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INVESTIGATION OF PION PRODUCTION IN INTERACTIONS OF COSMIC-RAY PROTONS AND α PARTICLES WITH CARBON NUCLEI IN THE STRATOSPHERE

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Pulse ionization chambers and a hodoscope were used to study the interaction of primary protons and α particles with carbon nuclei in the stratosphere at 31° N geomagnetic latitude. The electron cascade initiated in lead by γ quanta from the decay of the neutral π mesons produced in the interaction was investigated. It was found that the primary-particle energy consumed in π^0 production in the interactions between protons or α particles and carbon nuclei in the $\sim 10^{10}$ ev energy range is on the average $(10 \pm 3)\%$ and $(14 \pm 10)\%$ respectively.

INTRODUCTION

UNTIL 1954, no direct measurements had been made of the energy fraction consumed in the production of π mesons in a single act of interaction of cosmic-ray protons with light nuclei. Slight inelasticity of the interaction between nucleons and light nuclei in the energy range of $\sim 10^{10}$ ev was inferred indirectly through a study of the absorption of the nuclear-active particles in cosmic rays[1] and the production of the various secondary components of cosmic radiation in the atmosphere.[2] The validity of this conclusion depended substantially on the assumed value of the cross section for inelastic interactions.

The energy consumed in the production of π^0 mesons can be determined from a measurement of the ionization at the maximum of the cascade shower initiated by the γ quanta produced in π^0-meson decay. By measuring the total ionization produced by all the electrons at the shower maximum, and also the average ionization due to a single electron, we can determine the number of particles N_{max} at the shower maximum. The relation between N_{max} and the energy E of the primary electron or the photon initiating the cascade, given by Belen'kiĭ,[3] makes it possible to determine the average total energy E of the γ quanta produced in the π^0 decay from the number of electrons at the shower maximum, i.e., the average energy $E_{\pi^0} = E$ transferred to π^0 mesons:

$$N_{max} = K(E/\beta)E/\sqrt{\ln(E/\beta)}\,\beta, \qquad (1)$$

where $\beta = 6.4 \times 10^6$ ev is the critical energy in lead. Thus, a measurement of the number of electrons at the shower maximum, obtained by measuring the ionization due to these particles, yields directly the energy consumed in the production of π^0 mesons, without the need for any assumption regarding the cross section of the inelastic interaction.*

On September 20, 1954, measurements of the ionization at the maximum of cascade showers produced by γ quanta from the decay of π^0 mesons (average energy of primary protons — $\overline{E}_{0p} = 20$ Bev, that of the primary α particles — $\overline{E}_{0\alpha} = 40$ Bev) were carried out in the stratosphere at an altitude of 25 km and at 31° N geomagnetic latitude. Pulse ionization chambers and a hodoscope were used. The apparatus was lifted into the stratosphere by probe balloons. The results of the measurements were transmitted to the earth by radio.

EXPERIMENTAL SETUP

The arrangement of the counters, ionization chambers, and absorbers, together with a block diagram of the electronic circuits, is shown in Fig. 1. The telescope, which selected a vertical beam of particles, consisted of three trays A, B, and C of self-quenching Geiger-Müller counters. Each tray, consisting of three counters, was connected to a triple-coincidence circuit. The geo-

*In the 10^8–10^{10} ev range, $K(E/\beta)/\sqrt{\ln(E/\beta)}$ does not depend strongly on the energy. Therefore, the number of particles at the shower maximum can be regarded as proportional to the energy consumed in the production of π^0 mesons. According to Belen'kiĭ, the average value of $K(E/\beta)/\sqrt{\ln(E/\beta)}$ in the 10^8–10^{10} ev range is 0.080.

