Production of Heavy Unstable Particles in a p-p Collision*

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A hydrogen-filled diffusion cloud chamber was exposed to a 2.7-Bev proton beam. In a collection of 202 p-p collisions, there was one event interpreted as the associated production of a hyperon and a K-meson, via the reaction $p+p\rightarrow\Lambda^{+}+K^{+}+n$.

AN event best interpreted as the simultaneous production of a K-meson and a hyperon in a proton-proton interaction was recently observed in a diffusion cloud chamber exposed to an external beam of 2.7-Bev protons[1] from the Brookhaven Cosmotron. The cloud chamber contained hydrogen gas at 20 atmospheres and was located in a magnetic field of 9500 gauss. This event was found among a total of 202 observed p-p collisions.

Figure 1 shows the collision of the beam proton i with a hydrogen nucleus in the chamber. Two fast positively charged particles, a and b, are seen to emerge from the collision. The emission of at least one neutral particle is required since tracks i, a, and b are not coplanar. Table I gives the measured momenta, ionization estimates and angles in the laboratory system. The momenta were determined with a Cooke microscope at low magnification. Track a was too short to permit a momentum measurement.

Particle b, after a path length of $\sim$6 cm, is seen to decay through an angle of 12.5 degrees into the charged particle b' which is probably a pion or muon, but might be as heavy as a proton. The decay angle is such as to rule out π-μ decay. Particle a travels $\sim$3 cm and apparently decays through an angle of 2° into a'. Although this angle is small, the measurements are reproducible to $\pm 0.5°$ in the three-dimensional reprojection system used for the spatial analysis. Since the estimated ionization changes from $\sim$1 to 1.5–2.5 at the point of the 2° break, this further lends support to the hypothesis that a is indeed an unstable particle. On the basis of its ionization and momentum, a' was identified as a proton; this implies that a is a hyperon.

The two-body decay scheme,

$$\Lambda^{+}\rightarrow p+\pi^{0}+Q, \qquad (1)$$

is assumed for a, with a Q-value of 115 Mev.[2] This decay scheme together with the measured momentum of a' leads to the values 1.02 ± 0.16 Bev/c and 0.46 ± 0.13 Bev/c for the momentum of a, the latter value being ruled out on the basis of ionization. The identification of a as a hyperon, and the assumption of nucleon conservation leads to the following alternatives involving a single neutral secondary:

$$\text{(Ia)}\quad p+p\rightarrow\Lambda^{+}+n+K^{+},$$

$$\text{(Ib)}\quad p+p\rightarrow\Lambda^{+}+\pi^{0}+\Lambda^{+},$$

where n is a neutron. On the assumption of the scheme (Ia), M_b, the mass of b, may now be computed from the energy and momentum conservation laws, using the computed momentum of a and the measured momentum of b. One obtains $M_b=0.51\pm0.10$ Bev, in good agreement with the K-meson mass of $\sim$500 Mev.

Since there is a large uncertainty in the measurement of the momentum of b, it is of interest to utilize the more accurate momentum of the decay particle b', and calculate p_b, the momentum of b, on the assumption of the following two-body decay scheme:

$$K^{+}\rightarrow\pi^{+}+\pi^{0}+Q(217\text{ Mev}).^{3}$$

This leads to the value $p_b=0.87\pm0.19$ Bev/c; the mass of the neutral particle emitted in the p-p collision is found to be $M_n=0.93\pm0.04$ Bev, in agreement with the mass of a neutron.

TABLE I. Directly observable parameters of charged secondaries; p is the measured momentum, I the estimated specific ionization; θ and ϕ are the polar and azimuth angles, respectively, with the direction of the incident proton taken as the polar axis, except for $\theta_{a'}$ and $\theta_{b'}$ which are measured from the forward directions of a and b, respectively.

Particle	p (Bev/c)	I	θ (degrees)	ϕ (degrees)
a	not measurable	$\sim$1	24±0.5	30±2
a'	0.57±0.1	1.5–2.5	2±0.5	
b	0.83±0.5	$\sim$1	16±0.5	180±3
b'	0.73±0.1	$\sim$1	12.5±0.5	

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‡ On leave of absence from the Naval Research Laboratory, Washington, D. C.

[1] A value of 2.6 Bev was previously reported for the beam energy: Block, Harth, Fowler, Shutt, Thorndike, and Whittemore, Bull. Am. Phys. Soc. **29**, No. 7, 33 (1954). A more precise beam analysis indicated that 2.7 Bev is a better value; the results given here are relatively insensitive to the precise value.

[2] Bonetti, Levi-Setti, Panetti, and Tomasini, Nuovo cimento **10**, 345 (1953).

[3] Kim, Burwell, Huggett, and Thompson, Phys. Rev. **96**, 229 (1954).

FIG. 1. Stereoscopic view of incoming proton i interacting in the hydrogen gas to produce tracks a and b. Tracks a' and b' are interpreted as decay fragments of a and b, respectively. The pictures have been retouched to make the event visible in the reproduction.

