in fact, the yield per cm of material in the typical anticoincidence arrangement is no greater for tungsten than for copper).

[8] Edward S. Miller, Princeton-Pennsylvania Accelerator Report No. PPAD 630F 1967 (unpublished).

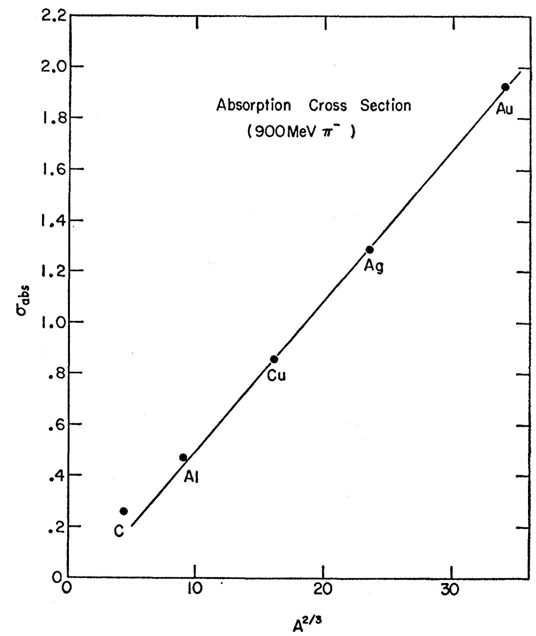

FIG. 6. The π^- absorption cross section in various nuclei as a function of $A^{2/3}$ (data of Ref. 8).

(b) The model that we have advanced makes the observed "hydrogenlike"[1] production of Λ^0's and K^0's produced in nuclei plausible.

(c) The model also suggests that Fermi-model calculations for strange-particle production must be carried out cautiously, since it is the motion of a restricted set of the surface nucleons only that must be used in the calculations.

ACKNOWLEDGMENTS

We should like to thank Dr. D. M. Wolfe for his valuable help on Monte Carlo calculations. We should like to thank Mrs. M. C. Takats, G. Kouroupas, H. Siegal, B. Zichy, and our scanning team for their assistance in the performance of this work. We should also like to thank all the staff of the Princeton-Pennsylvania accelerator, who helped us in this series of experiments.