neutral mesons to charged particles produced by collisions of cosmic-ray nucleons and α-particles with nuclei of copper. The techniques involved are described in reference 1. The energy per nucleon of the primary causing the event is usually estimated by the kinematical considerations of reference 1. Despite the energy being estimated on the single nucleon-nucleon assumption, in those cases where an accurate check is available by the energy balance method of reference 1, the two methods give agreement within statistical limits.

Table I summarizes the relevant data on the events completely or partially analyzed thus far. Column 1 designates the shower and the incident particle causing the shower (it is not possible in every instance to uniquely determine the primary, but we can be certain that it has either a charge of 0 or 1, or its charge is definitely>1). Column 2 gives the observed charged particle multiplicity per incident nucleon in the initial interaction and column 3 the ratio of neutral π-mesons to charged particles.[2] Column 4 gives the energy per nucleon in the laboratory system (γ) of the primary in units of the nucleon rest mass. Column 5 gives the observed value of the quantity $X=x/x_I$, where $x=\theta_{3/4}/\theta_{1/4}$ is the ratio of the laboratory angles containing a fraction $\frac{3}{4}$ and $\frac{1}{4}$ of the charged particles; x_I is the same ratio for a theoretical multiple process with an isotropic distribution in the center-of-mass system (c.m.) of 2 nucleons. Column 6 gives the impact parameter r/R for the shower corresponding to the Fermi theory,[3] and column 7 gives the charged meson multiplicity as determined from Fermi's theory[4] for a single nucleon-nucleon collision corresponding to an energy of the incident nucleon $E=\gamma mc^2$ and the impact parameter given in column 6.

An examination of column 5 reveals a distribution in values for the quantity X. In a nucleon-nucleon collision isotropic in the c.m. system one should find $X=1$, whereas for nonisotropic distributions in the c.m. system (e.g., such as predicted by the Fermi theory), X should show large deviations from the value 1. As the interactions occur in brass, the showers we observe must in most cases result from successive collisions inside the nuclei.

Such showers resulting from several collisions, each with different impact parameters, would be expected to show on the average similar angular distributions characterized by some average impact parameter. This behavior is not observed for single nucleon produced showers but is observed for α-particle showers, which from their multiplicities appear to involve the interaction of four separate nucleons. The three α-particle showers observed all have similar angular distributions characteristic of some average impact parameter.

We believe this is an indication that at high energies a nucleon-nucleus collision exhibits similar properties to a nucleon-nucleon collision. Multiple production of particles results from the first nucleon-nucleon interaction. These particles than all interact together in any successive collisions inside the nucleus.[5] This is consistent with the Fermi picture and results from the view that at extremely high energies a nucleon interacts in a similar manner whether it is accompanied by a real or virtual group of particles. If this is correct a characteristic impact parameter for a nucleon-nucleus collision is defined by the last target nucleon struck in the nucleus; the multiplicity should be near to that of a pure nucleon-nucleon collision.

On the basis of the foregoing assumptions the observed charged particle multiplicity is compared with that calculated from the Fermi theory (column 7). We note that the agreement is best for low impact parameters but is worse at high impact parameters. It would appear that the idea of impact parameter has meaning in describing the angular distributions in these interactions but that the multiplicity is not a strong function of impact parameter. Independent evidence for the view that a single nucleon-nucleon collision and a nucleon-nucleus collision give the same results at high energy is provided by the similarity of the S-star[6] (which resulted from a nucleon-nucleon collision), the Gerosa and Levi-Setti star[7] (formed in AgBr), and our stars of high impact parameters.[8]

The observed large ratio of neutral π-mesons to charged particles implies within the context of the Fermi theory a relatively small contribution of nucleon-antinucleon pair production as compared to π-meson production in this energy band.

We have also made approximate kinematical estimates of the energy of the showers given by Pickup and Voyvodic[9] (energies of the order of 10^{11} ev) and, by comparing their median energy and multiplicity with that derived from our data, find that the multiplicity of meson production varies as $\gamma^{\frac{1}{4}}$, which is in agreement with the predictions of the Fermi theory.

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* This work was supported by the AEC.

[1] Kaplon, Peters, and Ritson, Phys. Rev. **85**, 900 (1952).

[2] We assume that the soft component of mixed showers in its early stages arises exclusively from the 2-photon decay of the neutral π-meson. See R. E. Marshak, Phys. Rev. **74**, 1735 (1949).

[3] E. Fermi, Phys. Rev. **81**, 683 (1951).

[4] The charged particle multiplicity is calculated on the basis of Fermi's theory assuming only π-mesons are produced. If one also allows for the production of nucleon-antinucleon pairs, the calculated charge multiplicity is changed by the same factor (0.985) for each shower independent of the impact parameter.

