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ABSTRACT

In the "pre-accelerator years," when large stacks of emulsion were exposed to cosmic rays at high altitude, three events were found in which K^- mesons were emitted from slowly moving particles. The Ω^- is the only presently known particle that can give rise to a K^- when moving at non-relativistic speed, but none of the three events has until now been clearly identified as an Ω^-. One of the cosmic ray events (Eisenberg, 1954) has been incorrectly interpreted as an Ω^- decaying in flight; it is now shown to be an interaction in flight of an Ω^- with a silver nucleus. The second event is a clear-cut example of an Ω^- decaying in orbit, bound to an emulsion nucleus. The third event is quite complicated, but can be unambiguously attributed to the decay of an Ω^- atomically bound to an N^{14} nucleus, followed by a collision of the daughter Λ with the N^{14}, in which the compound system then framents into ${}_{\Lambda}C^{13}$ + p + n. The mass of the Ω^- as determined by each of the last two events (Fry, et al, 1955) agrees closely with the mean of all bubble chamber events.

I. Introduction

In 1962, when Gell-Mann[1] predicted the properties of the Ω^-, including its unique decay mode into a K^- meson, three cosmic ray events were known[2,3,4] that could most easily be explained by the decay of a heavy hyperon into a K^- meson. The hyperon masses calculated from the two cleanest events (Eisenberg, and Fry No. 2) differed by about 50 MeV, when the errors could scarely have been more than 2 MeV in either case. The third event (Fry No. 1) was complicated by a pair of related "evaporated prongs" that made the interpretation unclear, and the mass apparently uncertain by about 20 MeV.

Many high energy physicists believed that the Eisenberg particle was an Ω^- decaying in flight into $K^- + \Lambda$; it is still so listed in the latest Particle Data Group's tabulation.[5] The two Fry events have been largely forgotten or ignored; at least the present author is unaware of any critical analyses of these events as possible Ω^- events.

The study was undertaken to ascertain if all three event could be explained in terms of known particles, or if some new particle or process was required. (If something new were needed, this study could have made an accelerator search more meaningful.) It will be shown that:

1. The Eisenberg particle is difinitely not an Ω^- that decays in flight; it is an Ω^- that interacts in flight with a silver nucleus, giving the reaction

$$\Omega^- + Ag \rightarrow K^- + \Xi^0 + Ag \qquad (1)$$

2. Fry's second event is a very clean example of the decay of an Ω^- at, or nearly at rest. Fry concluded that the hyperon had come to rest, in which case its mass would be 1670.6 ± 1 MeV. If we

allow the Ω^- to have the momentum characteristic of a circular orbit with n = Z = 6, 7, or 8, its mass, as determined by the energy of the K^-, is consistent with that of Fry No. 1 and the mean of all Bubble Chamber Ω^-'s. (1672.5 ± 0.5 MeV).

3. Fry's first event is the decay of an Ω^- that is atomically bound to a N^{14} nucleus. The Λ from the decaying Ω^- then initiates the reaction: $N^{14} + \Lambda \rightarrow {}_{\Lambda}C^{13} + p + n$. The fit to this complicated reaction is highly constrained, as will be shown later, and there can be little doubt that the assignment has been correctly made. The ${}_{\Lambda}C^{13}$ hyperfragment subsequently decays via the reaction: ${}_{\Lambda}C^{13} \rightarrow \pi^0 + n + C^{12}$, leaving no visible stub. This event gives a value for the Ω^- mass that is more accurate than most single bubble chamber events: $M_{\Omega^-} = 1672.1$ MeV. With the aid of hindsight, it seems probable that had the Eisenberg event not been observed, the two Fry events would have been correctly used as a confirmation of the SU(3) prediction. The true Ω^- mass would then have been known two years before the Ω^- was unambiguously discovered in both production and decay modes, by the Brookhaven Bubble Chamber group[6] in 1964. But the apparent simplicity of the Eisenberg event, when incorrectly interpreted as a decaying Ω^-, led to the confusing situation that is resolved by the following analyses.

II. The Eisenberg Event

In 1954, Eisenberg[2] found an unusual event in nuclear emulsion exposed to cosmic rays at 100,000 feet. He interpreted it as the decay in flight of a heavy negatively charged hyperon into a K^- meson plus an unobserved neutral particle, most probably a Λ. He estimated the kinetic energy liberated in the decay to be very nearly 5 MeV, which

yielded a mass of 1625 for the heavy hyperon.

In 1962, when Gell-Mann[1] predicted the properties of the Ω^- from the measured properties of the $\Delta(1238)$, $\Sigma(1385)$ and $\Xi(1530)$, his estimate of the Ω^- mass was 1685 MeV. In view of the uncertainty in the mass of the newly discovered $\Xi(1530)$ and in the validity of the untested rule of "constant mass difference" between members of an SU(3) decuplet, the predicted mass of the Ω^- could easily have been as high as 1691, the calculated value for Eisenberg's particle if it had the postulated strangeness of -3 and a decay through the reaction:

$$\Omega^- \rightarrow \Sigma^0 + K^- + 5 \text{ MeV} \qquad (2)$$

In view of the remarkable agreement between the predicted properties of the Ω^- and the observed properties of Eisenberg's particle, the latter was widely believed to be a ready-made confirmation of the SU(3) predictions. (In fact 1691 MeV is closer to Gell-Mann's prediction than is the actual Ω^- mass.) In announcing his prediction, Gell-Mann said, "Perhaps it would explain the old Eisenberg event." Also, when the Ω^- was discovered at Brookhaven,[6] the Eisenberg particle was mentioned in a footnote as follows: " A possible example of the decay of this particle was observed by Y. Eisenberg."

The most recent compilation of the Particle Data Group[5] lists the Eisenberg particle as the first observed Ω^-. However, in order to make the assignment credible, the mass error is arbitrarily increased several fold to 25 MeV, and even so, the Eisenberg particle's (decay-derived) mass is 2 standard deviations from the measured Ω^- mass. (The relatively close fit between the predicted Ω^- properties and those of the Eisenberg particle, mentioned earlier, is no longer relevant since the Ω^- is known to be not massive enough to decay via the

$\Sigma^0 + K^-$ channel.)

Since the mass of the Ω^- is now known from about 30 bubble chamber events to be 1672.5 ± 0.5 MeV, we can look at the Eisenberg particle in a new light, and ask the question, "Can this particle be explained as an Ω^- decaying in flight?" As will now be shown, the answer to this question is an unequivocal, "No." That conclusion then leaves one in the interesting position of having an apparently clear-cut example of the decay of a heavy hyperon never seen at an accelerator laboratory. Eisenberg estimated the energy of the primary particle responsible for the "star" in which his particle was produced to be about 30 GeV so we can hardly ascribe its non-appearance in the laboratory to "insufficient beam energy." The non-appearance of the (improperly interpreted) Eisenberg particle in the laboratory has therefore been a largely unrecognized paradox, which is now resolved below.

