Inelastic Scattering of a Σ^- Hyperon with an Emulsion Nucleus

H. E. FISK AND D. J. PROWSE
Physics Department, University of California, Los Angeles, California
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During a systematic study of fast hyperons resulting from the nuclear capture of K^- mesons, an event has been found which is interpreted as the elastic scattering of Σ^- hyperon by a bound neutron. The reaction kinematics are insufficient to determine the nature of the nuclear potential for Σ^- hyperons but it appears that when about 10 of these events have been found and analyzed, it will be possible to infer the sign of the potential from the general effect it will have on the observable kinematics of the events.

DURING a systematic study of fast baryons resulting from the capture of K^- mesons by emulsion nuclei, an event has been found which we interpret as an inelastic scattering of a Σ^- hyperon with an emulsion nucleus. A number of examples of a similar process involving Σ^+ hyperons have previously been reported[1–3] and there are also a number of unreported examples which have recently been analyzed at UCLA. The event reported here, however, appears to represent the first identifiable example of a Σ^- hyperon scattering from a nucleon within a nucleus.

There are four possible channels for a Σ^- hyperon

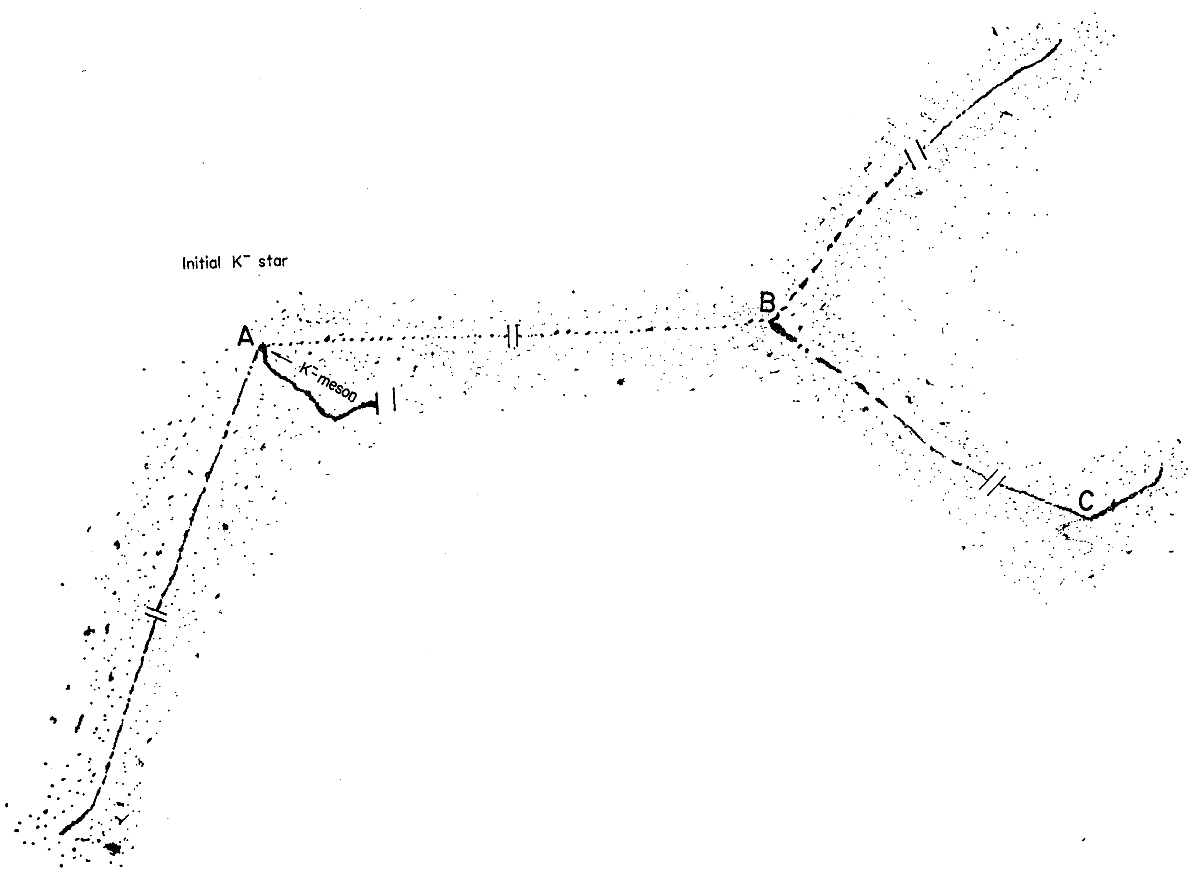

FIG. 1. A drawing of the event projected onto the emulsion plane. The original K^--meson capture star is at A. Two particles are emitted, a proton and a Σ^- hyperon which interacts at B. The hyperon re-emerges and comes to rest at C, producing a typical capture star of one prong and an Auger electron.

[1] W. F. Fry, J. Schneps, G. A. Snow, and M. S. Swami, Phys. Rev. **100**, 939 (1955).
[2] R. G. Glasser, N. Seeman, and G. A. Snow, Phys. Rev. **107**, 277 (1957).
[3] D. H. Davis, B. D. Jones, and J. Zakrzewski, Nuovo cimento **14**, 265 (1959).

interacting with a nucleon:

$$\Sigma^- + n \rightarrow \Sigma^- + n, \tag{1}$$

$$\Sigma^- + p \rightarrow \Sigma^- + p, \tag{2}$$

$$\Sigma^- + p \rightarrow \Sigma^0 + n, \tag{3}$$

$$\Sigma^- + p \rightarrow \Lambda^0 + n. \tag{4}$$

