Cross Sections for Associated Production by Protons*

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Associated production from different target nuclei has been investigated by detecting gamma rays originating from unstable particles which decay downstream of a target bombarded with 3-Bev protons. The variations in the intensities of these observed gamma rays with atomic weight of the target nucleus indicate that an appreciable fraction of heavy meson and hyperon production occurs as a result of some two-step process, such as intermediate π production. For processes which involve production of Σ^0, Λ^0, or K^0 by p-p and by p-n collisions, the ratio of the cross sections for associated production is $\sigma_{pp}/\sigma_{pn}=0.2\pm0.3$.

THE study of the production of unstable particles by 3-Bev protons incident upon nuclei has been continued.[1,2] These particles were detected by observing gamma rays which originated from a region several centimeters downstream from the target. The observed proton energy threshold of 1.1 Bev for the appearance of these gamma rays showed that the unstable particles responsible for them were created through associated production processes. Presumably the gamma rays come from the decay of π^0 mesons originating in the decay of hyperons or heavy mesons. A mean decay length of about 4.0 cm has also been observed and this information is consistent with a mixture of θ_1^0 and Λ^0 as a possible source of the gamma rays.

The presence of these "downstream" gamma rays can be used to study the associated production process and this circumstance has been used to examine how the associated production process by protons varies with the atomic weight of the bombarded nucleus. Accordingly the cross section for associated production by 3-Bev protons as indicated by the presence of downstream gamma rays has been investigated for elements ranging from hydrogen to lead.

The experimental arrangement was similar to the one used previously[1] and is shown in Fig. 1. The targets were mounted on a mechanism which enabled them to be moved relative to the viewed region and in the direction of the incident beam. It was so arranged that any one of three targets could be placed in the beam without opening the vacuum chamber. After a target was withdrawn from the beam its position relative to the occulter could be reset to within 0.010 in.

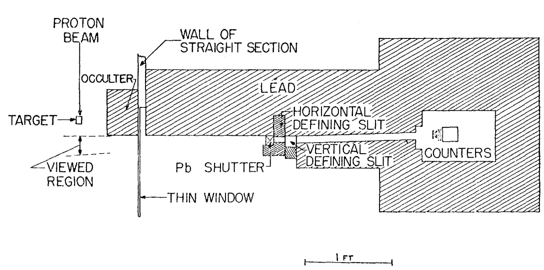

FIG. 1. Target, shielding, counter, and collimating system. The target is located inside the Cosmotron vacuum chamber at a straight section.

Each target was provided with a lip through which the beam was first required to pass before striking the target on a subsequent traversal around the machine. The purpose of this lip was to damp the radial betatron oscillations of the circulating protons. This process usually required several proton traversals through the lip, after which the proton passed through the lip with a small radial oscillation amplitude. The ionization loss due to the last lip traversal caused a proton to suffer a corresponding sudden decrease in its equilibrium orbit radius. A favorable betatron oscillation was thus induced, and resulted in a traversal of the proton through the entire target thickness upon the next proton revolution. In most cases, the ionization loss in the target was sufficient for the protons to strike the inside wall of the vacuum chamber some 90°–270° away from the target. However, when thin targets were used, stopper targets at judiciously chosen azimuthal positions were found necessary to prevent multiple traversals. Multiple traversals not only made the evaluation of total proton flux through the target difficult, but also created additional background.

The counting rate was obtained by comparing the number of counts registered in a given run with the number of circulating protons as indicated by the Cosmotron beam monitor. Counts were taken with a one-inch lead shutter open and closed. The attenuation of the observed radiation when different thicknesses of absorber were placed in front of the collimating slits indicated that the difference between the shutter-open and shutter-closed rates was proportional to the gamma-ray counting rate. The uncertainties introduced by considering the shutter-closed rate as background is estimated to be no more than a few percent.

