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Gamma Rays from Strange Particles

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Strange-particle production by protons in the Cosmotron range of energies was studied by observing gamma rays resulting from the decay of these particles at distances a few centimeters from the bombarded target. A laboratory energy threshold of 1.1±0.1 Bev was measured for protons on a copper target, consistent with the hypothesis of associated production. A free-particle threshold is estimated. The production below threshold, at 1.0 Bev, is less than 10^{-2} of the 2.9-Bev production. The mean survival distance for particles produced at 1.7 Bev is 3.8 cm. Upon analysis this yields a lifetime which matches the one known for the θ^0 and suggests $\theta^0 \rightarrow 2\pi^0$. Unless the Λ^0 is produced with a strongly ($\cos^2\theta$) peaked forward and backward angular distribution, it cannot be the dominant source of the gamma rays. Under the assumption that these particles are hyperons or heavy mesons, the total cross section, of that component which decays via π^0 mesons, is 0.1 mb per carbon nucleus.

WHEN a target nucleus is bombarded with protons in the Bev range, hyperons and heavy mesons with a mean life between 10^{-11} sec and 10^{-8} sec may be produced. Some of these particles decay into π^0 mesons, and these in turn will then produce a pair of gamma rays. Σ^+ hyperons and $K_{\pi 2}$ are known to decay in this way. Λ_0 hyperons and θ^0 mesons are possible examples. As a consequence of the collision which produced these unstable particles, they will in general have moved some distance in the direction of motion of the incident proton before creating gamma rays, and this circumstance permits an identification of these events.

Garwin[1] and Balandin *et al.*[2] used this method in an unsuccessful search for Λ^0 hyperons produced by, respectively, 400-Mev and 670-Mev protons. In the present experiment[3] a similar search was made, but under the more favorable condition of having available incident protons from the Cosmotron with energies up to 3 Bev.

The experimental arrangement shown in Fig. 1 was set up at the inner side of the magnet ring. The total counter-to-target distance was chosen to be five feet as a compromise between the desire to get the target as close to the counters as possible, and the necessity of providing sufficient shielding from the directly produced nucleonic component. Two functions of the shielding arrangement can be separated as being performed by different parts. That part next to the target is called the occulter since it hid the target, especially from the defining slits. The defining slits limited the view of the counters to a region of space 4 in. high, and $2\frac{1}{2}$ in. long in the direction of the proton beam. It was so arranged that the rather heavily irradiated occulter could not be seen by the counters, and the occulter was so arranged that the defining slits could not see the target. Part of the occulter was made of Hevimet to increase the available shielding of the slit system. At the entrance of the collimator, a lead shutter one inch thick was provided. The count with shutter closed was called the background.

The targets were mounted on a mechanism which enabled them to be moved relative to the viewed region in the direction of the beam. Targets could also be changed and withdrawn from the beam without opening the vacuum system.

The counting system which detected the gamma rays had to do so in the presence of an intense background of general radiation. (The single counting rate of a scintillation counter 1 in.×$\frac{3}{4}$ in.×$\frac{3}{16}$ in. averaged over the 20-millisecond proton pulse was found to be 10^6 per second at full proton beam.) After some preliminary attempts, the gamma-ray counting system diagrammed in Fig. 2 was evolved. A fourfold coincidence was demanded in the three scintillation counters S_2, S_3, S_4, and the water Čerenkov counter C_1. S_1' was in anticoincidence with these counters. A $1\frac{1}{4}$ in.×$\frac{3}{4}$ in. lead converter 3.5 g/cm^2 thick was between S_1' and S_2. A gamma ray converted in the lead converter and one or both members of the ensuing electron pair triggered the following counters. The anticoincidence counter excluded those fourfold coincidences due to charged particles incident on the system. The Čerenkov counter excluded nonrelativistic particles from events such as stars generated in the converter or first counter by neutrons and was an essential feature of the experiment. With this counter system, the accidental counting rate

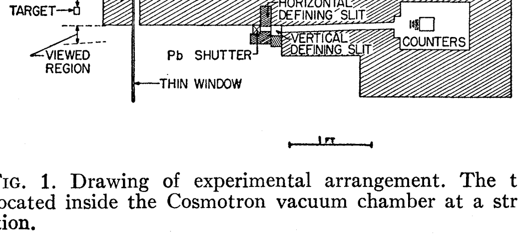

FIG. 1. Drawing of experimental arrangement. The target is located inside the Cosmotron vacuum chamber at a straight section.

