Λ^0 Production in Nuclei*

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Nuclear cross sections for Λ^0 production are interpreted in terms of production by pion-nucleon and nucleon-nucleon interactions.

CURRENT information concerning the Λ^0 particle[1] is drawn largely from studies of its production in the heavier nuclei. If the existing evidence for the similarity of the Λ^0-N and N-N interactions ($N\equiv$nucleon) is accepted,[2] it becomes possible to deduce from the data on nuclear production some characteristics of Λ^0 production in elementary π-N or N-N collisions. The present note reports on a calculation designed for this purpose, in which the Λ^0, produced at a point in the nuclear interior, and moving in the conventional nuclear potential well of some 25 Mev, is followed by Monte Carlo methods through a succession of nucleon collisions until it emerges from the nucleus or its kinetic energy falls below 25 Mev; in the latter event it is regarded as captured.

The results provide estimates of the fraction of Λ^0's captured in nuclei of various sizes (Fig. 1; Table I), the initial energy distribution of Λ^0 particles at production (Fig. 4), and the relation between nuclear cross sections for Λ^0 production and the cross sections for production in π-N or N-N collisions (Tables I, II).

The calculation refers specifically to Λ^0 production in the 1.5-Bev π^- beam available at the Brookhaven cosmotron. However, the nature of the primary particle enters principally in the value assumed for its total cross section in nuclear matter; in the Bev region this is roughly the same for pions and nucleons and insensitive to energy changes, hence the results should apply to nucleon primaries also, at energies of a few Bev.[3]

It is assumed that the nuclear interactions of the incident pion may be represented by the π^--p cross section. The magnitude of $\sigma(\pi^-,p)$ at 1.5 Bev is 33 mb,[4] composed of 70 percent inelastic and 30 percent elastic scattering, the latter confined within 30° in the laboratory system.[5,6]

The nucleus is described by the plane projection of a spherical distribution of nuclear matter. The circular area of the projection is divided into 35 zones in Pb and 20 zones in C, in each of which a fraction of the incident pion beam interacts, determined by the cross-sectional area of the zone and the attenuation of the beam in passing through the nuclear region above.

The subsequent history of an interaction is followed by Monte Carlo techniques. The pion may scatter elastically or inelastically, with respective weights 0.3 and 0.7, and elastically scattered pions are pursued until they suffer an inelastic scattering or leave the nucleus. The elastic angular distribution is represented by the assignment of weights 0.3, 0.4, and 0.3 to the angles −15°, 0°, and 15°, respectively.

It is assumed that a Λ^0 of given initial kinetic energy is produced in each inelastic pion scattering. The pion is regarded as energetically incapable of Λ^0 production after an inelastic scattering and is not considered further. The newly created Λ^0 is followed through collisions with nucleons up to the point of escape or capture. A crude description of Λ^0-N scattering was presumed adequate for the present purpose: the Λ^0 is assigned the measured n-p cross section, taken as isotropic, for its interaction; the internal motion of the nucleons is represented by a division of the

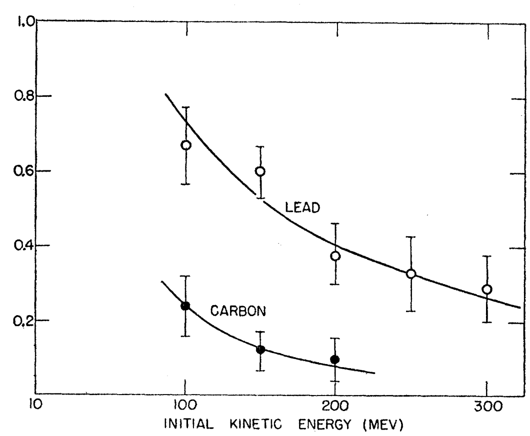

FIG. 1. Fraction of Λ^0's captured in the nucleus, *vs* T, the initial kinetic energy of the Λ^0.

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[1] $\Lambda^0\rightarrow p+\pi^-+37$ Mev, with a lifetime of 3×10^{-10} second.

[2] Light nuclear fragments emitted from cosmic-ray stars have been observed to disintegrate spontaneously under circumstances indicating the decay of a Λ^0 bound in the fragment, and in a few favorable cases it has been possible to deduce the binding of the Λ^0, assuming the Q of its decay to be 37 Mev. [Ciok, Danysz, and Gierula, Nuovo cimento **11**, 436 (1954); C. F. Powell, Nature **173**, 469 (1954).] The results are of the order of 0–5 Mev of binding, and suggest that the interaction of the Λ^0 with nuclear matter is comparable to, but somewhat weaker than, that of the nucleon.