III. Proof that the Eisenberg Particle is not an Ω^- Decaying in Flight

Figure 1a is a schematic drawing of the Eisenberg event. The track from A to G is an unambiguous K^- meson which comes to rest at C and makes a large "star." The 10° bend in the track from B to C appeared at first to indicate the scatter of a K^- emitted from the primary star at B; there was no apparent change in grain density, although a measurement later showed that the grain density might have decreased by 10% (velocity increased by 5%) at the point A. The bend at A was given significance when Eisenberg showed that while the mean scattering from A to C was consistent with that of a K meson, the mean scattering from B to A was less than that of a K meson, by 11 standard deviations, and consistent with that of a hyperon. Since the velocity change at A was so small, the Q of the decay was evaluated directly from the

transverse energy of the K^- in the center of mass system, that gave rise to the 10° bend. On the assumption that only one neutral particle was emitted in the decay, the Q was found to be about 5 MeV, regardless of the mass of the neutral, which had to be baryonic to explain the scattering measurements.

We now attempt to fit this event to the decay of an Ω^- at A. The measured range from A to C is 2.19 cm, so the K^- had a laboratory energy of 62.5 MeV and a laboratory β of 0.461 when emitted at A. In the C. M. of a decaying Ω^-, the β of the K^- is 0.393. The β of an Ω^- that would decay into a (forward) K^- of the observed range is then nearly the difference between 0.461 and 0.393, or actually 0.0824. Such a particle would appear as a "black track" in nuclear emulsion and quite obviously different from the "3 times minimum" grain density of the K^- track. This qualitative discrepancy constitutes the first element in the proof that the Eisenberg particle is not an Ω^- decaying in flight with the ejection of a K^- in the forward direction, as Eisenberg believed it to be.

There is still the possibility that the hyperon could have been going fast enough to eject the kaon almost backward. The required β of the Ω^- is then, ignoring the 10° deflection: $\beta_{\Omega^-} = 0.723$. To show that such a high value of β is not compatible with the measurements made by Eisenberg, we can examine his second figure, reproduced here as Figure 1b. Rather than calculate the expected grain density for a track made in Eisenberg's emulsion by a particle with a $\beta = 0.723$, we will simply note that Eisenberg also plotted grain density vs. residual range for pions; this is the diagonal line at the bottom left hand corner of Figure 1b. Since grain density is a function only of β, and not of the mass of the particle making the track, we can note the values of β corresponding to 4 marked points on Figure 1b. The following numbers have been added to Eisenberg's figure: A kaon with a 1 cm residual range has $\beta = 0.379$, a kaon above the arrow at A has $\beta = 0.461$, a pion with 1 cm range has $\beta = 0.517$, and a pion with 1.5 cm range has $\beta = 0.564$. All points inside the graph then refer to particles with values of β from about 0.35 (at the top edge) to about 0.58 (at the bottom edge). Therefore, if track BA were made by a particle with $\beta = 0.723$, the three points identified by the bracket near the right center of the diagram as K_1 would have been moved downward and off the bottom edge of the diagram. This second qualitative discrepancy completes the proof that track BA is not an Ω^- decaying in flight.

IV. Identification of the Eisenberg Particle as an Ω^- Interacting in Flight

The "fast reaction"

$$\Omega^- + \text{nucleus} \rightarrow \Xi^0 + K^- + \text{nucleus} \qquad (3)$$

has an energetic threshold, ignoring momentum conservation, when $E_T(\Omega^-) = M_{\Xi^0} + M_{K^-}$. Such a "threshold-$\Omega$" has a kinetic energy of 136.0 MeV. Since an additional 62.5 MeV is visible in the K^- at point A, the threshold kinetic energy for reaction (3) in the Eisenberg emulsion, again ignoring momentum conservation, is 198.5 MeV. The energy of an Ω^- at A, assuming its velocity to be that of the K^- at A, is 211.7 MeV, which is 13.2 MeV above the threshold for reaction (2). If one takes the Ω^- velocity to be Eisenberg's favored value of 95% of the K^- velocity, its corresponding kinetic energy is 187.4 MeV, which is 11.1 MeV below threshold. But since Eisenberg said explicitly that there was no significant velocity change at A, we can assume β_{Ω^-} to be 0.4605, the known value for a K^- with its measured range. Reaction (2) can then proceed, if we can find a way to absorb the excess momentum of

the incident Ω^-, without requiring the expenditure of much kinetic energy. Fortunately, we can solve the energy and momentum mismatch by invoking the aid of a heavy nucleus such as one of silver or bromine. Such invocation also solves the final problem, which can be expressed as, "How does one hide the dead body?" This latter reference is to the track of a charged particle that took up the missing momentum, or to the track of a residual nucleus from which a neutron had been knocked to balance the momentum vectors. Perhaps the main reason that Eisenberg assumed his heavy hyperon was decaying rather than interacting was that no "blob" or "stub" appeared at point A. For the heavy recoiling nucleus to be invisible in the emulsion, it must make a "track" with a range less than 0.5μ, the diameter of a single grain; this condition is met in the analysis below.

In Figure 2, we see the visible momentum vectors, p_{Ω^-} and p_{K^-}, with values of 867.7 and 256.2 MeV/c, respectively. The magnitude of the momentum vector required to close the triangle is 617.0 MeV/c. Table I lists 5 ways in which the available 13.2 MeV can split between the K.E. of a Ξ^0 and of a silver nucleus. In each case, the momenta of the two particles are tabulated, as well as the sum of their absolute values. The overall reaction can satisfy both the momentum and energy conservation laws for any entry in which the sum of the absolute values of the Ξ^0 and nuclear momenta is greater than the missing 617.0 MeV/c; Table I shows that the conservation laws can be satisfied if the kinetic energy given to a heavy nucleus is greater than 1.0 MeV. (A similar table was constructed for a "shared kinetic energy" of 7.5 MeV, rather than the 13.2 MeV of Table I. The minimum kinetic energy given to the Ag nucleus to satisfy momentum conservation was thereby raised only to 1.185 MeV. This calculation shows that one can allow the β of the

Table I

Kinetic energy of Ξ^0 + Ag = 13.2 MeV

T_{Ag}(MeV)	T_{Ξ^0}(MeV)	p_{Ag}(MeV/c)	p_{Ξ^0}(MeV/c)	$p_{Ag} + p_{\Xi^0}$(MeV/c)
0.9	12.3	425	180.3	606
1.0	12.2	448	179.6	627
1.1	12.1	470	178.4	648
1.2	12.0	491	177.6	669
1.3	11.9	511	176.9	688

Ω^- to be less than that of the K^-, and still account for the event via equation 3.) The range of a 1.25 MeV Ag ion in nuclear emulsion is less than 0.5 micron, so such an ion should make at most one developable grain.[7] (Although a Br nucleus could take up the required momentum, it would probably have shown up as a "blob"; any emulsion nucleus lighter than Br is ruled out on two counts: 1) if it had the required momentum it would surely have made a track - - 2) not enough energy is available to give the required momentum to such a light nucleus.)