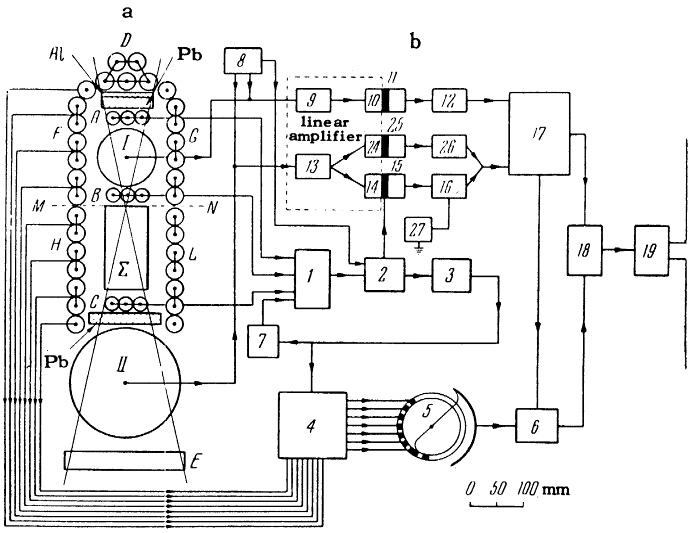

FIG. 1. a) Arrangement of the counters, ionization chambers, and absorbers in the apparatus. b) Block diagram of the electronic circuitry: 1 – triple coincidence circuit, 2 – gating univibrator, 3 – hodoscope master pulse shaping circuit, 4 – hodoscope, 5 – rotary switch, 6 – hodoscope pulse tube, 7 – triple-coincidence gating circuit, 8 – generator of calibration pulses, 9, 10, 13, 14 and 13, 24 – channels of linear amplification, 11, 15, 25 – gating circuits, 12, 16, 26 – pulse-stretching circuits, 27 – blocking of the sensitive channel of the lower chamber, 17 – circuit for simultaneous transmission of pulses from both chambers, 18 – modulator of the transmitter, 19 – transmitter. The elements in the block diagram are marked according to the block diagram of the apparatus in reference 4.

metrical factor of the array was $S\Omega = 9$. The investigated absorber Σ, of 19.5 g/cm^2 graphite, was placed between trays B and C. During the time of flight, the absorber was inserted into the telescope or removed from it every three minutes, so that the measurements with graphite were alternated with background measurements all the time. Two cylindrical pulse ionization chambers were incorporated into the setup, one inside the telescope between the trays A and B (chamber I), and the second below the lower tray C of the hodoscope counters (chamber II).* An absorber consisting of 2 cm of lead and 1 cm of aluminum was placed above the top tray A. The thickness of this absorber was sufficient to insure that practically all particles of the electronic component from the atmosphere underwent an electromagnetic interaction in it and initiated cascade showers, which were efficiently detected by the counters placed above the line MN. The top group D of counters, connected in parallel and actuated by a separate hodoscope cell, covered the total acceptance angle of the apparatus. Therefore, all triple-coincidence events due to single particles inside the acceptance angle of the apparatus were necessarily accompanied by a discharge in counters D (four-fold coincidences). Photons which traversed the instrument underwent conversion in the upper lead absorber, producing electron showers detectable by the instrument. In that case, however, counters D did not discharge.

*The dimensions of ionization chambers I and II were, respectively: cylinder diameter 100 and 200 mm; length 300 and 300 mm; wall thickness 0.5 and 0.9 mm brass; diameter of internal electrode (steel rod) 3.0 and 6.0 mm. The chambers were filled with spectrally pure argon at 5.0 and 3.0 atmos, respectively, and were operated at 1000 v.

A lead absorber 2 cm thick was placed above chamber II underneath tray C. The γ quanta from the decay of the π^0 mesons produced on carbon were converted in this absorber, and a cascade shower developed which attained its maximum within the absorber. The telescope, the ionization chambers, and the graphite and lead absorbers were surrounded by counters connected to the hodoscope (counters E, F, G, H, L). All the telescope counters were also connected to the hodoscope.*

The setup was triggered (see block diagram, Fig. 1b) by a triple coincidence (block 1) of discharges in the trays A, B, and C of the telescope counters. The resolving power of the triple coincidence circuit was 5×10^{-6} sec and that of the hodoscope cells was 2×10^{-5} sec. The linear amplifiers 9 – 10, 13 – 14, and 13 – 24 (connected to chambers I and II) were gated through junctions 11, 15, and 25, at the moment of passage of a particle through the telescope, by a square pulse of 2×10^{-4} sec duration, the length of the measured pulse being $\sim 1 \times 10^{-4}$ sec. The linearly amplified pulses of chamber I ranged from 10 to ~ 400 μv at the amplifier input (the probable pulse due to a single relativistic single-charged particle being 18 μv). For chamber II, which was meant mainly for the detection of showers containing a large number of particles, the range of linear am-

*The counters were filled with a mixture of argon and ethylene. A thin graphite layer spread on the internal surface of the glass walls served as the negative electrode. The wall thickness varied from 1.0 to 1.5 mm. The dimensions of the counters were: A, B, C – diameter 20 mm, length 200 mm; D – diameter 30 mm, length 300 mm (5 pieces); E – diameter 30 mm, length 200 mm (17 pieces); F, G, H, L – diameter 30 mm, length 300 mm (28 pieces).

plification was wider, from 10 μv to ~ 10 mv at the input.* This made it possible to measure accurately by means of chamber II the ionization produced both by a single relativistic particle and by a shower containing up to 500 particles (the probable ionization in chamber II due to a single relativistic singly-charged particle produced a pulse of 25 μv at the amplifier input).

