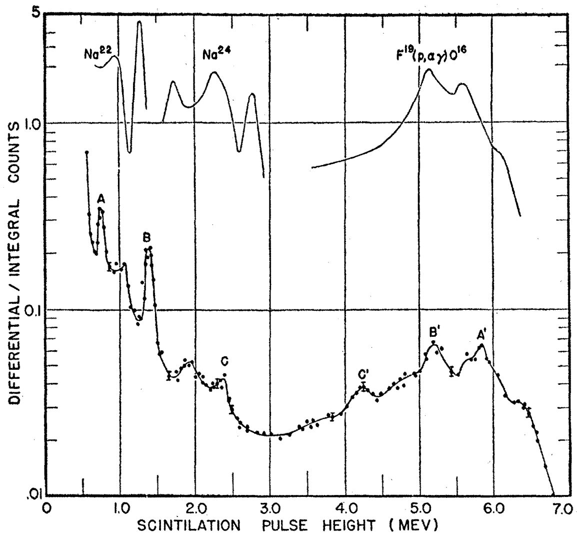

FIG. 1. Scintillation pulse-height spectrum (lower curve) for γ-rays produced by 277-kev protons on N^{14}. The ratio of differential to integral counts is plotted as a function of pulse height in Mev. Standard deviations of all data points are five percent and are indicated for scattering points on the curve. In the upper part of the figure is shown the pulse-height distributions for γ-rays from Na^{22} and Na^{24} and γ-rays from 340-kev protons on F^{19}.

An analyzed proton beam of from 200 to 400 μa from the Cockcroft-Walton generator impinged on a thick TaN target which had been formed by inductively heating a tantalum disk in a nitrogen atmosphere. Gamma-rays were detected by a NaI(Tl) crystal 2 inches long and 1.5 inches in diameter placed at 0° with respect to the proton beam. Scintillations were detected and analyzed by a 5819 photomultiplier, linear amplifier, and a single-channel analyzer.

A thick target yield curve showed a rise near 277 kev in agreement with the $N^{14}(p, \gamma)O^{15}$ resonance observed by Tangen.[1] The proton energy was set about 10 kev above the resonance and the pulse-height distribution in the lower part of Fig. 1 was obtained. Energy calibrations were made using γ-rays from Cs^{137} (0.661 Mev),[2] Na^{22} (1.277 Mev),[3] Na^{24} (2.755 Mev),[4] and the 6.13 Mev[5] γ-ray from 340-kev protons on F^{19}. To aid in the interpretation of the nitrogen spectrum the pulse-height distributions of the various calibration γ-rays is shown in the upper part of Fig. 1. Radiations from Na^{22} and Na^{24} produce photoelectric peaks at the γ-ray energies accompanied by Compton peaks at slightly lower energies. Na^{24} also exhibits a pair group 1.02 Mev below the γ-ray energy. A comparison with the nitroben spectrum indicates that groups B and C of Fig. 1 are photoelectric peaks accompanied in each case by a Compton group of slightly lower energy. Pairs associated with C contribute very little to the peak at B. Peak A is also a photoelectric peak whose Compton group is buried in the background.

In the higher energy region pair production predominates to give a pulse-height distribution which is illustrated by the $F^{19}(p, \alpha\gamma)O^{16}$ spectrum shown in the upper part of Fig. 1. The single γ-ray produces a triple peak by the following process. A part (1.02 Mev) of the γ-ray energy is used for pair production and reappears as annihilation radiation at the end of the positron track. Since the annihilation radiation usually escapes the crystal, the most prominent group of pulses is 1.02 Mev below the γ-ray energy. Occasionally one or both 0.51-Mev annihilation radiations are captured in the crystal so that the observed distribution shows subsidiary peaks 0.51 Mev and 1.02 Mev above the main group.

A comparison of the nitrogen and fluorine distributions indicates that groups A', B', and C' are pair peaks each 1.02 Mev below their γ-ray energies. A subsidiary peak associated with A' is clearly resolved, and there is some indication of subsidiary peaks above B' and C'. Thus the pulse-height distribution of Fig. 1 results from six γ-rays designated as A, B, C, C', B', A', whose energies are 0.75 ± 0.03, 1.39 ± 0.03, 2.38 ± 0.10, 5.29 ± 0.10, 6.21 ± 0.10, and 6.84 ± 0.10 Mev, respectively.