One can therefore conclude that the Eisenberg particle was an Ω^- interacting in flight with a silver nucleus according to equation 3, and the first Ω^- to have been seen. The interaction could involve either a single neutron or proton on the surface of the silver nucleus, or it could involve the nucleus as a whole. Although one can say with certainty that the mass of the Eisenberg particle is now consistent with that of the Ω^-, it does not seem useful at this late date to try to assess the mass error that might have been assigned to it had it been originally correctly identified as an interacting Ω^-.

V. General Discussion of the Two Fry Events

Figure 3 shows the rather complex "First Fry" event,[3] and Figure 4 shows the exceedingly simple "Second Fry" event.[4] In each of these events, a "stopped heavy particle" emits a negative K meson with very nearly the energy we would now expect to see from an Ω^- decaying at rest. Fry, Schneps and Swami[4] conclude their second article with these remarks: "It is interesting to note that the kinetic energy of the K-meson in this event (42 MeV) is nearly the same as in the previously reported event (43 MeV). It is possible that these two events are due to the same unstable particle." Again, with the aid of hindsight, we can conjecture that if the first Fry event had not been complicated by the improbable secondary interaction of the Λ, the two events would have been recognized as the decay at rest of the same negatively charged hyperon with a mass of 1672 MeV. Had that been the case, the famous Brookhaven Ω^- of 1964 would merely have confirmed for the third time the existence of Gell-Mann's predicted particle.

We may now ask, "Is there any significance to the fact that the K^- mesons in the two Fry events have energies slightly different from the expected 43.26 MeV?" For Fry's 42 and 43 MeV Kaons, the $\Delta\beta$'s relative to the canonical 43.26 MeV Kaon from an Ω^- at rest are .0051 and .0011 respectively. The characteristic β for an Ω^- in the n^{th} circular orbit about a nucleus with atomic number Z is

$$\beta = \frac{\alpha Z}{n} = 0.0073\frac{Z}{n} \tag{4}$$

Since Wiegand[8] observed Σ^- X-rays from atomic orbits with n = Z = 6, 7, 8, the $\Delta\beta$'s observed in the two Fry events are interpretable as "Doppler shifts" in the decay of Ω^-'s in atomic orbits about carbon, nitrogen or oxygen nuclei.

A second important question concerns the probability of decay of an

Ω^- in atomic orbit about a C, N or O nucleus. Particle physicists have an intuitive feeling that with the exception of the muon, negative particles have a negligible probability of decaying at rest, or when atomically bound to a nucleus. Since the two Fry events are being interpreted as decays of Ω^- hyperons under such circumstances, it is appropriate to counter such intuitive notions at this time. There are two independent experimental measurements of the "cascade time" for a K^- in the field of a helium nucleus, and one for the cascade time of a Σ^- hyperon in emulsion. Block, et al.[9] found $C_{K^-, He} = (2.4 \pm 0.4) \times 10^{-10}$, after Day[10] had predicted a very much shorter cascade time, invoking some of the "Stark mixing" that had played such an important role in the analysis of $K^- + p$ and $\overline{p} + p$ events. Bunnell et al.[11] repeated the measurement of $C_{K^-, He}$ for K^- in helium, using only the easily identifiable 3π decays of the K^-, and found $C_{K^-} = (3.2 \pm 0.5) \times 10^{-10}$ sec. Although there is no simple formula to convert measured cascade times of K^- in helium to predicted cascade times for Ω^- in nitrogen, it was concluded in the first draft of this paper (before the Σ^- data were known) that the cascade time of the Ω^- in nitrogen could be as short as 10^{-12} sec without causing any difficulty in explaining the existence of two Ω^- decays "at rest". Now that the magnitude of the Σ^- cascade time has been measured in emulsion[12] by Tovee et al. to be $C_{\Sigma^-, em} \lesssim 10^{-12}$ sec., we can use this value, without extrapolation, as the cascade time for the Ω^- in emulsion.

We now ask how many Ω^- hyperons should have been produced in emulsion during the years before the large accelerators took over from the cosmic rays, and the bubble chambers later displaced the emulsion stacks as hunting grounds for new particles. No Ω^- hyperons have yet been brought to rest in liquid hydrogen bubble chambers, but two such

occurrences in nuclear emulsions can explain the events discussed in this paper. This disparity can be resolved in terms of three differences between the two media. Bubble chamber Ω^- productions have all been initiated by high energy negative kaons. The high energy is needed because two kaons of positive strangeness must be produced along with the Ω^-, and the interaction takes place on a free proton. The C. M. velocity is therefore high, so the produced Ω^- has a range in liquid hydrogen long compared to its "decay length." In emulsion, the two stopped Ω^- particles of Fry were produced on heavy nuclei (many heavy prongs from the primary stars), and by neutral primaries. Each of these departures from bubble chamber practice can contribute to the production of an Ω^- with an energy low enough to permit stopping in the much denser emulsion, before decay can take place.

The two Fry events were most probably produced in heavy nuclei via the reaction

$$\Xi^0 + n \to \Omega^- + K^+. \qquad (5)$$

Since we start with -2 units of strangeness rather than the -1 of the bubble chamber negative kaons, we need less CM energy to produce one rather than 2 kaons of positive strangeness. Secondly the heavy nucleus is available to absorb the momentum of the incoming particle, so the outgoing Ω^- can have any laboratory energy greater than zero. In fact, in Fry 1, the Ω^- has a range of only 9 microns, so its laboratory energy was only 1 MeV. In Fry 2, the Ω^- had a range of 44 microns, or an energy of 2.8 MeV.

To return to an estimation of the probable number of Ω^- particles produced in the "emulsion years", we make use of some "educated guesses." The cosmic ray exposure of emulsion probably amounted to several thousand liter-days. To estimate the number of events of a particular kind, we must know the energetic threshold, since the number of cosmic rays above a given energy falls as $E^{-1.6}$. We also need the effective cross section, including the contributions from all secondary interactions -- the two Fry events were produced by neutral secondaries.