A description of the block diagram of the apparatus, some characteristics of the operation of the individual circuits, and also the method of radio transmission and of the recording of the signals received on earth are given in reference 4, which describes an experiment carried out with similar apparatus.

RESULTS OF MEASUREMENTS

The hodoscope data were used to determine the nature of the shower and the place of its initiation. In this experiment, we were interested only in events in which charged particles traversed the apparatus. These particles were selected by the discharges they produced in counter group D. Using the hodoscope data, we excluded cascade showers produced by electrons in the upper lead absorber. In that absorber, practically all of the electronic component (~ 98%) underwent cascade multiplication. A shower was considered electron-produced when discharges occurred either a) in more than one counter of trays A or B, or b) in one counter each of trays A and B together with a discharge of at least one counter out of those placed above the graphite absorber (counters F and G located above the line MN). The other detected events represented either singly-charged particles which did not interact with the absorbers (discharge of one counter each in trays A, B, C, and not more than one counter in tray E), or showers in the lower part of the instrument, the particles of which were detected by a counter located below line MN. This category of showers also included electron-nuclear showers emerging from graphite and from the lead located above chamber II. (These showers caused either a) the discharge of one counter each in trays A and B and the discharge of more than one counter in tray C, or b) the discharge of one counter each in A, B, C together with the discharge of at least one counter in the side trays H and L, or together with the discharge of two or more counters in tray E.) Since the showers produced in graphite were recorded against a large background of electron-nuclear showers from the lower lead absorber and of nonlocal showers, the effect due to the carbon was evaluated from the difference of measurements with and without graphite. We disregarded the possible variation in the background of the nonlocal showers upon changing from measurements with the graphite to measurements without it. However, there was no reason to believe this variation to be large.

The particle that produced an electron-nuclear shower in graphite was identified by the ionization produced by this particle in the upper chamber I. Because of the presence of large fluctuations in the ionization in the chamber gas, and also because of fluctuations in pulse size due to the superposition of noise, we assumed that the ionization primary protons in the upper chamber could produce ionization in the range $J/J_0 = 0 - 3.0$, and primary alpha particles could yield $J/J_0 = 3.0 - 7.5$ (where J_0 is the probable ionization due to a relativistic singly-charged particle, and J is the ionization due to the given particle).[4]

Figure 2a shows the ionization spectra of showers in the lower part of the apparatus (below the 2-cm lead layer), obtained at an altitude of 25 km from the data of the lower chamber II, under the condition that the pulse in the upper chamber I was $0 - 3.0$ times that due to probable ionization by a relativistic singly-charged particle (this being the range of showers produced by primary protons). A correction is applied to this spectrum for the ionization due to δ showers, based on data obtained on earth, since it could be assumed that all local showers detected at the surface of the earth in the lower part of the apparatus were δ showers. The solid and dotted histograms were obtained for measurements with and without graphite, respectively. The results of the measurement without graphite were multiplied by 1.26 to reduce them to the period of the measurements with graph-

*The range of the amplifier connected to chamber II was extended in the following way: after two amplification stages (block 13), the pulse from chamber II was fed simultaneously to the sensitive (14, 15, 16) and "coarse" (24, 25, 26) channels. The pulses were stretched (see description of the block diagram in reference 4) by circuits 16 and 26 and, as long as the pulse from chamber II was small, both stretched pulses were fed to circuit 17. This circuit recorded the longer of the two received stretched pulses, i.e., the pulse from the sensitive channel. If the pulse from chamber II was larger than ~ 400 μv at the amplified input, then the sensitive channel was blocked by circuit 27. As a result of this, only the stretched pulse from the "coarse" channel 24, 25, 26 of chamber II was fed to circuit 17. In order to note the passage of the pulse from the chamber along the "coarse" channel, the voltage pulse from the blocking neon tube in circuit 27 was fed to a marking circuit. As a result, every time the sensitive channel was blocked a voltage pulse appeared on the switch contact connected to the cathode of the neon tube in the marking circuit.