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[1] R. L. Garwin, Phys. Rev. **90**, 274 (1953).

[2] Balandin, Balashov, Zhukov, Pontecorvo, and Selivanov, J. Exptl. Theoret. Phys. (U.S.S.R.) **29**, 265 (1955).

[3] S. L. Ridgway and George B. Collins, Phys. Rev. **98**, 247 (1955).

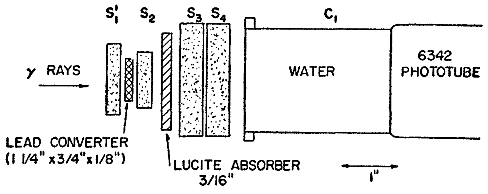

FIG. 2. Counter arrangement.

was about 1% of the true counts at full beam corresponding to 2×10^{10} protons per pulse.

This counting system was designed to be relatively insensitive to nuclear gamma rays compared to gamma rays of mesonic energy. The absolute energy threshold of the counter arrangement is estimated at 10 Mev because of the requirement that a charged particle traverse at least 5 grams per cm^2 made up of S_2, S_3, S_4, $\frac{1}{2}$ of C_1, and the Lucite absorber. Above 20 Mev the counting efficiency should be nearly constant.

The number of counts obtained in a given run was compared with the number of protons incident on the target as given by the Cosmotron's circulating beam monitor, and the data are presented in the form of a counting rate, i.e., counts per 10^{10} incident protons. Runs were made with lead shutter open and closed, and the difference between the counting rates obtained under these circumstances presumably represents gamma rays originating from the space defined by the collimating system. It is important to establish that the gamma rays detected do indeed originate in the presumed manner. One obvious spurious source, the thin aluminum exit window of the vacuum chamber, was examined by noting the effect of increasing the thickness of the aluminum at that point. Another source of background was the scattering of radiation at the collimating slits. Some contributions from these sources were observed when the target was near the edge of the occulter and data subject to this error were discarded.

The significant data from this experiment are presented in the form of two curves, one showing the intensity of the gamma rays as a function of the incident proton energy, and the second showing how the intensity of these gamma rays diminished as the target was moved away from the observed region. The former data have been taken at two target positions and the latter curves have been obtained at several incident proton energies.

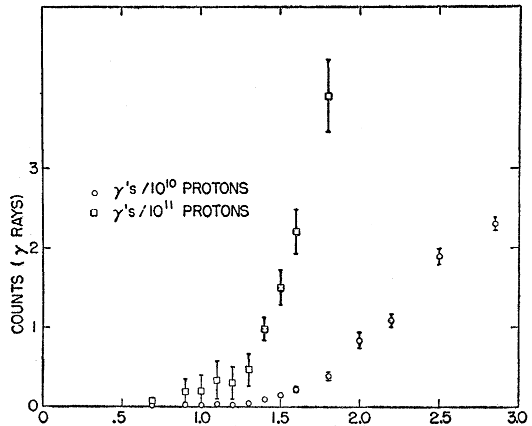

FIG. 3. Excitation function of γ rays produced more than 1.3 cm downstream of copper target 0.94 cm thick.

Figure 3 shows the net counting rate as a function of proton energy when the downstream edge of the bombarded copper target was distant 1.3 cm from the upstream edge of the observed volume. To illustrate the behavior of the excitation function near the threshold, which appears to be near 1.1 Bev, the data are also plotted on an expanded scale. Points below 1 Bev represent the background, 25% of which originates from the aluminum exit window of the vacuum chamber. The lowest point, at 670 Mev, was selected to correspond to the energy employed by Balandin *et al.*[2]; at this energy they report a cross section for Λ^0 production $\lesssim 10^{-31}$ cm^2/nucleon.