The decay distance of downstream gamma rays produced in various nuclei was observed by measuring the variation of gamma-ray intensity as the target was moved away from the viewed region. Figure 2 shows how the gamma-ray intensity from the elements D, Be, C, Cu, and Pb diminished as the targets were moved

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[1] Ridgway, Berley, and Collins, Phys. Rev. **104**, 513 (1956).
[2] D. Berley and G. B. Collins, Bull. Am. Phys. Soc. Ser. II, **1**, 321 (1956).

away from the viewed region. The curves were normalized at 1.6 cm from the target. The deuterium points were obtained by a C-CD_2 subtraction. Except for points taken with the target within a centimeter of the occulter where slit scattering may be important, all the data are consistent with a simple value of exponential decay. It is significant that within the limits of accuracy obtained, the falloff in intensity seems to be uninfluenced by the size of the nucleus in which the unstable particle is produced. A survival distance of 4.0 cm applies to any of the elements from D to PG. This is consistent with a mixture of K^0 meson and Λ^0 hyperon decays.[1]

In order to compare the relative gamma-ray production cross sections from different elements, it was important to establish the number of nuclei the target and lip presented to the circulating proton beam. The number of proton traversals through the lip and multiple traversals through the target were found to be nontrivial considerations, especially for the lighter targets. The beam distribution over the upstream face of the target and the number of traversals through the lip were measured by counting the activity from aluminum foils which had been mounted on the upstream side of the targets. Beam distributions over the target, and stopper target shadow curves, provided no evidence for multiple traversals under the targeting conditions which were used. This possible source of error contributed a negligible uncertainty to the effective target thickness. The number of lip traversals was measured by comparing the foil over the lip with the one over the target. This was done for sufficiently many lip thicknesses and materials to make sensible interpolations to those which were not monitored. Uncertainties due to multiple traversals through the targets and lips were included in the errors accompanying the results.

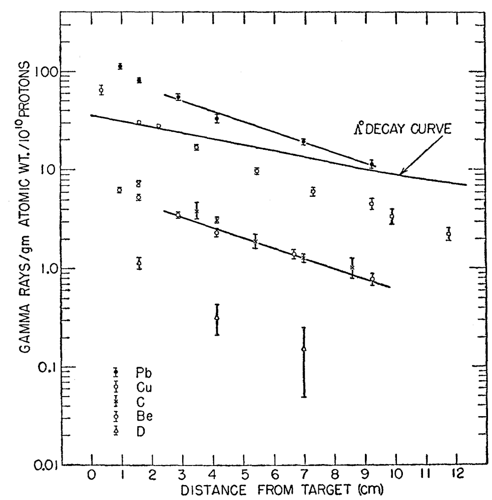

FIG. 2. Decay curves of downstream gamma rays from several nuclei. The distance from target refers to the distance from the downstream edge of the target to the upstream edge of the region of view. The mean decay distances corresponding to the curves are: Pb, 4.1±0.2 cm; Cu, 4.1±0.1 cm; C, 3.5±0.2 cm; Be, 4.1±0.3 cm; and D, 1.6 to 4.0 cm (90% confidence interval). A theoretical Λ^0 decay curve computed under the assumption of production in nucleon-nucleon collisions is shown to illustrate the nearly exponential behavior expected. A mixture of gamma rays from Λ^0 and θ^0 decays is consistent with the observed decay distance.

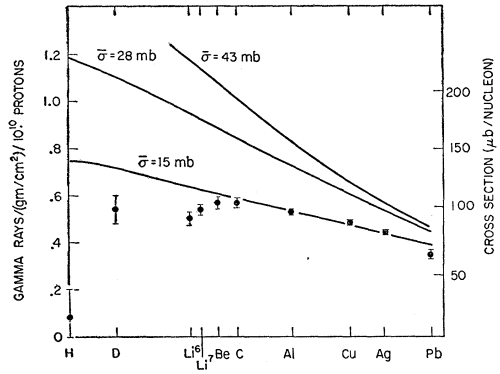

FIG. 3. Relative gamma-ray yield 1.6 cm from target. The solid curves are calculated and represent the relative gamma-ray yields assuming that production occurs only by direct proton-nucleon interactions. Only the shadowing effect of one nucleon by another was taken into account for three different elementary cross sections, $\bar{\sigma}=43$ mb, 28 mb, and 15 mb. The cross section scale shown on the right is based on the process $p+n\rightarrow K^0+\Lambda^0+p$.