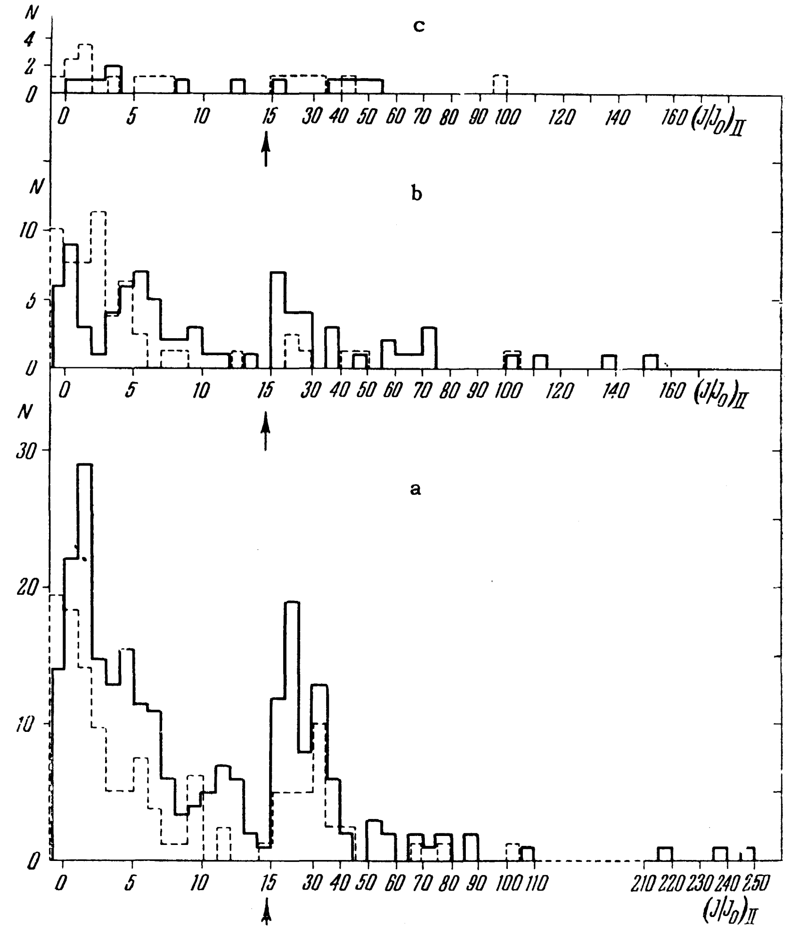

FIG. 2. Ionization spectra in the lower chamber II, obtained in the stratosphere at an altitude of 25 km, in measurements with the graphite absorber (solid line) and without it (dotted line) for pulse in the upper chamber equal a) $0 < (J/J_0)_I < 3.0$; b) $3.0 < (J/J_0)_I < 7.5$; c) $(J/J_0)_I > 7.5$. For ionization values $(J/J_0)_{II} > 15$, the scale of the y axis is compressed by a factor of five. N — number of showers with a given ionization.

ite (t = 42.3 min). Equivalent data are shown in Fig. 2b for an ionization range in the upper chamber equal to 3.0 — 7.5 times the probable ionization (range of showers from primary α particles); a correction for δ showers was not introduced here. Figure 2c represents the same for an ionization range in the upper chamber greater than 7.5 times the probable ionization. The excess of the number of showers in measurements with graphite, due to the showers produced on carbon by protons (Fig. 2a)* and by α particles (Fig. 2b), is clearly noticeable. For an ionization in the upper chamber greater than 7.5, the effect of carbon has not been detected, within the limits of the very scant statistical data (Fig. 2c).

Using the data of Fig. 2, we can calculate the average ionization in chamber II under 2 cm of lead per shower initiated in carbon by a proton or an α particle. The average ionization per shower initiated in the carbon, expressed in units of the average ionization due to a relativistic singly-charged particle, gives directly the average number of charged relativistic particles in the shower. To obtain the average number $\bar{\nu}$ of electrons at the shower maximum of a cascade produced by the γ quanta from π^0 decay, we should apply to the measured average number of charged relativistic particles in the shower a correction for the number $\bar{n}$ of penetrating particles in the shower.