[5] One can easily show that the c.m. system defined by an assemblage of particles produced by a nucleon of energy $E=\gamma mc^2$ with a nucleon at rest is identical to that formed by the incident nucleon ($E=\gamma mc^2$) and a nucleon at rest.

[6] Lord, Fainberg, and Schein, Phys. Rev. **80**, 970 (1950).

[7] A. Gerosa and P. Levi-Setti, Nuovo cimento **8**, 601 (1951).

[8] A further test of this hypothesis is possible with observations on energetic showers made in a very heavy nucleus such as Pb. Such an experiment is now being planned.

[9] E. Pickup and L. Voyvodic, Phys. Rev. **82**, 265 (1951).

Primary Flux of High Energy Protons and α-Particles*

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MEASUREMENTS utilizing the emulsion cloud-chamber technique described in the previous letter have been used to obtain flux values in the 10^{12}–10^{13}-ev region.

70 cm^2 of emulsion halfway down in the "cloud chamber" were systematically scanned for all showers crossing the emulsion; a total of fifty-six such showers were found. Many of these showers could only be followed for a short distance and then become too diffuse to follow further. These showers must have come largely from low energy interactions of the order of 10^{11} ev. (Showers with a γ-ray in excess of 3×10^{11} ev can be followed through the entire stack.)

To obtain flux values it was necessary to eliminate those showers which were detected with a low and unknown efficiency. The condition was imposed that all showers must contain at least one secondary electron shower with an energy greater than 3×10^{11} ev. This left a total of fourteen showers. Detailed examination of these events showed that six were γ-ray induced and eight caused by nuclear interactions. The median energy of these eight events estimated from kinematic considerations was 4.5×10^{12} ev. (We can arrive at an independent estimate from our requirement of one secondary electron shower whose energy is in excess of 3×10^{11} ev; we infer from this a median energy of $\sim3\times10^{12}$ ev.) In all these eight cases the primary had a charge $Z\leq1$.

Using an absorption mean free path for nucleons in air of 100 g/cm^2 and a geometric interaction mean free path in the stack, we evaluate the integral primary flux with energy greater than 4.5×10^{12} ev as 0.04 particles per meter^2 per sterad per sec at the top of the atmosphere assuming an isotropic flux. On the assumption of a power law for the integral primary spectrum we find an exponent of 1.45 ± 0.15 using the known values at low energies.[1] The error takes into account the uncertainty of the median energy which we consider to be of the order of 2.

In a less systematic survey of an additional 70 cm^2 we have found two α-particle induced showers with energies per nucleon in the same range as the proton induced showers. It therefore appears that α-particles constitute about 10 percent of the primary flux and that accordingly the ratio of α-particles to protons remains relatively constant over a large energy range. This seems to be in agreement with results previously reported,[2] which indicate a similar velocity spectrum for all components of the primary beam, and is not in agreement with the predictions of the simple Fermi[3] theory of acceleration of cosmic-ray primaries.

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* This research was assisted by the AEC.

[1] Winckler, Stix, Dwight, and Sabin, Phys. Rev. **79**, 656 (1950).

[2] Kaplon, Peters, and Ritson, Phys. Rev. **85**, 900 (1952).

[3] E. Fermi, Phys. Rev. **75**, 1169 (1949). For an integral energy spectrum varying as $N=K/\epsilon^{\gamma}$, where ϵ is the kinetic energy in Bev/nucleon, Fermi gives $\gamma_p/\gamma_\alpha=\lambda_\alpha/\lambda_p$, where λ is the absorption mean free path. As $\lambda_\alpha \approx \frac{1}{2}\lambda_p$, we find $N_p/N_\alpha=(K_p/K_\alpha)\epsilon^{\gamma}$. For the energy region of this experiment one obtains $N_p/N_\alpha \approx 8\times 10^5$; $(K_p/K_\alpha \gtrsim 5)$. We believe therefore that our results are significant, notwithstanding the poor statistics.

Neutrons and Gamma-Rays from the Proton Bombardment of Beryllium

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The neutron and gamma-ray yields in the forward direction resulting from the proton bombardment of beryllium have been extended to a maximum proton energy of 5.3 Mev. Voltage calibration of the electrostatic generator has been previously discussed.[1] Targets were thin (approximately 11 kev at threshold) foils obtained through the courtesy of Dr. Hugh Bradner. Neutron yields were measured with a "long" counter placed in the forward direction. Gamma-rays were detected with a large sodium iodide crystal also located along the beam axis. Pulses from the crystal were amplified and fed into two discriminators so that the yields of gamma-rays above approximately 2 and 6 Mev were obtained.