[3] Primaries of greater energy can produce additional particles—pions and knock-on nucleons—having sufficient energy for Λ^0 production.

[4] Cool, Madansky, and Piccioni, Phys. Rev. **93**, 249 (1954).

[5] Crussard, Walker, and Koshiba, Phys. Rev. **94**, 736 (1954); **95**, 852 (1954).

[6] R. P. Shutt (private communication). (1.4 Bev.)

Fermi circle (a projection of the Fermi sphere) into 5 zones; and the scattered Λ^0 is permitted to emerge in one of 4 states, corresponding to scattering angles of 0°, ±90°, and 180° in the center-of-mass system of the Λ^0 and recoiling nucleon. Collisions which leave the nucleon within the Fermi circle are voided; however, the exclusion principle is not applied to the Λ^0.

Initial kinetic energies of 100, 150, 200, 250, and 300 Mev were assumed for production in Pb, and 100, 150, and 200 Mev for C, the trend of the results indicating that nuclear capture and secondary interactions were unimportant above these energies. A total of 175 pion interactions were followed in C, and 435 in Pb.

The resulting yields of Λ^0's must be multiplied by the probability, assumed $\ll 1$, for Λ^0 production in a single π-N collision.

FRACTION CAPTURED; ENERGY AND ANGLE DISTRIBUTIONS

Figure 1 indicates the fraction of Λ^0's captured in C and Pb, as a function of T, the initial kinetic energy of the Λ^0. The variation with T is rapid, and some knowledge of the actual distribution of initial energies is needed for an estimate of the mean capture probability.

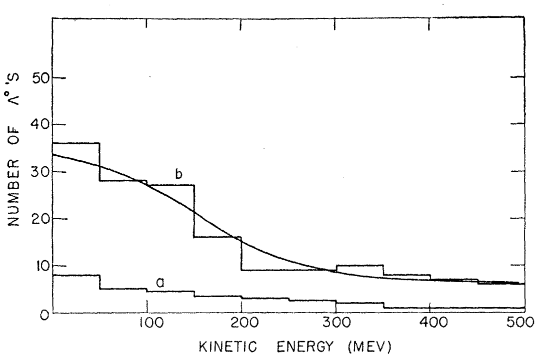

FIG. 2. Distribution of Λ^0 kinetic energies: (a), observations of the Princeton group (see reference 3); (b), compilation from several sources (see reference 3, 8–10).

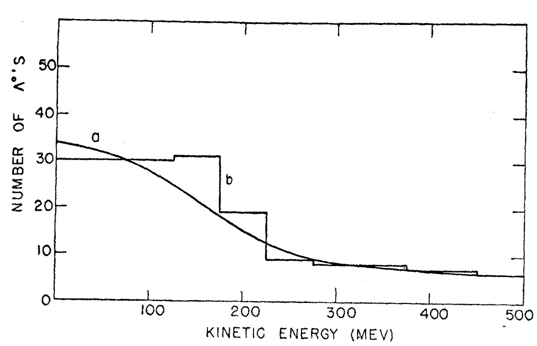

FIG. 3. Comparison of observed and calculated Λ^0 spectra. (a) Observed spectrum, from Fig. 2(b). (b) Calculated spectrum of emerging Λ^0's, weighted over T according to Fig. 4.

Information concerning the initial energy distribution may be obtained from a comparison of the observed spectrum with the calculated spectrum of Λ^0's emerging from Pb, which also depends strongly on T. Although the spectra associated with individual values of T are far from the observed spectrum, a composite distribution in fair agreement with experiment may be obtained by adding suitably weighted contributions from all values. The assignment of relative weights constitutes the desired T-distribution.

The Λ^0 spectrum seen in cosmic ray events by the Princeton group[7] is shown in Fig. 2(a), and a compilation of data from this and other sources in Fig. 2(b).[8–10]

Figure 3 presents the calculated composite distribution of emerging Λ^0's, (3b), compared with observation, (3a); the spectrum of initial Λ^0 energies required to obtain (3b) is given by Fig. 4.[11] Table I lists the fraction captured, averaged over the T distribution of Fig. 4.