A formula for calculating $\bar{\nu}$ on the basis of the obtained ionization spectra was derived from simple considerations, and is of the form

$$\bar{\nu} = 0.80\left[\frac{\sum(N_i^{C+ph}J_i/1.20J_0) - \sum(N_i^{ph}J_i/1.20J_0)}{\sum N_i^{C+ph} - \sum N_i^{ph}} - \bar{n}\right]. \quad (2)$$

where J_0 is the probable ionization of a relativistic singly-charged particle, $1.20\ J_0$ is the average ionization of a relativistic singly-charged particle, J_i is the ionization of the given particle, N_i^{C+ph} is the number of showers with a given ionization J_i/J_0 obtained in measurements with graphite in the telescope, N_i^{ph} is the same for measurements without graphite, $\bar{n} = 4.2 \pm 0.5$ is the average number of charged penetrating particles (protons and π mesons) per shower initiated in carbon by a proton (according to our data), and $\bar{n} = 9.1 \pm 0.7$ is the same per shower produced by an α

*The absolute number of interactions between protons and carbon nuclei obtained in the present experiment is in agreement with our 1955 data.[5]

Results of measurements of the energy consumed in production of π^0 mesons in electron-nuclear showers initiated in carbon by protons and α particles

Primary particle	Proton $\bar{E}_0 = 20 \cdot 10^9$ ev	α-particle $\bar{E}_0 = 40 \cdot 10^9$ ev
Ionization range J/J_0 in chamber I	0—3.0	3.0—7.5
Measured average number of electrons at cascade shower maximum, $\bar{\nu}$	11.4 ± 3.5	32.2 ± 23.0
Number of electrons in the shower N_{max} with corrections	26 ± 8	73 ± 52
$\bar{E}_{\pi^0}$, ev	$(2.1 \pm 0.6) \cdot 10^9$	$(5.8 \pm 4.2) \cdot 10^9$
$(\bar{E}_{\pi^0}/\bar{E}_0) \cdot 100$, %	10 ± 3	14 ± 10

particle in carbon, from the data of Rao et al.,[5] obtained from emulsion measurements.

The correction for the production of π^0 mesons in secondary interactions in graphite and lead is accounted for by the factor 0.80 in Eq. (2).

The directly-measured average number of electrons $\bar{\nu}$ at the cascade shower maximum, produced by γ quanta from the decay of π^0 mesons in showers initiated by protons and α particles in carbon, is given in the table (row 2). This was obtained by means of Eq. (2) from the data of chamber II (Figs. 2a and 2b). To obtain N_{max}, we introduced a number of corrections to the measured value of the number of electrons:

1. The ionization pulses from particle showers was expressed in Eq. (2) in units of the average ionization produced in the chamber by relativistic particles. In reality, however, because of a different geometry of the passage of shower particles through the lower chamber, the average path of a single particle in the chamber was somewhat longer than the average path of a shower particle. Therefore, the average ionization due to a single particle was greater than the average ionization due to a shower particle, and the measured number of particles $\bar{\nu}$ was underestimated. Taking into account the difference in the geometry* and also the dependence of the electron momentum on the place of incidence of the particle in the chamber, we found that the measured number of particles, $\bar{\nu}$, had to be multiplied by 1.11.

2. Since no lead scatterer was present in the instrument below chamber II, the energy spectrum of particles as measured by chamber II was harder than the equilibrium spectrum of Tamm and Belen'kiĭ.[3] The spectrum of electrons in the showers under 2 cm of lead, was measured in a cloud chamber, in the absence of backward scattering, by Nassar and Hazen.[7] Since chamber II was made of brass, it was necessary to take into account the effect of transition from lead to copper in the chamber walls. (The effective thickness of chamber walls was ~ 2.3 mm or 1.9 g/cm² Cu.) For this purpose, we used experimental data of Hereford and Swann[8] on the range-energy relation (extrapolated) for electrons in copper. According to these data, a range equal to the effective wall thickness of chamber II, $d_{eff} = 1.9$ g/cm² Cu, corresponds to 3.8×10^6 ev. The number of electrons with energy $E < 3.8 \times 10^6$ ev, according to the spectrum of Nassar and Hazen,[7] amounts to 25% of the total number; i.e., 25% of the electrons were absorbed in the chamber walls. Hence, the correction factor for the absorption in chamber walls is 1.33.