The first two represent elastic scattering and the last two, reaction processes. These latter reactions are very frequent in K^--meson capture stars, as commonly the Σ^- hyperons produced by the K^--meson capture process have a very low energy and react in the same nucleus to form Λ^0 hyperons.[4] Little is known about the relative channel widths of the four interactions listed above at higher energies such as occur when the K^- meson reacts with two or more nucleons at a time. It is thus impossible to estimate whether the event described here should be rare compared with a reaction producing a Λ^0 hyperon which would commonly go undetected in emulsion.

It is likely that the event is the result of a single Σ^- interaction because successive elastic collisions are unlikely in the face of a large reaction cross section.

A drawing of the event is shown in Fig. 1. The parent K^--meson capture star (A) consists of two prongs, the Σ^- hyperon and a proton of 6 Mev. The hyperon itself is identified as such because it re-emerges from an interaction and comes to rest, producing a well-identified one-prong capture star. Confirmatory information comes from scattering versus blob density measurements made on the track. These indicate a mass of 1176$\pm$200 Mev and an energy at emission of 172$\pm$15 Mev. The hyperon travels through 5 emulsion pellicles and interacts a distance of 1.15 cm from the parent star at point (B). Two prongs emerge; one is identified as a proton of 23 Mev, and the second comes to rest after a range of 1.92 mm and gives rise to a one-prong star. The particle pronounced in this capture star is probably an alpha particle; it has a range of 29.6 μ and hence an energy of 6.5 Mev. The possibility of the capture star being a single scattering event is ruled out because of the very marked change in track thickness at the interaction. The thickness of the emergent prong is a factor of two greater than the thickness of the Σ^--hyperon track, despite the fact that this track is the flatter of the two. In addition there is the track of an Auger electron present.

The energy of the hyperon after its interaction in flight is 22.7 Mev. The energy before the interaction, obtained from blob density determinations along the track, is 155$\pm$15 Mev. The energy lost is therefore 132$\pm$15 Mev. The angle through which the hyperon was scattered is 39°, and a proton is emitted at an angle of 51° to the incident Σ^--hyperon direction. This proton is unlikely to be the collision partner of the hyperon be-

[4] European Collaboration, Nuovo cimento 14, 315 (1959).