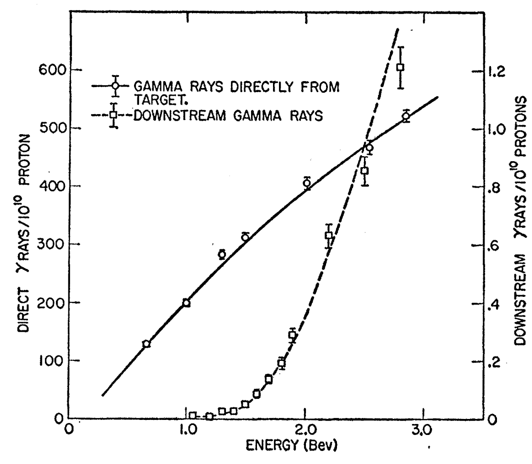

FIG. 4. Comparison of the π^0 excitation function with the excitation function of gamma rays produced with the target occulted. The downstream gamma-ray points are the net counting rate as a function of energy for a copper target, 0.94 cm thick, whose downstream edge was 3.7 cm from the upstream edge of the viewed region. The dashed curve is the theoretical energy dependence for K+hyperon production in S angular momentum states with a free-nucleon threshold of 1.53 Bev.

The counting rate as a function of energy was also measured with the target 3.7 cm from the viewed region and is shown in Fig. 4. The results are similar to those taken at the less distant target to viewed-region position.

By moving the target into the viewed region, gamma rays are counted which originate mainly from π^0 mesons. The production of gamma rays directly from the target was measured on a carbon target 4.1 g/cm^2 thick. Figure 4 shows the yield of π^0 gamma rays produced directly in the target as a function of proton energy as well as the yield of gamma rays produced downstream of the target. It might be expected that the π^0 excitation curve represents the increase in general background with incident proton energy, and as its shape is markedly different from the obscured target curve it provides evidence that the latter does not originate from the background radiation.

By moving the target upstream from the observed region, one indirectly measures the lifetime of the particles responsible for the effect. In Fig. 5 the intensity is plotted as a function of distance for incident protons at 2.8, 1.7, and 1.05 Bev. At the two higher energies the data are consistent with an exponential decay except for high points taken with the target within a centimeter of the edge of the occulter. This rise is also present in the 1.05-Bev curve and, as stated previously, is due mainly to radiation scattered by the aluminum exit window and collimator. In interpreting these curves, this rise is assumed to be spurious. A copper target 0.94 cm thick was used to obtain these data. Less complete data taken with a 4.1-g/cm^2 carbon target were consistent with both the excitation and decay curves from copper.

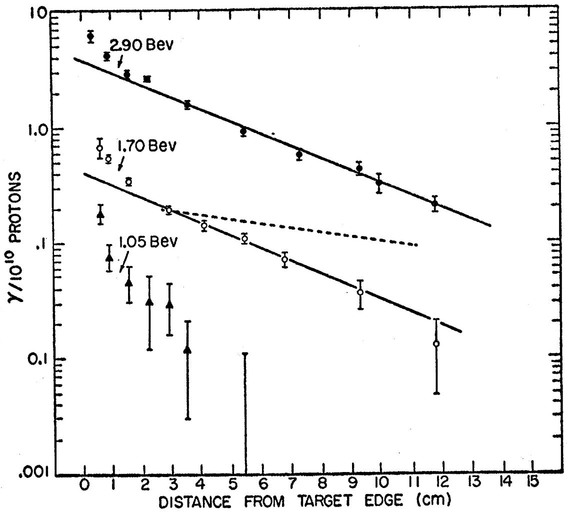

FIG. 5. Decay curves of gamma rays from a copper target 0.94 cm thick. The counting rate is plotted as a function of the distance from the downstream target edge to the upstream edge of the viewed region. The solid straight lines have slopes corresponding to $1/e$ decay distance of 4.16 and 3.87 cm for the 2.90-Bev and 1.70-Bev curves respectively. The dashed curve represents the expected curve for the Λ^0 if the angular distribution of the Λ^0 is isotropic.