The distribution of angles between the line of flight of the Λ^0 and the direction of the primary is generally observed to be strongly forward. Figure 5(a), for example, gives the angular distribution of 10 Λ^0's

TABLE I. Cross sections for Λ^0 production by 1.5-Bev π^- mesons ($\alpha=0.03$).

	(a) Captured (mb)	(b) Emerging[a] (mb)	(c) Mean fraction captured[a]
C	0.6	5.8	0.10
Cu	8.5	13.5	0.39
Ag	15.7	17.3	0.48
Pb	27.2	23.8	0.54

[a] Averaged over initial Λ^0 energy according to Fig. 4.

reported by Fretter *et al.*,[9] with a mean angle of 35°. In the Monte Carlo calculations, initial angles of ±30° were assigned to the Λ^0 at production; the resultant angular distribution of emerging Λ's, weighted over T according to Fig. 4, is shown in Fig. 5b.

CROSS SECTIONS

The nuclear cross sections for Λ^0 production are proportional to the probability, α, for Λ^0 production in a single interaction of the primary with a nucleon. They are given in Table I for $\alpha=0.03$, referring to incident 1.5-Bev π^- mesons, for which cross sections are observed of approximately 1 mb for Λ^0 production[12] and 33 mb for total interaction.[4] The listed Ag and Cu cross sections were obtained by interpolation, assuming a power law for the variation with atomic number: $\sigma=kA^m$, with k and m derived from the values for Pb

[7] Ballam, Harris, Hodson, Rau, Reynolds, Treiman, and Vidale, Phys. Rev. **91**, 1019 (1954).
[8] Leighton, Wanlass, and Anderson, Phys. Rev. **89**, 148 (1953).
[9] Fretter, May, and Nakada, Phys. Rev. **89**, 168 (1953).
[10] Bridge, Peyrou, Rossi, and Stafford, Phys. Rev. **91**, 362 (1953).
[11] The range above 300 Mev is taken directly from Fig. 3a.
[12] Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **93** 861 (1953).

and C. We find for total production [columns (a) plus (b)], $\sigma=1.02A^{0.74}$, and for emerging Λ^0's, $\sigma=1.68^{0.50}$.[13]

The corresponding interpretation of Λ^0 yields by nucleon primaries in terms of (direct) N-N production is complicated by the existence of an alternative (indirect) process, *viz.*, creation of a fast pion by N-N collision and subsequent Λ^0 production by a π-N interaction in the same nucleus. The Z dependence of the yields may differentiate between these alternatives, as noted by Reynolds,[14] because indirect production requires a greater thickness of nuclear matter than direct, and will contribute little in light nuclei. This expectation is verified by Table II, in which the cross sections for direct and indirect production are compared for several nuclei. These were obtained by assuming all particles to travel forward, reducing the computation to a succession of simple integrations. Nuclear Λ^0 capture was represented by a Λ^0 absorption or capture cross section of 20 mb,[15] and the additional refinement of a nonuniform profile of nuclear density was introduced,[16] the direct/indirect ratio in carbon being appreciably affected by the increased transparency of the diffuse boundary. The collision cross sections employed were appropriate to π-N and N-N events at Cosmotron energies.

TABLE II. Production of Λ^0 particles by nucleons: (a) by direct N-N interaction; (b) by pion intermediaries. Listed are the ratios of nuclear cross sections for Λ^0 production to elementary cross sections for Λ^0 production by an N-N interaction [column (a)], or a π-N interaction [column (b)].

	Direct (a)	Indirect (b)
C	5.6	0.12
Cu	12.9	0.64
Pb	27.0	1.34

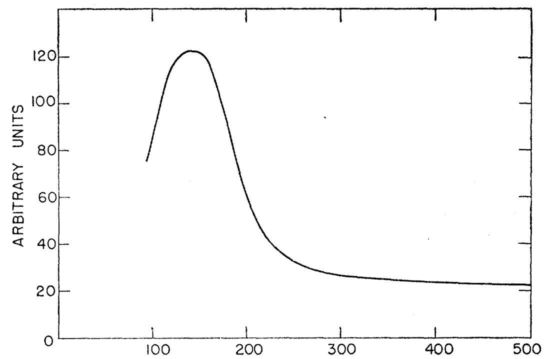

FIG. 4. Distribution of initial Λ^0 energies.