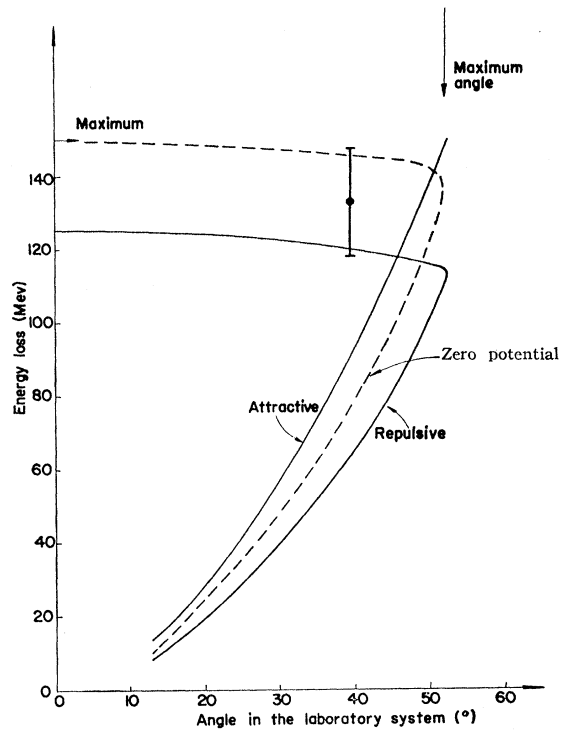

FIG. 2. Kinematic curve for the scattering of 150-Mev Σ hyperons from free nucleons showing the energy loss of the hyperon plotted against the scattering angle in the laboratory system. The dashed line is for zero potential for the hyperon in the nucleus, and the full lines are for 25-Mev repulsive and attractive as labelled.

cause its energy is much too low. It is probable that a neutron was first involved which knocked on the proton in escaping the nucleus. The energy loss expected for a hyperon of this energy (150 Mev) is shown plotted against the laboratory scattering angle for a *free* collision in Fig. 2. Because the incident particle is the heaviest, there is a cutoff in laboratory angle beyond which no scattering is possible. Angles greater than this may be expected to occur, both on account of the Fermi momentum of the struck particle and on account of refraction at the nuclear boundary. Although extreme values of the Fermi momentum can give rise to points far removed from the central line shown in Fig. 1, it is likely that any deviation from the free kinematics would be systematically increased by the existence of a potential for the hyperon in the nucleus. A double scattering (two successive elastic scatterings) can give rise to a change in the ΔE value, or nuclear refraction can modify the true scattering angle. A double scattering is very unlikely, however, in view of the reaction channel available to the Σ^- hyperon which is probably wide. Curves computed for attractive and repulsive potentials of 25 Mev are shown in Fig. 2; it is clear that a number of events could distinguish between attractive and repulsive potentials. An attractive potential for the Σ^- hyperon is expected from an analysis of hyperon spectra from

K^--meson capture stars.[5] We are continuing our search and analysis in the hope that this might be confirmed by a trend of ΔE values larger than those expected from free scattering for a given scattering angle in the forward center-of-mass hemisphere.

[5] I. E. MacCarthy and D. J. Prowse, Nuclear Phys. **17**, 96 (1960).

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Demonstration of Quantum Mechanics in the Large*

T. B. Day
University of Maryland, College Park, Maryland
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An example is given which demonstrates in a straightforward and dramatic manner that when two particles like $(K^0+\bar{K}^0)$ or (2γ) are created simultaneously, the probabilities involved in observing any further events related to their simultaneous creation must be calculated quantum mechanically and are correlated, even for macroscopic distances in absorbing media. In particular, a correlation in the polarization of the two γ rays from positronium annihilation as a function of the thickness of magnetized iron through which they are passed is pointed out by way of a proposed experiment.

RECENTLY, Lee and Yang pointed out a striking effect of quantum mechanics in the large.[1] The effect bears on the objections raised by the Einstein-Rosen-Podolsky paradox,[2] and is yet another facet of the fascinating neutral K-meson system.