If we use an effective cross section of 1 microbarn, and a threshold of 10 BeV, we expect 25 events per litter day. So, with exposure of 4000 liter days, (Eisenberg[13] estimated 5-10,000) we would predict that 10^5 Ω^- particles were produced. It is therefore not surprising that $2\Omega^-$ decays at rest were observed, given the earlier evidence that the cascade time for Σ^- in emulsion atoms is of the order of the Ω^- life-time divided by 200. Fry[17] estimates that in his study, "about 300,000 high energy interactions were observed, so perhaps it is not too improbable to have found the two events." The present author looks at the matter of probabilities in the following way: from the volume of emulsion scanned in the early 1950's, one would have been more surprised if an "Eisenberg-like particle", and a decay from orbit, "a la Fry No. 2" had not been found. If one adopts this view that these two events were to be expected, then he is left with at most a single "improbable" event. In the later discussion, it will be argued that no conclusions can be drawn from this single event, so long as its properties were not catalogued before it was seen.

VI. The Second Fry Event

In view of what has been said so far, the interpretation of this event is simply that an Ω^- made in a heavy nucleus by a Ξ^0 slowed down and then cascaded into an atomic orbit of relatively low Z and n, and decayed. The velocity of the Ω^- in its atomic orbit is reflected in a slight departure of the observed negative kaon's kinetic energy (42 MeV) from the

canonical 43.3 MeV. Fry suggested as one possibility that his particle was a hyperon with mass greater than 1475 MeV, its mass if the neutral decay fragment were a neutron. If we assume the neutral to be a Λ and assume that the Ω^- is decaying at rest, we obtain an Ω^- mass equal to 1670.6, in excellent agreement with the "world average"[5] of 1672.5 MeV.

VII. The First Fry Event

Figure 3 is a projection drawing of "Fry No. 1." (The observed tracks are shown projected normally onto the plane of the microscope stage.) A neutral primary (probably a Ξ^0) produces a multipronged star, from which a short black track emerges. This track 1 "exhibits all the characteristics of the last few microns of a stopped nuclear particle. We conclude that the particle stopped or was of very low velocity."[3]

From the end of track 1, three tracks emerge. Track 2 is a proton, deuteron or triton, with a range of 583 microns. We shall assume that the track was made by a proton with an energy of about 10 MeV; the event cannot be explained in terms of an Ω^- (or any other known particle) if track 2 was made by a deutron or triton. Track 1 is too short to be identified by any measurement confined to that track itself. We shall identify it as a recoiling ${}_{\Lambda}C^{13}$, from the reaction:

$$\Lambda + N^{14} \rightarrow {}_{\Lambda}C^{13} + p + n \qquad (6)$$

and show that this particular assignment is the only possible one, consistent with track 1's observed behavior, plus the highly constrained nature of the whole series of measurements made by Fry, et al.

To return to Figure 3, track 3 is identified by Fry, using four different criteria, to be a K meson; since no decay particle is visible at its end, it is assumed to be negatively charged. Its measured kinetic energy (from its range) is 43 MeV; the C. M. kinetic energy of a K^- from a decaying Ω^- is 43.26 MeV. The coincidence of these two energy values plus the fact that the Ω^- is the only known particle that can give rise to a kaon, when moving slowly, strongly suggests that Fry No. 1 involves an Ω^- decaying "at rest".

The probability that the Λ from the decaying Ω^- in Fry No. 1 should strike the nitrogen nucleus, giving tracks 1 and 2 in Figure 3 is small, as we shall now see. But the appearance of a single rare event is not a cause of real concern to an experimentalist, if its rare characteristics have not been specified in detail before it shows itself. For example, no one suggested that anything was wrong with the first Brookhaven Ω^-, even though both γ-rays from the π^0 converted in the hydrogen.[6] Each γ-ray converted after traversing about 1 foot of liquid hydrogen, which has a radiation length of about 30 feet. So the probability of this signature showing in the first Ω^- decay observed in only about 10^{-3}. It will be shown later that the probability of the Λ striking the N^{14} nucleus in Fry No. 1 is about 4×10^{-3}. Davis[15] notes that the chance of a K^- stopping without making a visible star is 0.05, the chance that the orbit is about a N nucleus is 10^{-1}, and the chance that a ${}_{\Lambda}C^{13}$ decays without a visible track is about 1 in 15. If we were to ask the probability that a particular Ω^- event would give the particular signature seen in Fry number 1, it would be correct to multiply all these probabilities together. But probability theory is of no help to a person who is analyzing a single peculiar event that (1) turned up, as a "zoon", in an extensive area search of 300,000 "nuclear stars", (2) that was described in a special communication because it was so extraordinary, and (3) that has a straightforward (even through improbable) explanation

in terms of the known laws of physics.

In order to explain tracks 1 and 2, we must introduce a nucleus into the event. If this nucleus were involved in the actual decay, one would not expect the K^- to have its canonical decay energy of almost 43.3 MeV; a calculation of this energy value involves the recoil of the K^- against a free Λ. However, the Ω^- must have been very close to the nucleus at the time of decay, so it was no doubt bound in a "Bohr orbit" about the nucleus. The argument here is that the energy needed to break up the nucleus must have come from the recoiling Λ; the K^- retains all its canonical energy. As an illustrative example, the chance that a Λ would strike a nitrogen nucleus that was one Angstrom away is of the order of 10^{-9}. But if the Ω^- is bound in a circular orbit about a C, N or O nucleus, the probability that the Λ collides with the nucleus is greatly increased. For an Ω^- in the n^{th} circular orbit about a nucleus, the probability of collision is proportional to n^{-4}. Wiegand who has seen Σ^- X-rays from light atoms, estimates that Ω^- hyperons "should survive down to n = 4 or 5 in nitrogen, assuming that the Ω^- and Σ^- interact equally strongly with nuclei."[8] The probability that an Ω^-, decaying in the n = 4 circular orbit around a nitrogen nucleus will yield a Λ that subsequently strikes the nucleus is about 4×10^{-3}. (The elimination of C and O from the last sentence will be justified on energetic grounds in the next paragraphs.)

We will now calculate the energy and momentum balances in such a collision, and show that there is only one possible solution that fits the measured properties of the secondary star at the end of the Ω^- track. The Λ (from an Ω^- at rest) has a kinetic energy of 19.8 MeV, so we must use no more than this amount of energy in 1) breaking up the nucleus, 2) giving the observed 10 MeV of kinetic energy to the proton, (track 3), 3) giving kinetic energy to whatever it is that makes the short stub (track 2), 4) giving some finite kinetic energy to the recoiling Λ, (or to a recoiling neutron, if a hyper-fragment rather than an ordinary nucleus is the heavy residual nucleus), and 5) conserving overall momentum and energy. It is not difficult to show, after adding and subtracting an appropriate sample of masses of the isotopes,[14] that there is no energetically possible solution of the form:

$$\Lambda + 19.8\ \text{MeV} + Z^{A} \rightarrow p + X + Z'^{A'} + \Lambda, \qquad (7)$$

where X might be the p, d, t, He^3 or He^4, showing as the "short stub," for any constituent of nuclear emulsion, if we add the required kinetic energies (from the measured ranges of tracks 1 and 2) to the right hand side of equation (7). The two silver isotopes come close, but still do not satisfy equation (7) with the emission of an α particle. All other possibilities are excluded by large energy imbalances.) This statement takes no account of any extra energy that might have to be given to some nucleus, in order to balance momentum; such additional energies make it "more impossible" to satisfy equation (7).