There are a number of comments to be made about the excitation curves shown in Fig. 3 and Fig. 4. Table I shows the thresholds for the simultaneous production of a number of meson combinations by protons incident on free nucleons ($\bar{E}_p=0$) and on nucleons with a maximum internal energy of $\bar{E}_p=25$ Mev. The energies refer to incident proton kinetic energies in the laboratory system.

TABLE I. Threshold energies (in Bev) for various production processes with and without Fermi motion of the target nucleons.

	$\bar{E}_p=0$ Mev	$\bar{E}_p=25$ Mev
$\Lambda^0+\Lambda^0$	0.77 Bev	0.49 Bev
$\Sigma+\Sigma$	1.16	0.78
$K+\Lambda^0$	1.57	1.10
$K+\Sigma$	1.80	1.27
$K+\pi$	1.45	1.08
$K+K$	2.50	1.81

Figure 3 indicates a threshold at 1.1±0.1 Bev, and this value is consistent only with the associated production of $K+\Lambda^0$, $K+\Sigma$, and $K+\pi$ if processes involving more than one pion are neglected. In view of the presently accepted status of the concept of associated production, it seems reasonable to assume that the observed gamma rays originate from either K mesons or hyperons produced together.

An attempt was made to determine whether the excitation curve indicated a Λ^0+K or a $\Sigma+K$ threshold. Excitation curves were calculated based on a constant interaction for the nucleon-nucleon production process and a Gaussian momentum distribution of the copper nucleons with a $1/e$ width[4] of 170 Mev/c. Production in both S and P angular momentum states was considered. The S-wave curve gives a reasonable fit to the data with a free-nucleon threshold of 1.53±0.04 Bev (Fig. 4). This is close to the Λ^0+K threshold. A curve calculated on the assumption of P-wave production also gives a good fit and yields a free nucleon threshold of 1.44±0.05 Bev. If one considers the effect of an uncertainty of ±50 Mev/c in the mean of the nucleon momentum distributions, one must add an additional uncertainty of ±100 Mev to the threshold. These data and analysis suggest agreement with the Λ^0+K threshold of 1.57 Bev. These data, however, would be consistent with the $\Sigma+K$ free-nucleon threshold if a momentum distribution with a $1/e$ width of 270 Mev/c, and S-wave production, is assumed.

Conceivably, associated production could occur by means of the intermediate production of a π meson, and since Fermi motion of the nucleons could then enter twice, a threshold as low as 740 Mev would be possible. It is significant that the gamma rays observed at 1.0 Bev are less than 1/100 those observed at 2.9 Bev. There is no evidence for anything other than background radiation below 1.1 Bev.

The decay curves in Fig. 5 for 2.9 and 1.7 Bev show a $1/e$ distance of decay of 4.16±0.1 cm and 3.87±0.3 cm, respectively. To convert these distances into a mean life of the particle in its own rest system, a number of assumptions must be made with regard to the velocity and angular distribution of the unstable particles and their decay products.

The measured mean decay length d, is related to the lifetime of the observed particle by

$$d=\tau\langle p_x P_\gamma\rangle/mc,$$

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[4] For a summary of some of the available literature see J. M. Wilcox and B. J. Moyer, Phys. Rev. 99, 875 (1955).

Table II. Predicted lifetimes and values of f at 2.9 Bev for various angular and energy distributions of K mesons. It was assumed that $\partial^2\sigma/\partial\Omega\partial T \sim |H|^2 \times$ density of final states. The following nomenclature was used for the distributions: G:1:1 target nucleons with Gaussian momentum distribution, $|H|^2=1$ (independent of angle and energy); $G:1:\cos^2\theta$, target nucleons with Gaussian momentum distribution, $|H|^2=\cos^2\theta$; $G:\gamma^2-1:1$, target nucleons with Gaussian momentum distribution, $|H|^2=(E^2/m^2)-1$; F:1:1 Fermi gas target nucleon distribution $|H|^2=1$.