If a similar calculation is carried out for scheme (Ib), it is found that this alternative can be ruled out because energy and momentum cannot simultaneously be conserved if there is creation of two hyperons and a pion with the observed momenta and angles of emission.

We now wish to consider the possibility that a is a proton, and that both the 2° break between a and a', and the apparent change in ionization are spurious; the momentum of a' is taken as representative of the momentum of this particle. The following interpretations of the event may now be investigated:

$$\text{(IIa)}\quad p+p\rightarrow p+\Lambda^0+K^+,$$

$$\text{(IIb)}\quad p+p\rightarrow p+n+K^+,$$

$$\text{(IIc)}\quad p+p\rightarrow p+\pi^0+\Lambda^+.$$

Proceeding as before, scheme (IIa) leads to a mass value of $M_b=0.58\pm0.13$ Bev for particle b, which is compatible with the K-meson mass. Scheme (IIb) yields a mass of 0.70 ± 0.15 Bev for b; this mass is somewhat high for a K-meson, but the interpretation cannot be ruled out.

Assumption (IIc) leads to the following alternatives:

$$\Lambda^+\rightarrow\pi^++n+115\text{ Mev},$$

or

$$\Lambda^+\rightarrow p+\pi^0+115\text{ Mev}.$$

The first decay scheme leads to computed momenta for b that are incompatible with the measured momentum. If we assume the latter decay scheme, energy and momentum conservation is violated using the measured momenta and angles. Thus, (IIc) is ruled out.

In summary, if the interpretation is made in terms of particles of established masses, there remain the three possibilities:

$$\text{(Ia)}\quad p+p\rightarrow\Lambda^++K^++n,$$

$$\text{(IIa)}\quad p+p\rightarrow p+K^++\Lambda^0,$$

$$\text{(IIb)}\quad p+p\rightarrow p+K^++n.$$

All interpretations imply that the K-meson observed in this event is a boson. The first two are cases of associated production of heavy unstable particles. However, (Ia) is very strongly favored by the arguments given in identifying a as a hyperon, as well as by the high degree of compatibility of all measured quantities with this interpretation. It is therefore suggested that the event represents an example of the simultaneous production of a hyperon and a K-meson in a proton-proton collision.

A transformation of the event into the center-of-mass system of the colliding protons has been carried out on the basis of interpretation (Ia). The results are given in Table II. The laboratory value $p_a=1.02$ Bev/c, as derived from the two-body decay scheme (1), was used.

TABLE II. Transformation into c.m. system of colliding protons, based on interpretation: $p+p\rightarrow\Lambda^++K^++n$.

	$\bar{p}$ (Bev/c)	$\bar{E}$ (Bev)	$\bar{\theta}$ (degrees)	$\bar{\phi}$ (degrees)
Hyperon (a)	0.59	1.33	136	30
K-meson (b)	0.165	0.53	111	180
Neutron	0.53	1.08	34	248

A value for p_b in the laboratory system was then determined which was kinematically consistent with a mass of 500 Mev for the K-meson. This momentum turns out to be 0.56 Bev/c, which is well within the limits of error given for p_b.

The interpretation of the event as the simultaneous production of a K-meson and a hyperon is in accord with the predictions of Pais[4] and Gell-Mann[5] that heavy unstable particles are produced in pairs.

The authors wish to express their appreciation to Mr. M. Blevins of Duke University for aiding in the computations.

[4] A. Pais, Phys. Rev. **86**, 663 (1952).
[5] M. Gell-Mann, Phys. Rev. **92**, 833 (1953).

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Disintegration of Aluminum by Protons in the Energy Range 0.4 to 3.0 Bev*

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Excitation functions for the production of Na^{24}, Na^{22}, F^{18}, O^{15}(?), N^{13}, C^{11}, and Be^7 in proton bombardments of Al have been measured from 0.4 to 3.0 Bev. The formation cross sections have strikingly small energy dependence, and this feature is discussed in the light of possible energy transfer mechanisms. The absolute cross-section values are based on a calibration method (suggested by A. Turkevich) which is discussed. It is based on measurements of gross radioactivity in copper irradiated at various energies and on the assumption that the fraction of inelastic collisions with copper nuclei that lead to radioactive products is independent of proton energy from 0.3 to 3 Bev. The validity of this assumption is examined.

When proton beams with kinetic energies up to 3 Bev became available in the Brookhaven Cosmotron, it seemed desirable to extend radiochemical studies of nuclear reactions into this new range of bombarding energies. In an initial survey the yields of many radioactive products from the bombardment of a few selected target elements in different mass regions were measured at a given energy (usually 2.2 Bev) and compared with similar data at lower energies.[1–3] For target elements of medium[2] and high[3] Z the product yield distributions at 2.2-Bev bombarding energy were found to differ markedly from those observed with 300- to 400-Mev protons. For low-Z targets such as carbon[4] and aluminum[1] the most striking observation was the relatively slight difference between the cross sections in the two energy regions. In the present paper we report more detailed data on the excitation functions for the production of several radioactive nuclides in the bombardment of aluminum with protons in the energy range from 0.4 to 3.0 Bev.