Three or four targets were mounted on a multitarget assembly and their positions adjusted relative to the direction of the incident protons and with respect to the viewed region. During the runs, which were usually of 10 to 15 hours duration, repeated counting rates from the different targets were obtained by rotating them into the proton beam in cyclic order. Eight percent counting statistics could be obtained for a given target in less than one-half hour and three to five complete cycles were obtained during a run. The effects of slow systematic drifts in the sensitivity of the equipment were thus greatly reduced.

The relative cross sections for the production of gamma rays are plotted in Fig. 3 for the nuclei, H, D, Li^6, Li^7, Be, C, Al, Cu, Ag, and Pb. The hydrogen and deuterium points were measured by both $C-CH_2-CD_2$ and $Li^7-Li^7H-Li^7D$ subtractions. A weighted average of these two measurements is shown. The downstream edge of each target was 1.6 cm from the upstream edge of the viewed region. The number of gamma rays per 10^{10} incident protons was divided by the effective thickness of material, effective target thickness plus effective lip thickness, 1.6 cm from the target and the results are stated in terms of gamma rays/(g/cm²)/10^{10} protons. The effective target thickness is the amount of target material per unit area diminished by the fraction of particles which decay in the target. A mean decay distance of 4.0 cm was assumed. The uncertainties shown in Fig. 3 include statistical uncertainties and uncertainties in the effective target thickness.

There are two aspects of the relative gamma cross

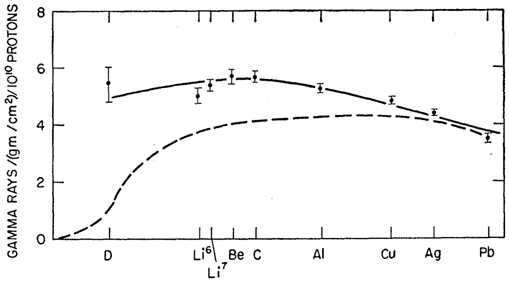

FIG. 4. The dashed curve shows the expected variation with atomic number of associated production due to the intermediate π process. The solid curve shows the sum of the direct-production yield with $\bar{\sigma}=28$ mb and the intermediate π contribution.

sections which are of interest: (1) the variation of gamma-ray yield with atomic weight of the target nucleus and (2) the p-p and p-n cross sections.

The variation of gamma-ray yield with atomic weight is considered first. It is assumed that protons enter the nuclei, make elastic and inealstic collisions with the target nucleons, and occasionally make strange particles by associated production. In most of the elastic collisions the energy loss is small and the protons are still capable of producing heavy unstable particles in a subsequent collision. In inelastic collisions which involve the production of π mesons, the energy of the protons is usually reduced to a value below or very close to the associated production threshold. These protons are now incapable of interacting again to produce strange particles but in about 15% of the inelastic collisions[3] the π mesons produced are energetic enough to do so. Finally, in escaping from the nucleus the strange particles may be altered in a variety of manners.

The experimental data have been interpreted in terms of this model. If associated production occurs only as a direct result of proton-nucleon interactions, the gamma-ray intensity per target nucleon would depend only upon the nucleon-nucleon cross section and the shadowing effect of one nucleon by another. Accordingly, the optical model[4] was used to compute the expected variation of gamma-ray yield with atomic number. Elementary nucleon-nucleon cross sections of $\bar{\sigma}=43$ mb, 28 mb, and 15 mb were assumed. These values were chosen to represent respectively the total cross section for proton-nucleon collisions,[5] the cross section for meson production in nucleon-nucleon collisions, and a cross section significantly smaller than either. These curves, together with the observed data, are shown in Fig. 3. The curve with $\bar{\sigma}=28$ mb is the one which should most closely apply, since it is by meson production that most of the protons are attenuated as far as heavy unstable particle production is concerned and in turn nucleons emerging from these inelastic collisions have a negligible probability of creating a strange particle.