3. In view of the fact that the measured electron spectrum was harder than the equilibrium spectrum, the scattering in the chamber gas was not large. The scattering in the energy range $E > 4 \times 10^6$ ev, for which $\cos\theta > 0.95$, was assumed to be practically nil. A correction for scattering in the gas chamber was introduced for particles that had an energy less than 4×10^6 ev after passing through the chamber walls. The mean scattering angle in the energy range 0 to 4×10^6 ev was calculated for the electron spectrum of Nassar and Hazen[7] from formula 1.55a of Sec. 22 of the article by Rossi and Greisen.[9] The measured path length and hence the ionization due to the scattering of electrons in the chamber gas, was found to be equal to 10% (correction factor 0.90).

4. To permit comparison of the experimental data with the cascade theory, which deals with an equilibrium spectrum of electrons, we transformed our spectrum to an equilibrium spectrum, taking into account the electrons of the "reverse" current which would flow into the chamber if the chamber were surrounded from all sides by lead and if there were no absorption in the chamber walls. The value of this correction for the "reverse current" was determined by us from the experimental data of Blocker et al.,[10] who used a thin-walled ionization chamber. The correction factor for lead, according to these data, equals 1.70.

The resulting correction factor equals 2.26. It should be noted that a considerable contribution is made to this by the correction for the "reverse current," well-known from experimental data. The contributions of the other corrections are less sub-

*The correction for the difference in the geometry took into account the angular distribution of the electrons emerging from lead, in accordance with the calculations of I. P. Ivanenko.[6]

stantial, and the possible inaccuracy in that determination cannot substantially change the obtained result. The table (row 3) lists the number of electrons at shower maximum, N_{max}, with all corrections. Substituting the result obtained for N_{max} into formula (1) of Tamm and Belen'kiĭ, we find the average energy $\overline{E}_{\pi^0}$, consumed in the production of π^0 mesons, for one shower in carbon, to be $(2.1 \pm 0.6) \times 10^9$ ev for protons and $(5.8 \pm 4.2) \times 10^9$ ev for α particles (row 4 of the table). The average energy of a proton is $\overline{E}_0 = 20 \times 10^9$ ev and that of an α particle is $\overline{E}_0 = 40 \times 10^9$ ev, making the fraction k of the energy consumed in production of π^0 mesons, in interactions involving carbon,

$$k_p = (10 \pm 3)\ \% \text{ and } k_\alpha = (14 \pm 10)\ \%$$

for protons and α particles respectively. Thus, our result confirms the earlier conclusion[1,2] about the small inelasticity of the interaction of protons with light nuclei in the energy range of $\sim 10^{10}$ ev. The value of k_α obtained for primary α particles under analogous conditions is, within the statistical error of the measurements, not different from the value obtained for protons.

CONCLUSIONS

The average fraction of energy transferred by a $\sim 10^{10}$ ev proton to π^0 mesons in a single act of interaction with a carbon nucleus is equal to 0.10 ± 0.03.

The corresponding value 0.14 ± 0.10 obtained for primary α particles is, within the limits of the statistical error of the measurements, not different from the value obtained for protons.

L. G. Landsberg took part in the experiment.

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[1] G. T. Zatsepin, JETP **19**, 1104 (1949).

[2] N. L. Grigorov, Usp. Fiz. Nauk **58**, 599 (1956).

[3] S. Z. Belen'kiĭ, Лавинные процессы в космических лучах (Cascade Processes in Cosmic Rays), GTTI 1948, p. 82, 125, and 126.

[4] K. I. Alekseeva and N. L. Grigorov, JETP **37**, 380 (1959), Soviet Phys. JETP **10**, 271 (1960).

[5] K. I. Alekseeva and N. L. Grigorov, JETP **35**, 599 (1958), Soviet Phys. JETP **8**, 416 (1959). Appa, Rao, Daniel, and Neelakantan, Proc. Indian Acad. Sci. **43**, 181 (1956).

[6] I. P. Ivanenko, Dokl. Akad. Nauk SSSR **122**, 367 (1958), Soviet Phys.–Doklady **3**, 962 (1959).

[7] S. Nassar and W. E. Hazen, Phys. Rev. **69**, 298 (1946).

[8] F. L. Herenford and C. P. Swann, Phys. Rev. **78**, 727 (1950).

[9] B. Rossi and K. Greisen, Revs. Modern Phys. **13**, 240 (1941) (Russian Translation).

[10] Blocker, Kenney, and Panofsky, Phys. Rev. **79**, 419 (1950).

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120