We can reduce the energy that is expended in breaking up a nucleus by having it come apart into two pieces, one of which shows as the "short stub," rather than into the three fragments shown in equation (7). The reaction would then be

$$\Lambda + 19.8\ \text{MeV} + {}_{Z}A \rightarrow p + {}_{(Z-1)}(A-1) + \Lambda. \qquad (8)$$

When the first draft of this paper was sent to interested physicists, the only secondary reaction that fitted equation (8) was shown to be

$$\Lambda + N^{14} \rightarrow \Lambda + p + C^{13}. \qquad (9)$$

But it was pointed out that this reaction could only fit the projection drawing of Fry et al[3], if those authors had made a siginificant error in the

direction of the 3μ long "stub", which was identified as the track of the C^{13} recoil; Fry et al had tentatively labeled it as an alpha particle. The 3μ length of the stub fitted reaction (11), but the constraints of the conservation laws were so tight that the fit was not possible if the direction of the stub had been drawn correctly. Although the original pellicules had been lost, Professor Fry[16] described his technique of making the projection drawing, and it was apparent that the stub could not have been misdrawn. This immediately killed the only reaction candidate the present author deemed even marginally acceptable. But at the moment of this impasse, Dr. D. H. Davis[15] asked why the Λ recoiled after initiating the secondary reaction; it seemed much more probable to him that the Λ would remain bound to the heavier nucleus, turning it into a hypernucleus.

The present author had not previously considered the possibility of hypernucleus formation, since no decay particle or recoil stub was seen at the end of the 3μ-long track. But spurred by Davis' remark, the following reaction was investigated:

$$\Lambda + N^{14} \rightarrow {}_{\Lambda}C^{13} + p + n. \qquad (10)$$

This reaction differs from (9) simply by the interchange of a Λ for a neutron bound to the C^{12} core, and a neutron for a Λ as one of the two elementary particles on the right hand side of the equation. It can easily be shown on energetic grounds that this reaction type could take place on N^{14}, but not on either C^{12} or O^{16}, so in the more likely event that the 3μ-long track was a hyperfragment, it could only be ${}_{\Lambda}C^{13}$. Davis' suggestion that the reaction might be of the type

$$\Lambda + N^{14} \rightarrow {}_{\Lambda}C^{14} + p \qquad (11)$$

was untenable, since the recoiling neutron was needed to provide the momentum to align the hyperfragment with the direction shown in Fry's drawing; in the absence of a neutron, the three tracks -- K^-, proton and ${}_{\Lambda}C^{14}$ would have to be coplanar.

The reason that reaction (10) can fit Fry's event, whereas the very similar reaction (9) cannot follows directly from the relative binding energies[14, 18] of ${}_{\Lambda}C^{13}$ and C^{13}. The Λ in ${}_{\Lambda}C^{13}$ is bound by 11.3 MeV, whereas the neutron in C^{13} is bound by only 5 MeV. The extra 6 MeV availabe to the neutral recoil particle (n rather than Λ) can contribute an impluse of 100 MeV/c, and that was the momentum missing in the earlier attempt to fit Fry's event, without "changing the drawing".

To make reaction (10) fit the drawing, the ${}_{\Lambda}C^{13}$ would have to decay via the reaction

$$ {}_{\Lambda}C^{13} \rightarrow \pi^0 + n + C^{12} \tag{12}$$

with the Λ decaying almost as a free particle into two neutral particles, sharing little of the available momentum with the C^{12} nucleus. A more detailed discussion of the probability and kinematics of this decay will be given later.

Reaction (10) was then fitted to Fry's drawing, subject to additional constraints, beyond those of the tabulated energies, momenta, ranges and projected (azimuth) angles of the three tracks shown in figure 3. Even though the original emulsion plates no longer exist, the present author found two statements by Fry, one in reference 3, and the other in a later review paper,[17] that permit the polar angles of the three tracks to be reconstructed with rather small error. These additional constraints on the event, soon to be described ruled out reaction (9) as being responsible, with absolute certainty.

VIII. Fitting the first Fry Event to three successive reactions.

The sequence of events to be fit to the first Fry event is the following:

$$\Omega^- \rightarrow K^- + \Lambda, \tag{13}$$

$$\Lambda + N^{14} \rightarrow {}_{\Lambda}C^{13} + p + n, \tag{14}$$

$$ {}_{\Lambda}C^{13} \rightarrow \pi^0 + n + C^{12} \tag{15}$$

The Ω^- is the only particle known to give rise to a K^- meson when moving slowly; an Ω^- making such a black track as this must produce its K^- by decay, with a c.m. energy of 43.3 MeV. Fry's first event shows a heavy particle moving very slowly (most probably stopped in the emulsion) and emitting a K^- meson with an energy of 43 MeV. (In Fry's paper, all energies are given to the closest integral number of MeV, so the agreement between the observed and expected K^- energy is perfect.) So by two separate tests, the first reaction is shown to be an Ω^- decaying "at rest".

The "evaporation prongs" in figure 3 will now be fitted to equation (14), making use of the following constraints.

a) The energy, momentum and direction of the Λ is known from the observed K^- direction, plus the decay kinematics of the Ω^-. Fry's projection drawing shows only the azimuthal direction, ϕ, of a recorded particle, and gives no information concerning its polar angle, θ. But in the first Fry event, the K^- track is so long (12,200μ) and is seen in only 5 pellicles (600μ thick), that it and its oppositely directed Λ can be considered to be in the equatorial plane; $\theta = 90°$.

b) The exact masses of all the particles in reaction (14) are known,[14, 18] as well as the kinetic energies of Λ, p and ${}_{\Lambda}C^{13}$. The proton and ${}_{\Lambda}C^{13}$ energies are known from their tabulated ranges. By subtraction, the sum of the kinetic energies of the neutron and ${}_{\Lambda}C^{13}$ are determined.