In comparing these curves with the data, it should be realized that the magnitude of gamma-ray production from neutrons was found to be greater than that from protons (see the following text) and the neutron excess in the heavier elements can increase the yields. If some allowance is made for this fact, the curve corresponding to $\bar{\sigma}=15$ mb appears to fit the data. Since the π-meson production cross section is 28 mb, the cross section $\bar{\sigma}=15$ mb is probably too small to be consistent with heavy-particle production by 3-Bev protons. It is, therefore, concluded that the data favor a penetration of the incident proton into the nucleus which is larger than expected on the basis of the known proton-nucleon interactions.

The data are thus not easily explained if one only considers the shadowing of some nucleons by others in heavy nuclei.[6] For example, a nucleon in a heavy nucleus is more effective in producing the observed gamma rays than a free nucleon. This suggests that cascade processes are playing roles which enhance associated production in a heavy nucleus. A likely one is the production in a proton-nucleon collision of a high-energy π meson which then in the same nucleus creates a hyperon and heavy meson by the usual associated production process. This intermediate π-meson production process has been investigated with the aid of a simple nuclear model.[7] A spherical, uniform-density optical model was used. Some of the π mesons produced by the incident protons are effective in producing hyperons and K mesons. Both protons and π mesons are removed from the beam by inelastic collisions and the elementary cross sections corresponding to these collisions are assumed to be 30 mb in both cases. The dashed curve in Fig. 4 shows the variation with atomic number of associated production due to this process. This secondary process has the desired qualitative feature that it results in an increased effectiveness of large nuclei for producing particles which can be detected. The consistency of the data with the simultaneous production by direct and by intermediate π processes is also illustrated in Fig. 4. The gamma-ray yield was assumed to be the sum of two terms, one proportional to the direct production cross section by protons with $\bar{\sigma}=28$ mb and the other proportional to the intermediate π cross section. The

[3] The energy distribution of the π mesons produced in nucleon-nucleon collisions was estimated from the isobar theory of S. Lindenbaum and R. Sternheimer, Phys. Rev. **105**, 1874 (1957).

[4] B. Rossi, *High-Energy Particles* (Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1952), p. 359.

[5] For a summary of nucleon-nucleon cross sections see *Proceedings of the Sixth Annual Rochester Conference on High-Energy Physics, Session IV*, (Interscience Publishers, Inc., New York, 1956).

[6] Fermi momentum of a target nucleon could enhance the production on a heavy nucleus (and to a lesser extent on deuterium), but from an analysis of the excitation function reported,[1] it is estimated that the gamma-ray production cross section from copper is increased by only 12% over the production from hydrogen.

[7] This analysis was done in collaboration with Dr. R. Sternheimer and is reported in a Cornell University thesis by D. Berley (unpublished). G. T. Reynolds and S. Treiman have done a similar calculation (unpublished).

contributions by direct and indirect processes were adjusted to fit the data by the method of least squares. The good agreement between the measured and computed curves shown in Fig. 4 demonstrates that this intermediate process is compatable with the data. From this analysis, an estimate of the π-p cross section for associated production necessary to be consistent with the data was found to be $\sim$1 mb. The result is reliable only to several factors of 2 but is in excellent agreement with the measured cross section.[8] There is evidence that hyperons and heavy mesons produced by 960-Mev π mesons have a mean decay distance close to the one measured in this experiment[9] and this is also consistent with the idea of the intermediate π process.

There are other cascade processes which could produce the observed results. Modifications in the nature of the strange particles resulting from their passage out of the nucleus can also explain the enhancement of the observed gamma rays from large nuclei. For example, K^+ mesons cannot be detected in this experiment but can be detected if converted to K^0 mesons by the process $K^+ + n \rightarrow K^0 + p$. Similar processes are $\Sigma^- + p \rightarrow \Sigma^0 + n$ and $\Sigma^+ + n \rightarrow \Lambda^0 + p$. The strange particles also suffer scattering in leaving the nucleus and this process lowers their momentum and increases the average angle of emission. Both these effects are such as to increase the probability of detecting them in this experiment. Scattering effects, however, cannot by themselves distort the detection efficiency, as the mean decay distance is also sensitive to the momentum of the decaying particles and, as seen from Fig. 2, no change in the mean distance of decay is observed as the mass number is increased.