The upper curve of Fig. 1 shows a typical neutron yield. In addition to the geometrical peak and the well-known rise at 2.56 Mev,[2] a third peak is obtained at a proton energy of 4.7 Mev. The existence of a level at high energy had been predicted from work done at the University of Wisconsin.[3] A run, not shown, using a low energy neutron counter similar to that described by Bonner and Butler[4] showed no obvious levels in the residual B^9 nucleus between 2- and 5.3-Mev proton energy.

The middle and lower curves of Fig. 1 show the yield of gamma-rays with energy greater than approximately 6 Mev and 2 Mev, respectively. The level at 2.57-Mev proton energy is observed in both the high and low energy gamma-ray yields. The level at 4.7 Mev does not appear in the low energy yield due to the relatively high intensity of the nonresonant, low energy gammas.

The gamma-ray yield curves are, in this particular case, essentially free of interferences from neutron reactions occurring in the NaI crystal. This is indicated by the considerably narrower resonance in the gamma-ray yield at 2.56 Mev as compared with the corresponding one in the neutron yield. Boron layers placed between the target and the crystal confirmed this hypothesis.

The new level occurs at a proton bombarding energy of 4.72 ±0.01 Mev and has a full width at half-maximum of approximately 0.5 Mev. We find the lower energy level at 2.57±0.01 Mev. These energies are the averages obtained from several runs.

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[1] Willard, Bair, Kington, Hahn, Snyder, and Green, Phys. Rev. **85**, 849 (1952).

[2] W. J. Hushley, Phys. Rev. **67**, 34 (1945); Richards, Smith, and Browne, Phys. Rev. **80**, 524 (1950).

[3] Richards, Laubenstein, Johnson, Ajzenberg, and Browne, Phys. Rev. **81**, 316 (1951).

[4] T. W. Bonner and J. W. Butler, Phys. Rev. **83**, 1091 (1951).

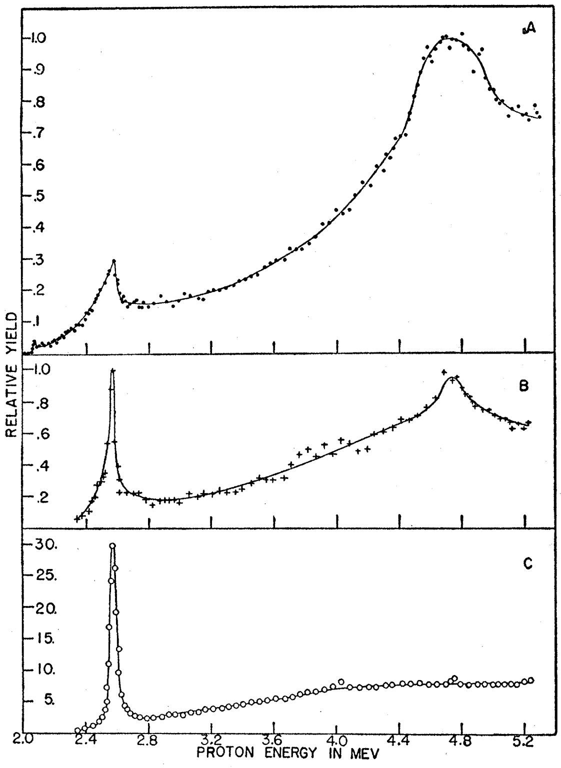

FIG. 1. Yield curves for neutrons and gamma-rays from beryllium bombarded by protons. Top curve, neutron yield; middle curve, gamma-rays of energy greater than approximately 6 Mev; lower curve, gamma-rays of energy greater than approximately 2 Mev. All yields are in arbitrary units.

Total Cross Sections of Negative Pions in Hydrogen*

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The interaction of negative pions and protons has been investigated by Steinberger and co-workers[1] for pions of 85-Mev energy by transmission measurements and by Shutt and co-workers[2] for pions of 55 Mev by direct observation of pion tracks in a Wilson chamber. Both measurements indicate a surprisingly low value for the cross section in this range of energies. We have undertaken to extend the total cross section measurements to higher energies.

The negative pions are produced in the large Chicago cyclotron by protons of 450 Mev striking a target which in some of the experiments was copper and in others beryllium. The negative pions are bent in the fringing field of the cyclotron and enter channels in a 6-foot steel shield which separates the cyclotron from the experimental room where the measurements are taken. Further monochromatization and purification of the pion beams are carried out by a deflecting magnet located in the experimental room. In this manner one obtains a sharply collimated beam containing pions with energy defined within ±3 percent. In addition to the pions this beam contains some muons and electrons of the same momentum. Their number has been determined from a range curve. The muons amount to between 5 percent and 10 percent. The electrons are present in negligible numbers for beams above 100 Mev. Below this energy the electron contamination increases rapidly. For this reason low energy measurements have been taken by reducing with a beryllium absorber the energy of the 122-Mev beam.

By using various channels we have taken measurements over the energy range from about 80 to 230 Mev.