c) One might think that no information was available on the polar angles of the proton and the $_{\Lambda}C^{13}$ tracks, but fortunately that is not the case. In their article, Fry et al[3] say, "The residual momentum of the three charged particles "(K^-, proton, and recoil)" is about 200 MeV/c if one assumes that the recoil particle is an alpha particle and track 2 is a proton track". With this constraint added to the observation that the K^- is "flat", one can easily show that the proton track must be emitted almost vertically; the polar angle of the proton must be between 0 and 15°, so the plane containing the Λ and proton momenta must be tipped almost vertically with respect to the plane of the pellicles. The polar angle of the $_{\Lambda}C^{13}$ track is not so accurately determined, but it must be in the hemisphere opposite to that of the proton, and close to 135°. It is thus seen that Fry's observation concerning the residual momentum of certain tracks permits the polar angle, as well as the azimuthal angle of all tracks to be determined within reasonable limits.

d) As indicated in b) above, we know the sum of the kinetic energies of the neutron plus the $_{\Lambda}C^{13}$. The kinetic energy of the $_{\Lambda}C^{13}$ is known from its range of 3μ. (This range is never mentioned explicitly, but since the "recoil" was assumed by Fry to be an alpha particle with an energy of 0.8 MeV, we can find its range from an alpha particle range-energy graph.) Now that we know the energy of the $_{\Lambda}C^{13}$, we find the energy of the neutron by subtraction, and calculate the magnitude of its momentum.

e) Total energy has been conserved in the steps outlined above, and it now remains to see if momemtum can be conserved by the insertion of the vector momentum of the neutron, whose length (but not direction) is known from energy considerations. The incoming vector momentum of the Λ is known, and the outgoing vector momenta of $_{\Lambda}C^{13}$, and

proton are also known. From these three momenta, which do not lie in a plane, the magnitude of the missing momentum can be calculated. This value comes entirely from track directions, ranges and particle assignments; it does not involve the precise masses of any of the particles. The fact that the value of the missing momentum calculated without regard to detailed energetic arguments agrees with that of the assumed neutron, derived completely on energetic grounds -- neglecting all angular information, constitutes the "fit" of the assumed reaction to the observed tracks. On the first attempt, the two momenta had absolute values of 100 ± 5 MeV/c. After many unsuccessful attempts to fit the first Fry event to reaction (9), the author is convinced that the immediate and close fit obtained for reaction (14) could scarcely be coincidental.

Now that the Fry event has been fitted accurately to the reaction (13) followed by reactions (14) and (15), we must convince ourselves that the $_{\Lambda}C^{13}$ could decay via reaction (15), showing no visible C^{12} stub. It is well known that the fraction of hyperfragments decaying mesonically drops rapidly with increasing mass. Although little is known about the neutral mesic decay of $_{\Lambda}C^{13}$, the following quotation from J. McKenzie may be of interest:[19] "No significant confusion of non-mesonic decays is thought to arise from π^0 decays (of $_{\Lambda}H^4$), since it is assumed, following (a private communication from) Sacton that more than 95% decay via ($\pi^0 nHe^3$) with the He^3 not seen". Sacton is a collegue of Davis, working with emulsion, while McKenzie uses a helium bubble chamber. This quotation certainly does not translate directly to the behavior of $_{\Lambda}C^{13}$ in emulsion, but it is the only relevant comment the present author has seen. For a given momentum fraction transferred to the daughter nucleus in π^0 decay, C^{12} would have a much smaller range than He^3, and so be less visible as a stub.

Therefore, in view of the remarkable fit of Fry's event to reaction (13), followed by reaction (14), plus the fact that reaction (15) is an allowed one that also fits Fry's projection drawing, we can consider the whole event now to be completely understood.

IX. Acknowledgments

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FIGURE LEGENDS

Fig. 1a. The Eisenberg event.

Fig. 1b. Grain density measurements on the Eisenberg tracks.

Fig. 2. Momentum conservation in the Eisenberg event.

Fig. 3. The first Fry event.

Fig. 4. The second Fry event.