Gamma-rays from protons on nitrogen can arise only from capture followed by positron decay to N^{15}. Positron decay could leave N^{15} with up to 1.68-Mev excitation; however, since the observed positron spectrum is apparently not complex[6] and since no low-lying states are known in N^{15},[7] it is assumed the decay occurs to the ground state and all γ-rays result from direct capture. According to recent mass values,[8] 277-kev protons on N^{14} form O^{15} with 7.60-Mev excitation energy. The six γ-rays contributing to the distribution of Fig. 1 can be attributed to proton capture by nitrogen only if there are three intermediate levels in O^{15} giving rise to three cascade processes of two γ-rays each. These cascade groups are AA', BB', and CC', and their energies add to the total excitation as follows:

$$A+A'=0.75+6.84=7.59\pm0.13 \text{ Mev}$$
$$B+B'=1.39+6.21=7.60\pm0.13 \text{ Mev}$$
$$C+C'=2.38+5.29=7.67\pm0.20 \text{ Mev.}$$

The strongest groups B and B' must certainly be assigned to nitrogen since the integral yield curve shows the 277-kev resonance. The weaker groups (A, A', C, and C') could possibly be attributed to target contaminants; however, the fact that they can be arranged in cascade groups in the above manner is strong evidence that all observed γ-rays come from nitrogen. No direct transition to the ground state was found.

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Extremely High Energy Nuclear Interactions*

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(Received December 26, 1951)

BY utilizing the technique of an "emulsion cloud chamber" to select high energy events[1] we have studied the angular distribution, multiplicity of penetrating particles, and ratio of

TABLE I. Summary of data.

(1) Shower and primary	(2) Number of charged particles (N_{ch})	(3) $\frac{N_{\pi^0}}{N_{ch}}$[a]	(4) $\gamma\times10^{-3}$	(5) X	(6) $\frac{r}{R}$	(7) N_{ch} (Fermi)[b]
$A(\alpha)$	21(84)	0.6 ± 0.2	3	1.17	0.18	15
$178(\alpha)$	23(92)	0.72 ± 0.15	6	2	0.46	14
$R(\alpha)$[c]	14(56)	0.75 ± 0.25	0.48	2.33	0.57	6.6
$77(p)$	24	···	4	1.17	0.18	16.5
$104(p)$	20	0.5 ± 0.3	1.3	1.33	0.23	11.7
$67(p, n)$	9	1.2 ± 0.5	4.5	1.33	0.23	16
$60(p, n)$	26	···	19.5	1.33	0.23	23
$91(p, n)$	16	0.6 ± 0.35	1.3	1.7	0.34	10.8
$17(p)$	24	1.1 ± 0.3	5.1	3.7	0.76	7.9
$59(p)$	24	0.5 ± 0.3	8.9	4	0.78	8.8
$66(p, n)$	11	0.75 ± 0.4	0.64	6.67	0.87	2.7
$T(p)$	36	0.6 ± 0.2	19.4	6.67	0.87	6.3
$Z(p, n)$	15	0.5 ± 0.25	50	24	~1	≤3.4
$S(p)$[d]	15	···	32	···	~1	≤6
$G-L(p)$[e]	18	···	23	≥9	~1	≤6
		Av. 0.71 ± 0.3				

[a] This ratio is not corrected for seconday nuclear interactions. An approximate estimate for this indicates that the observed ratio can be lowered by as much as 30 percent. The correction will vary for each individual shower.
[b] See reference 4.
[c] Kaplon, Peters, and Bradt, Phys. Rev. **76**, 1735 (1949).
[d] See reference 6.
[e] See reference 7.

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 $\gamma^{1/4}$, which is in agreement with the predictions of the Fermi theory.

* This work was supported by the AEC.
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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.
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Primary Flux of High Energy Protons and α-Particles*

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(Received December 26, 1951)

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