Distribution	$\langle p_x P_\gamma \rangle/mc$	τ (sec)	f
G:1:1	1.034	1.34×10^{-10}	6.9
$G:1:\cos^2\theta$	0.911	1.52×10^{-10}	7.2
$G:\gamma^2-1:1$	0.994	1.40×10^{-10}	7.2
F:1:1	0.970	1.43×10^{-10}	6.9

where P_γ is the probability of observing a gamma ray at 90° to the beam direction from a particle whose component of momentum in the beam direction is p_x.

$$\langle p_x P_\gamma \rangle = \frac{\displaystyle\int\int_0^{4\pi} \frac{\partial^2\sigma}{\partial\Omega\partial T} P_\gamma(\theta,\varphi,T) p_x dT d\Omega}{\displaystyle\int\int_0^{4\pi} \frac{\partial^2\sigma}{\partial\Omega\partial T} P_\gamma(\theta,\varphi,T) dT d\Omega},$$

where T is the energy of the unstable particle whose x component of momentum is p_x and which is traveling in a direction determined by the polar angles (θ,φ).

Using the energy distributions for K mesons produced in nucleon-nucleus collisions at 2.9 Bev,[5] Sternheimer has performed the calculation of $\langle p_x P_\gamma \rangle$ and the corresponding mean life τ for the decay of K mesons, with various angular and momentum distributions in the center-of-mass system and a uniform angular distribution of gamma rays in the rest system of the K meson. The results are given in Table II. Sternheimer[5] has also made an approximation for $\langle p_x P_\gamma \rangle$ by assuming the unstable particles are emitted, on the average, at 90° in the center-of-mass system. The average value of p_x was then approximated as the mean of its maximum and minimum values and an estimate of the average value of P_γ obtained from a linear interpolation of $\langle P_\gamma \rangle$ for the uniform angular distribution at 2.9 Bev and at the experimental threshold of 1.1 Bev. The results of these computations are shown in Table III. A comparison of Table II with Table III shows that the estimate of $\langle p_x P_\gamma \rangle$ at 2.9 Bev in Table III agrees reasonably well with the results of the more lengthy calculations and is therefore presumed to yield a fairly good estimate at 1.7 Bev. The lifetime obtained is in good agreement with the known θ^0 lifetime of $(1.7_{-4.4}{}^{+0.7})\times10^{-10}$ second[6] and the decay curves are compatible with the decay of the $\theta^0 \rightarrow 2\pi^0$.

In considering Λ^0 hyperons as a possible source of the observed gamma rays, the decay curve closest to the threshold energy (1.70 Bev) was chosen for the most complete analysis. This was done in order to minimize the kinematic complications. Nucleon-nucleon collisions and Λ^0 hyperons produced in association with K mesons was assumed. Unfortunately, from this analysis, it is not possible to exclude Λ^0 hyperons as the only source of the observed gamma rays. If an isotropic angular distributions to the Λ^0 hyperons in the rest system is assumed no more than 10% of the observed gamma rays can come from these particles assuming a lifetime[7] of $(3.5_{-0.5}{}^{-0.6})\times10^{-10}$ sec. If, however, the angular distribution of the Λ^0 hyperons is sharply peaked $(\cos^2\theta)$ in the forward and backward direction, these particles alone could account for the observed mean decay distance. The decay $\Sigma^+ \rightarrow p+\pi^0$ is an unlikely source since the Σ^+ life from decays in flight is found to be[8]

$$\tau = (3.5_{-1.1}{}^{+1.5})\times10^{-11} \text{ sec.}$$

There is, of course, also the possibility that some unknown particle is the source of these gamma rays.