This part of the experiment suggests that primary collisions between incident 3-Bev protons and target nucleons cannot account for all the observed associated production. The deep penetration into the nuclei of the particles responsible for much of the associated production calls for secondary processes such as the two-step process involving an intermediate high-energy π meson.

There remains the question of gamma-ray production from p-p collisions as compared to that from p-n collisions. The observed gamma ray yields have been converted into the more interesting cross sections for associated production on the basis of the following assumptions: (1) The branching ratio for decay into neutral mesons is 1:3 for Λ^0 and 1:15 for θ^0.[10] (2) All particles are emitted in relative S angular momentum states and the production cross section is proportional to the density of final states. It has been pointed out by Sternheimer[11] that as a consequence of successive decays which lead ultimately to the gamma rays, the cross sections obtained are insensitive to the assumed angular and momentum distributions. (3) The efficiency of the gamma-ray detector is independent of energy and equal to 0.8 times the conversion efficiency for a gamma ray of several hundred Mev. (4) The gamma rays detected originate only from Λ^0 and Σ^0 hyperons and K^0 mesons. The mean life of the Σ^+ is inconsistent with the observed decay length of 4.0 cm. The Σ^+ is therefore assumed to make no contribution to the observed intensity.[12]

TABLE I. Total heavy-particle production cross sections. The cross sections listed are derived from the gamma-ray yield, in the following way: It is assumed that only one production process (for example, $p+p \rightarrow K^+ + \Lambda^0 + p$) proceeds. From the detection efficiency for the process a cross section was computed and this is the cross section listed.

Process	Production cross section from observed gamma rays
$p+p \rightarrow K^+ + \Lambda^0 + p$ }	
$K^+ + \Lambda^0 + p$ }	$(40\pm 60)\times 10^{-30}$ cm^2
$K^0 + \Sigma^+ + p$ }	
$K^+ + \Sigma^+ + n$	Not observed
$p+n \rightarrow K^0 + \Lambda^0 + p$ }	$(210\pm 30)\times 10^{-30}$ cm^2
$K^0 + \Sigma^0 + p$ }	
$K^+ + \Sigma^- + p$	Not observed
$K^+ + \Sigma^0 + n$ }	$(420\pm 60)\times 10^{-30}$ cm^2
$K^+ + \Lambda^0 + n$ }	

Table I lists the known processes for associated production from p-p and p-n interactions. When the above assumptions are used to estimate the chance of observing Σ^0, Λ^0, and K^0 particles, they lead fortuitously to the result that the probability of observing any of them is nearly the same. Thus the probability of observing any of the reactions listed in Table I is proportional to the number of unstable neutral particles produced. The conversions to cross sections have been made in the last column in Table I. It should be noted that there are two processes which produce no neutral particles and, therefore, cannot be observed, and that the first two processes listed under p-n interactions have a double chance of being observed because two neutral particles are produced. The interesting result is that the cross section for associated production by p-p interactions is significantly smaller than the cross sections by p-n interactions. The ratio is less than 0.2 ± 0.3. The errors given in Table I are relative ones. An estimate of the absolute cross section is also shown on the right-hand side of Fig. 3. Here, as in Table I, due to uncertainties in proton flux, counter geometry and detection efficiency, the uncertainty can be as large as a factor of two. The absolute value of 0.1 mb per nucleon

[8] L. Leipuner and R. K. Adair, Phys. Rev. **109**, 1358 (1958).
[9] M. Schwartz, private communication about the work of Plano, Saminos, Schwartz, and Steinberger on associated production by 960-Mev π^- mesons incident on propane in a bubble chamber.
[10] Plano, Samios, Schwartz, Steinberger, and Eisler, Nuovo cimento **5**, 1700 (1957).
[11] R. M. Sternheimer, Cosmotron Internal Reports RMS-60 and 63, 1956 (unpublished).
[12] It is difficult to evaluate the possible contribution of gamma rays from Σ^+ decays. If, however, the Σ^+ were observed with large efficiency it would tend to lower the estimated total p-p cross section relative to the p-n cross section.