We amplify on Lee's remarks as follows. Consider first the creation of a K^0 (or $\bar{K}^0$) meson at some point. If we move some distance from the point of creation such that $\tau_1 \ll t \ll \tau_2$, where τ_1 and τ_2 are the lifetime, respectively, of the K_1^0 and K_2^0 meson and t is the time of flight, then we expect that the probability of observing a regenerated K^0 (or $\bar{K}^0$) meson will be $\sim\frac{1}{4}$.[3] Now consider the *simultaneous* creation of two neutral K mesons, say K^0 and $\bar{K}^0$, which move off in opposite directions. Then we ask the question: given that we see a $\bar{K}^0$ meson downstream at a time of flight t_a in one direction, what is the probability of observing in coincidence another $\bar{K}^0$ meson downstream at a time of flight t_b in the opposite direction? One is tempted to answer, according to the ideas of reference 2 (and of classical physics, for large t_a, t_b) that if $\tau_1 \ll t_a, t_b \ll \tau_2$, then again we should see a $\bar{K}^0$ meson at t_b with probability $\sim\frac{1}{4}$. But as Lee points out, this is not so!

When the $(K^0, \bar{K}^0)$ pair are created, they are, in general, created in a mixture of eigenstates of the charge conjugation operator with eigenvalues $C=\pm1$.[3] Thus, the initial wave function describing one neutral meson moving in direction a, and one in the opposite direction b is (for $C=-1$)

$$\psi_{\text{in}}=\frac{1}{\sqrt{2}}[|K_a^0,\bar{K}_b^0\rangle-|\bar{K}_a^0,K_b^0\rangle]. \tag{1}$$

When this wave function is rewritten in terms of the K_1^0 and K_2^0 eigenfunctions appropriate for decay, and then allowed to propagate down directions a and b, we get (for $m_{1,2}$ equal to the mass of K_1^0, K_2^0)

$$\psi_{\text{fin}}=\frac{i}{\sqrt{2}}[|K_2^a,K_1^b\rangle\exp(-\lambda_2t_a-\lambda_1t_b) \\ -|K_1^a,K_2^b\rangle\exp(-\lambda_2t_a-\lambda_2t_b)], \tag{2}$$

where $\lambda_{1,2}=(2\tau_{1,2})^{-1}-im_{1,2}$. If this is re-expressed in terms of the K^0 and $\bar{K}^0$ eigenfunctions, and then the probabilities of making various coincidence measurements at times t_a and t_b are computed, we find (for $C=-1$)[4]

$$P(K_a^0,K_b^0)=P(\bar{K}_a^0,\bar{K}_b^0)=\tfrac{1}{8}|\exp(-\lambda_2t_a-\lambda_1t_b) \\ -\exp(-\lambda_1t_a-\lambda_2t_b)|^2,$$
$$P(K_a^0,\bar{K}_b^0)=P(\bar{K}_a^0,K_b^0)=\tfrac{1}{8}|\exp(-\lambda_2t_a-\lambda_1t_b) \\ +\exp(-\lambda_1t_a-\lambda_2t_b)|^2. \tag{3}$$

* Supported in part by a National Science Foundation grant.

[1] T. D. Lee and C. N. Yang, reported by T. D. Lee at Argonne National Laboratory, May, 1960 (unpublished).

[2] A. Einstein, B. Podolsky, and N. Rosen, Phys. Rev. **47**, 777 (1935); D. Bohm and Y. Aharanov, Phys. Rev. **108**, 1070 (1957).

[3] R. H. Dalitz, *Reports on Progress in Physics* (The Physical Society, London, 1957), Vol. 20, p. 229; M. Gell-Mann and A. H. Rosenfeld, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Palo Alto, California, 1957), Vol. 7, p. 407; A. Pais and O. Piccioni, Phys. Rev. **100**, 1487 (1955).

[4] The analysis for $C=+1$ is similar, and we get

$$P(K_a^0,K_b^0)=P(\bar{K}_a^0,\bar{K}_b^0)=\tfrac{1}{8}|\exp(-\lambda_1(t_a+t_b)) \\ -\exp(-\lambda_2(t_a+t_b))|^2,$$
$$P(K_a^0,\bar{K}_b^0)=P(\bar{K}_a^0,K_b^0)=\tfrac{1}{8}|\exp(-\lambda_1(t_a+t_b)) \\ +\exp(-\lambda_2(t_a+t_b))|^2.$$

In this case, we get no zero probabilities (except at the origin). As Lee pointed out, this difference in behaviors between $C=+1$ and $C=-1$ may, in principle, be utilized to determine in what mixture of eigenstates the $K^0-\bar{K}^0$ pair is created.