An estimate was made of the differential cross section for the production of the observed downstream γ rays. The estimate is based on: (1) an assumed efficiency of the counter system, (2) the geometry of the apparatus, and (3) the assumption that the Cosmotron's circulating beam monitor indicates the number of proton traversals through the target. The result is $d\sigma_\gamma(90°)/d\Omega = 0.02$ mb/sterad with an estimated uncertainty of a factor of two. To convert this differential cross section into a total cross section for the production of strange particles, some assumptions must be made about their production processes. The differential cross section for the production of gamma rays at 90° is

$$\frac{d\sigma_\gamma(90°)}{d\Omega} = \frac{1}{\pi}\int_0^{\pi/2}\int \frac{\partial^2\sigma}{d\Omega dT} P_\gamma(T,\theta) \sin\theta d\theta dT.$$

Using the energy and angular distributions of Table II and assuming an isotropic distribution of the gamma rays in the center-of-mass system of the K mesons, Sternheimer[5] has calculated the total cross section σ_{total} in terms of $d\sigma_\gamma(90°)/d\Omega$:

$$\sigma_{\text{total}} = f d\sigma_\gamma(90°)/d\Omega.$$

Values of f for various energy and angular distributions are shown in Table II. With the assumption that θ^0 is the only source of gamma rays, a cross section per

Table III. Predicted lifetimes assuming that a K meson is emitted, on the average, at 90° in the center-of-mass system of the colliding nucleons.

E (Bev)	$\langle p_x P_\gamma \rangle/mc$	τ (sec)
1.7	0.89	1.44×10^{-10}
2.9	1.24	1.12×10^{-10}

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carbon nucleus for the production of $\theta^0 \rightarrow 2\pi^0$ is ~ 0.1 mb. This cross section also applies approximately if the observed gamma rays originate from the process $\Lambda^0 \rightarrow n+\pi^0$. The kinematics of the latter process are more favorable than the kinematics of the θ^0 process for observing gamma rays at 90°. This condition compensates for the fact that only a single π^0 meson is produced in the Λ^0 decay instead of the two π^0 mesons produced in the θ^0 decay.

If an appreciable fraction of either Λ^0 hyperons or θ^0 mesons decay via π^0 mesons, and there is evidence that this may be the case,[9,10] the relatively low cross section for downstream gamma-ray production in p-carbon collisions observed here is striking compared to the cross section of ~ 1 mb observed by Fowler *et al.*[11] for the production of heavy unstable particles by 1.37-Bev pions on hydrogen.

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Angular Distribution in Electron-Photon Showers without the Landau Approximation

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The track-length angular distribution of electrons in an electron-photon cascade is calculated without the use of the Landau approximation which was invariably used in all previous work. The Tamm-Belenky model of the cascade is used. The results are presented in the form of a series, the first term of which is of the same form as the result yielded by the Landau approximation but with a modified value of the parameter E_s.

It is shown that the use of the Landau approximation introduces large errors not only for large values of the argument but for small values as well. The bearing of this result on previous theoretical work on the lateral distribution function is discussed.

1. INTRODUCTION

SEVERAL calculations of the track-length angular distribution of the electron-photon cascade have been made,[1-5] giving results in quite good agreement with each other especially at values of the angular variables $E\theta/E_s$ less than unity, where E_s, the "characteristic scattering energy," is 21 Mev and the angle θ between the directions of motion of the cascade electron and the primary particle is measured in radians. Several of these distributions are graphed in Figs. 1 and 2, where the essential agreement between them can be seen. However these calculations were all made under a common approximation, the Landau approximation, so there is as yet no check on the validity of this approximation nor upon the accuracy of these distributions.

Now the Landau approximation is the cascade equivalent of the well-known multiple-scattering approximation which, when applied to the elastic scattering of a particle without loss of energy, yields a Gaussian angular distribution. It has always been appreciated that because of the θ^{-4} dependence of the scattering cross section at large angles, the multiple-scattering approximation (in common with the Landau approximation) has no validity in the "tail" of the angular distribution. In the theory of multiple scattering this error in the tail can be corrected by the addition of a component corresponding to one or a few single scattering acts each through a large angle (the "single-scattering tail"). However the calculations of Snyder and Scott[6] and of Molière[7] of the angular distribution resulting from multiple scattering show that there is a considerable error in the Gaussian approximation to this distribution even at very small angles. The

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