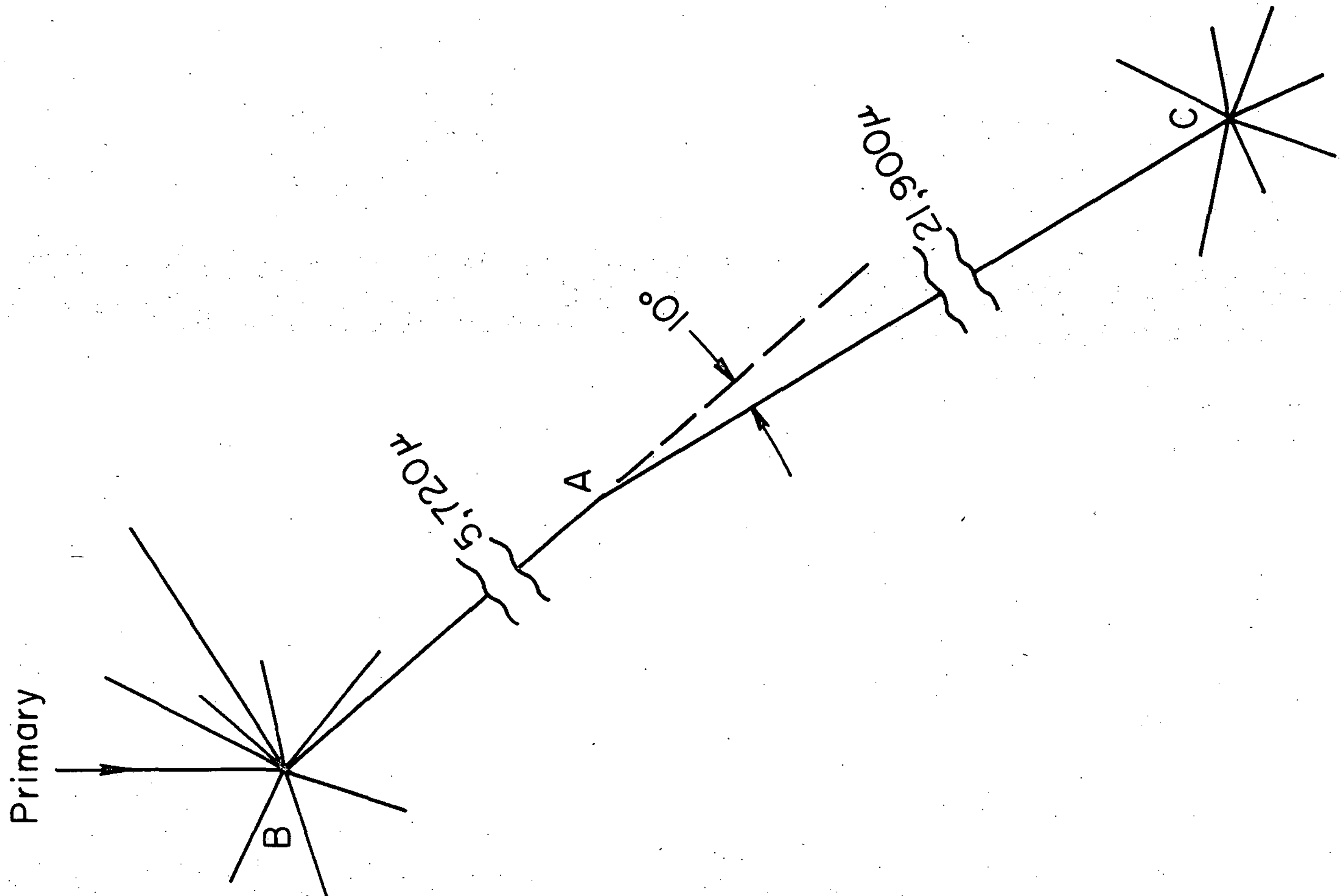

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Fig. 1a

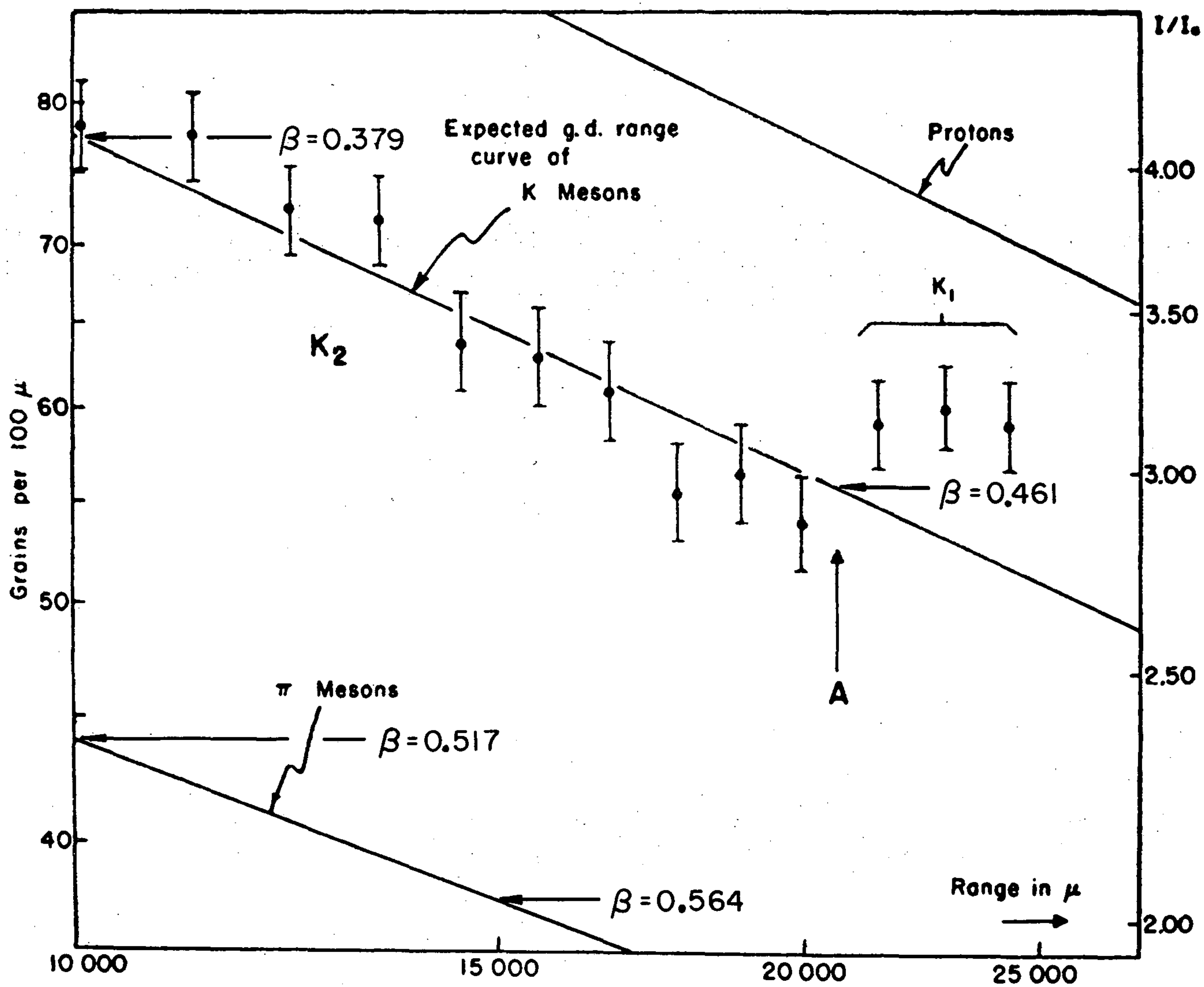
I/I₀
80
70
60
50
40
Grains per 100 μ
β=0.379
Expected g.d. range
curve of
K Mesons
Protons
4.00
3.50
3.00
2.50
2.00
K₁
K₂
β=0.461
A
π Mesons
β=0.517
β=0.564
Range in μ
10 000
15 000
20 000
25 000