The products studied include Na^{24}, Na^{22}, F^{18}, N^{13}, C^{11}, and Be^7. The production of all these nuclides from aluminum was investigated previously at lower proton energies. Hintz and Ramsey[5] published excitation functions for the formation of Na^{24}, Na^{22}, and F^{18} with protons of kinetic energies up to 120 Mev. Marquez and Perlman[6] and Marquez[7] reported cross sections for the production from aluminum of all six of the aforementioned nuclides by 335-Mev and 420-Mev protons, respectively.

EXPERIMENTAL

The irradiations were all carried out in the circulating beam of the Cosmotron. The proton energy was varied by variation of the turn-off time for the rf accelerating voltage. To prevent bombardment by stray protons of lower than the desired energy the targets were rammed into the bombardment position at the end of each acceleration cycle as previously described.[2] Circulating proton beams of about 10^{10} protons per pulse and a repetition rate of 12 pulses per minute were used in most of this work. Bombardments of one to two minutes' duration were found to produce adequate counting rates of the short-lived activities investigated: 15.0-hr Na^{24}, 112-min F^{18}, 20.5-min C^{11}, 10-min N^{13}, and some 2-min activity, probably largely O^{15}. The yields of 53-day Be^7 and 2.6-year Na^{22} were studied in aluminum samples irradiated up to a few hours.

Bombardments were carried out at a number of proton energies between 0.4 and 3.0 Bev. At each energy the yields of the various product activities were determined relative to the yield of Na^{24}. The excitation function for the $Al^{27}(p,3pn)Na^{24}$ reaction was measured in a separate set of experiments as described below.

* Research performed under the auspices of the U. S. Atomic Energy Commission.
[1] Wolfgang, Sugarman, and Friedlander, Phys. Rev. **94**, 775 (1954).
[2] Friedlander, Miller, Wolfgang, Hudis, and Baker, Phys. Rev. **94**, 727 (1954).
[3] Sugarman, Duffield, Friedlander, and Miller, Phys. Rev. **95**, 1704 (1954).
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[5] N. M. Hintz and N. F. Ramsey, Phys. Rev. **88**, 19 (1952).
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[7] L. Marquez, Phys. Rev. **86**, 405 (1952).

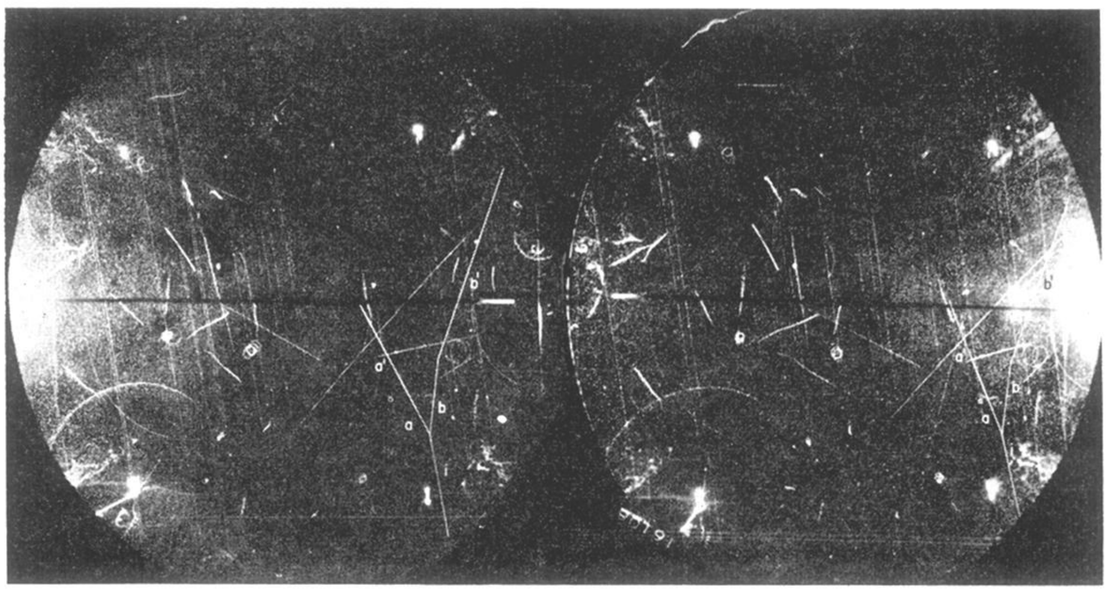

FIG. 1. Stereoscopic view of incoming proton i interacting in the hydrogen gas to produce tracks a and b. Tracks a' and b' are interpreted as decay fragments of a and b, respectively. The pictures have been retouched to make the event visible in the reproduction.