for the cross section for associated production by protons on copper is, however, in agreement with values obtained by Baumel *et al.*,[13] Lindenbaum and Yuan.[14]

Other experiments have been performed to measure the cross section for production of heavy unstable particles by *p-p* collisions and the results are conflicting. The diffusion chamber experiment by Cool *et al.*[15] indicated extremely small or possibly zero cross sections for the production of Σ^+, Λ^0, or K^0 particles. Baumel *et al.*[13] report a cross section of between 0.1 and 0.3 mb for K^+-meson production obtained from differential cross sections measured at 0°. Lindenbaum and Yuan[14] have also observed K^+ production at 60°.

[13] Baumel, Harris, Orear, and Taylor **108**, 1322 (1957).
[14] S. J. Lindenbaum and L. C. L. Yuan, Phys. Rev. **105**, 1931, (1957).
[15] Cool, Morris, Rau, Thorndike, and Whittemore, Phys. Rev. **108**, 1048 (1957).

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Electron-Deuteron Scattering by the Impulse Approximation*

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The cross section for inelastic scattering of high-energy electrons by deuterons is calculated using the impulse approximation. The results agree with those of Jankus. The cross sections are given for several neutron charge and moment distributions. The peak cross sections are simply related to the free-nucleon cross sections with this approximation.

I

RECENT high-energy electron-deuteron scattering experiments by Hofstadter and Yearian[1] have yielded information about the neutron's electromagnetic structure. In these experiments, the electrons are scattered inelastically, disintegrating the deuteron, and the energy spectrum of the outgoing electrons is measured. The results show an inelastic peak of about 26- to 45-Mev width, centered slightly below the energy of elastic scattering from a free nucleon. The objective of this paper is to relate the peak cross sections or the area under these curves to the sum of the free proton and neutron cross sections. Since the proton cross section has been measured independently, the neutron cross section can then be determined.

Jankus[2] has calculated these cross sections by considering the Møller potential acting on the nuclear charge and current. At small momentum transfers, where the nucleons can be treated nonrelativistically, his results can be fitted to the experimental data. However, for large values of q^2, Jankus' curves show the peak at too low an energy. Blankenbecler[3] has suggested that the corrections to Jankus' results can be estimated by replacing the three-momentum transfer by the corresponding four-vector. With this modification, Hofstadter and Yearian have been able to fit the peak cross sections to their data within experimental limits.

Although Jankus' model breaks up the nuclear charge and current into separate proton and neutron terms, the electrons interact with the deuteron as a whole. Hence he obtains interference effects between the proton and the neutron. At large bombarding energies, with the electron wavelength much shorter than the separation between nucleons, the interference is expected to be small. To test the importance of these interference effects, we have used the impulse approximation to calculate the inelastic scattering cross section as a function of outgoing electron energy.

In this approximation, the nucleons are free particles, with a distribution of momenta due to the deuteron binding. The electron interacts separately with the neutron or the proton as a moving free particle. As a result, the interacting nucleon is given a large outgoing momentum, while the other is unaffected. The scattering from the two nucleons is then incoherent, and one may add the cross section for each process. This must then be averaged over the initial nucleon momenta to give the total differential cross section.

II

If we consider scattering by a free proton of initial momentum $\mathbf{p}_p$, the transition rate for the electron from the state of momentum $\mathbf{k}$ to momentum $\mathbf{k}'$ (energy k

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† Holder of a National Science Foundation Fellowship for the years 1955–56, 1956–57, and 1957–58.
[1] M. R. Yearian and R. Hofstadter, Phys. Rev. **110**, 552 (1958).
[2] V. Jankus, Phys. Rev. **102**, 1586 (1956).
[3] R. Blankenbecler, Phys. Rev. **111**, 1684 (1958).