Fig. 1b

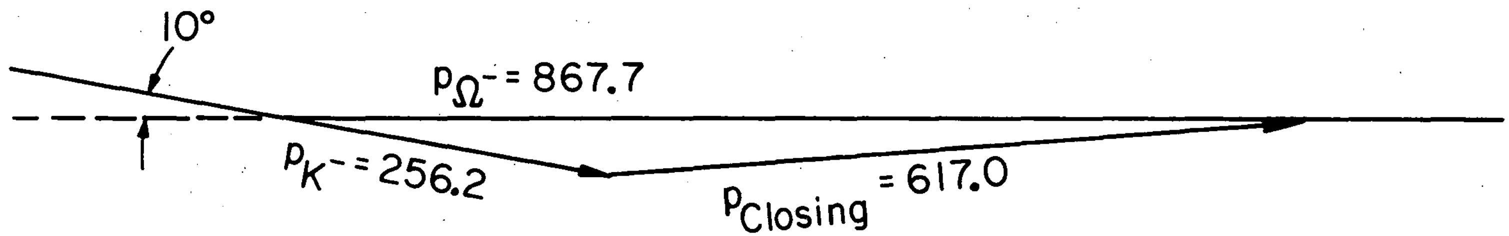

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Fig. 2

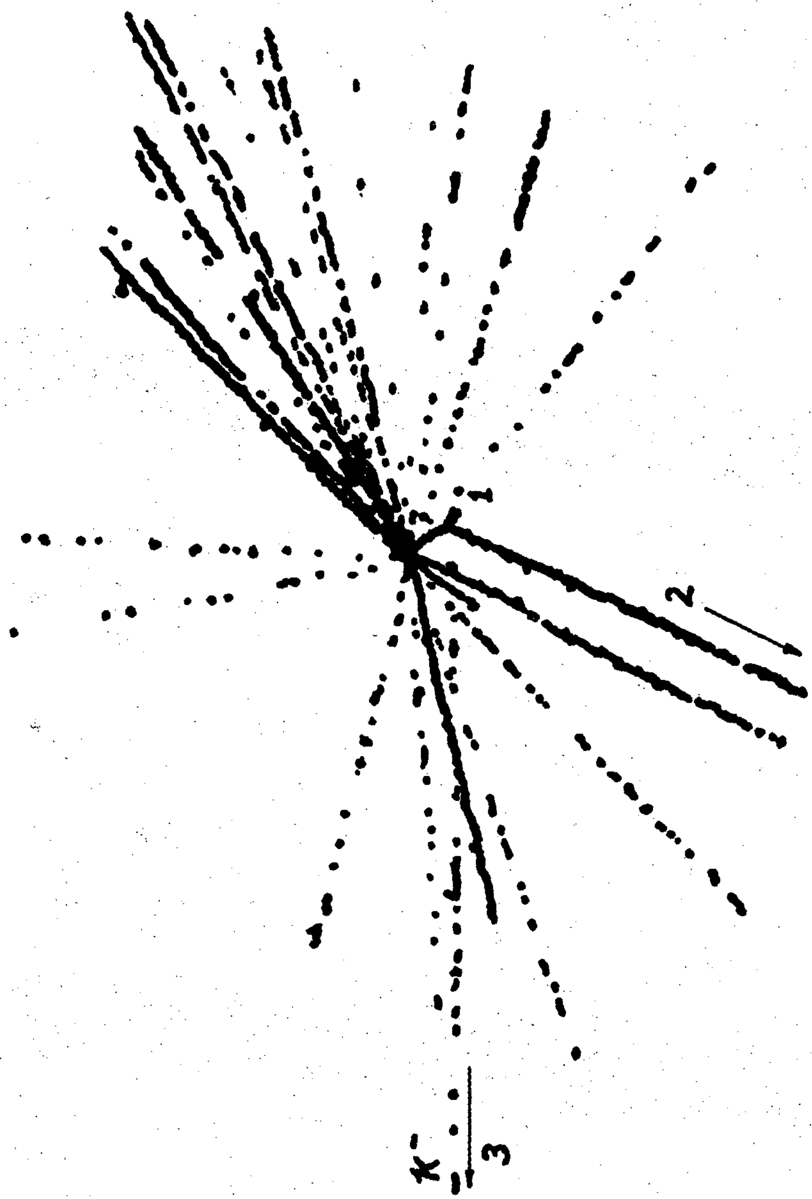

Fig. 3

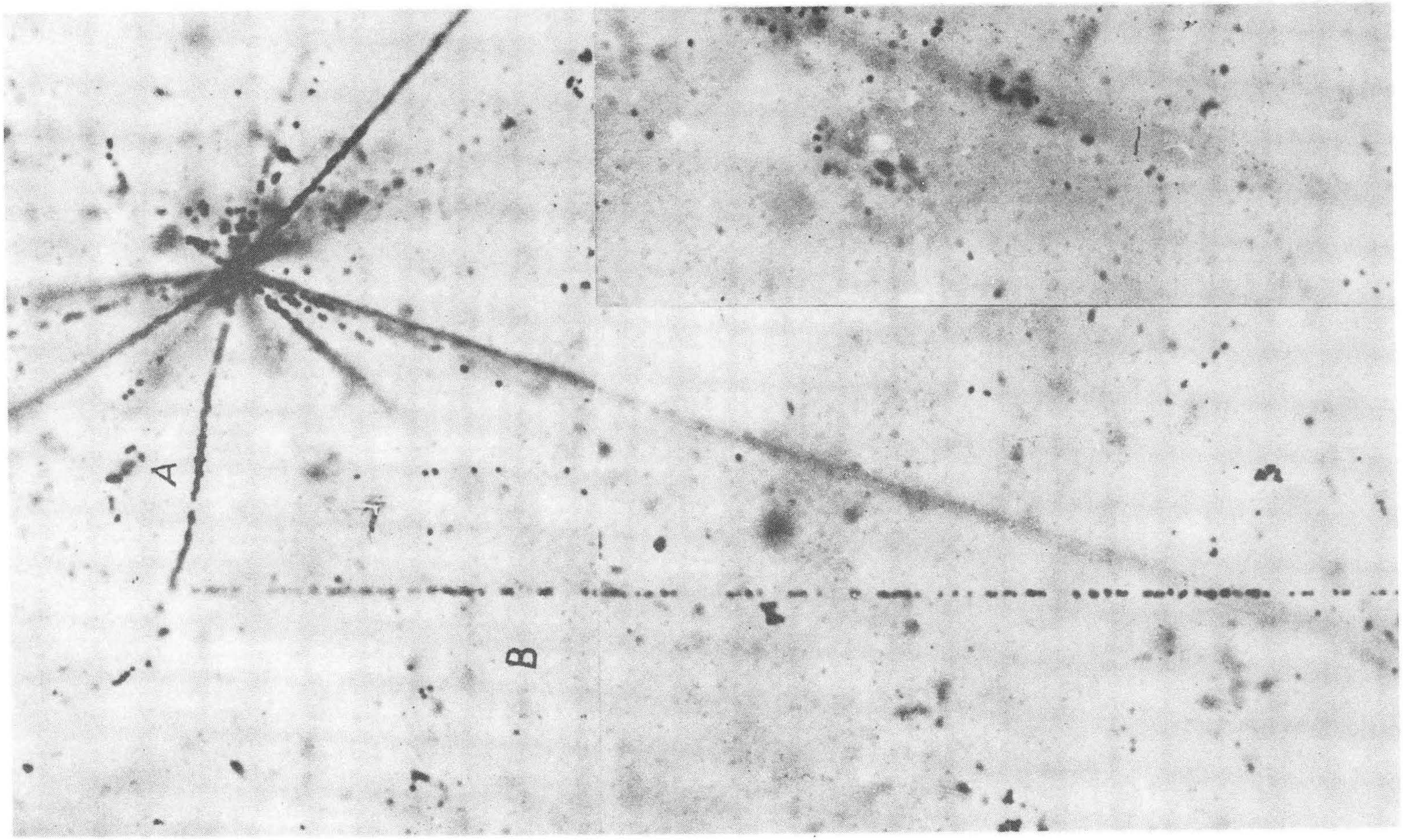

Fig. 4

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