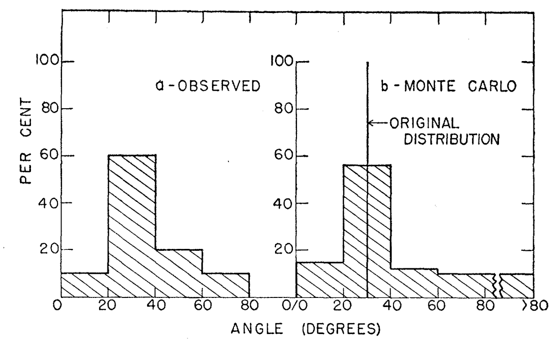

FIG. 5. Λ^0 angular distribution. (a) Fretter *et al.* (see reference 9). (b) Calculated distribution of Λ^0's emerging from Pb.

As in the Monte Carlo calculations, the nuclear yields are proportional to the cross section (σ_0) for Λ^0 production in an elementary π-N or N-N interaction.[17] Table II gives the ratios of nuclear to elementary cross sections; these ratios represent the effective numbers of nucleons contributing to Λ^0 production.

Power law approximations to Table II yield: $\sigma/\sigma_0=2.00Z^{0.47}$ (direct); $\sigma/\sigma_0=0.011Z^{0.92}$ (indirect).

A cross section of $\sim$1 mb has been reported[18] for the Λ^0 yield from Pb placed in the forward neutron beam of the cosmotron, of maximum energy 2.2 Bev. Table II(b) indicates that this value may be attributed entirely to indirect production if a cross section of 0.5 Mb, consistent with observations of Fowler *et al.*,[12] is assumed for π-N production of Λ^0's. On the other hand, if Walker's Λ^0's originated directly in N-N interaction, II(a) indicates a corresponding cross section of 0.02 mb for N-N Λ^0 production averaged over the 1–2 Bev region.

[13] The frequency of emission of an unstable nuclear fragment (one containing a Λ^0) may be estimated from these cross sections and observations on disintegrations produced by 2 Bev protons: For the majority of unstable fragments observed, $Z\geq3$. We note a cross section of $\sim$10 mb for production of Be^7 by 2-Bev protons on Ag [Baker, Friedlander, and Hudis, Phys. Rev. **95**, 612 (1954)], and estimate 50 mb for the production of all fragments with $Z\geq3$. The angular distribution of the Be^7 nuclei is strongly forward, suggesting direct ejection as the production mechanism, rather than evaporation. If the fragments are directly ejected, Λ^0's contained therein must have been created in the interaction causing the ejection. The probability (P) for unstable fragment emission is then the product of the chance for Λ^0 production among the neutrons of the fragment by the chance for its ejection from the nucleus. For Ag($\sigma_{\mathrm{geom}}=1370$ mb) we have (Table I), $P=4\times(15.7/1370)\times(50/1370)=1:400$. The observed frequencies of emission are lower: 1:1000 for cosmic-ray primaries and 1:1500 for 3-Bev proton primaries (J. Fry, private communication).

The cross section for tritium emission from Ag at 3 Bev is perhaps 200 mb [300 mb in Pb; W. F. Libby (private communication)], indicating a frequency of 1:70 for excited triton production by the previous arguments, whereas few excited tritons are actually seen. It is possible that the Λ^0-N bond is too weak for formation and ejection of an unstable triton.

[14] G. T. Reynolds, Proceedings of the Fourth Annual Rochester High-Energy Conference (University of Rochester Press, Rochester, 1954).

[15] An absorption cross section of 20 mb represents the Λ^0 capture process to the extent of yielding a fraction absorbed (i.e., captured) of $\sim$0.5 in Pb, in agreement with the Monte Carlo result of Table I(c).

[16] R. Jastrow and J. Roberts, Phys. Rev. **85**, 757 (1952).

[17] The cross sections for indirect production are also proportional to the probability for creation of a fast pion by N-N collision, which we estimate as 0.03 for pions of momentum greater than 1.5 Bev/c, from the work of Fowler, Shutt, Thorndike, and Whittemore on n-p interactions at $\sim$1.8 Bev [Phys. Rev. **95**, 1026 (1954)].

[18] R. W. Walker, dissertation, Yale University, 1954 (to be published).