SOVIET PHYSICS JETP VOLUME 11, NUMBER 4 OCTOBER, 1960

DISINTEGRATION OF COSMIC-RAY NUCLEI BY SOLAR PHOTONS

N. M. GERASIMOVA and G. T. ZATSEPIN

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor August 16, 1959; resubmitted October 30, 1959

J. Exptl. Theoret. Phys. (U.S.S.R.) **38**, 1245-1252 (April, 1960)

A calculation is made of the effect of disintegration of cosmic-ray nuclei in the field of solar photons, leading to the production of correlated showers in the atmosphere. The energy of the disintegrated nuclei is found to be of the order of 10^{16} ev per nucleon, and their flux of the order of 10^{-4} to 10^{-3} km^{-2} $hour^{-1}$ sr^{-1}. As a result of the divergence of the photonuclear disintegration products before they enter the atmosphere, the distances between the shower cores turn out to be approximately of the order of 1 km.

INTRODUCTION

BECAUSE of the Doppler effect, the energy of solar-radiation photons is sufficient to cause the disintegration of cosmic-ray nuclei if the energy of the nuclei is high.[1]

If, in the coordinate system of the sun, the photon possesses an energy ϵ_0, and a cosmic-ray nucleus with mass M possesses an energy $E = \gamma Mc^2$, then, in the coordinate system in which the nucleus is at rest, the photon energy is given by

$$\varepsilon = \varepsilon_0 (\gamma + \sqrt{\gamma^2 - 1} \cos \alpha) \approx 2\gamma\varepsilon_0 \cos^2 \frac{\alpha}{2}, \qquad (1)$$

where α is the angle between the direction of motion of the photon and that of the nucleus in the coordinate system of the sun (Fig. 1).

Since the mean energy of a solar photon amounts to about 1 Mev, and the photodisintegration of nuclei occurs at a photon energy of about 10^7 ev, nuclei with energy corresponding to $\gamma \approx 10^7$, i.e., $E \approx 10^{16}$ ev per nucleon, can undergo photodisintegration.

A nucleus undergoing photodisintegration decays into two or more fragments, depending on the reaction type: (γ, n), (γ, p) or $(\gamma, 2n)$, (γ, np), $(\gamma, 3\alpha)$ The moving fragments all reach the earth's atmosphere practically simultaneously (the relative delay is of the order of 10^{-12} sec), and each of them produces an extensive air shower. Thus, the photodisintegration effect of the nuclei should lead to the existence of correlated air showers.

The divergence of nuclear fragments before reaching the atmosphere is determined by the distance from the earth at which the photodisintegration occurs, and by the angles of emission of the fragments in the coordinate system of the sun. An estimate shows that the distances between the shower cores should be of the order of 1 km. The divergence due to the deflection of the charged particles by the magnetic fields is negligible. (For a field of 10^{-5} gauss, the deviation would be of the order of 10^{-2} cm.)

The study of correlated showers can yield information about the composition of cosmic-ray nuclei in the range of ultra-high energies. In fact, when one photonucleon is emitted from a nucleus of atomic weight A, two particles are produced, one with nucleon mass and the other with a mass greater by a factor of $(A-1)$. Their energies will also differ by a factor of $(A-1)$. Therefore, one of the correlated showers will have about $(A-1)$ more particles than the other. This provides the possibility of determining the atomic weight of the original nucleus.

Unfortunately, as will be shown in the following discussion, an estimate of the number of expected photodisintegrations of nuclei before they reach the earth's atmosphere yields a very small value. However, arrays having an effective area of the order of several square kilometers are at present being planned for the detection of EAS. There is hope that such arrays will yield sufficient material not only to assess the effect of correlated showers, but also to investigate some features of this phenomenon. It is therefore of interest to consider this process in somewhat greater detail. (In reference 1, an arithmetical error was committed, as a result of which the effect has been overestimated by a factor of 100.)

NUMBER OF PHOTODISINTEGRATIONS

In the calculation, we shall use the diagram shown in Fig. 1. The following notation has been

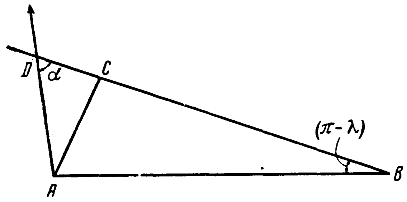

FIG. 1. Diagram of the motion of a nucleus in the field of solar photons. A – position of the sun; B – position of the earth; AD – direction of motion of the photon; DC – direction of motion of the nucleus.

chosen: distance from the sun A to the earth B, AB = R_0. Distance from the sun A to the nucleus D moving towards the earth, AD = R. Distance from the nucleus D to the earth B, DB = L. The angle between the direction of the photon stream and the motion of the nucleus at an arbitrary point of the trajectory of the nucleus, angle ADC = α. The same angle at the moment of the arrival of the nucleus at the earth, $\alpha = \lambda$. It is evident that

$$R = R_0 \sin\lambda / \sin\alpha, \quad L = R_0 (\sin\lambda / \tan\alpha - \cos\lambda),$$
$$-dL = R_0 \, d\alpha / \sin^2\alpha. \tag{2}$$

We shall assume that the energy spectrum of the solar photons corresponds to black-body radiation. For the calculation, we set T = 5800°K, which corresponds to kT = 0.5 ev.

The number of photons per cm^3 at a distance R from the sun in the energy interval ϵ_0, $\epsilon_0 + d\epsilon_0$ is

$$\rho(\varepsilon_0) d\varepsilon_0 = \frac{\rho_0}{(kT)^3} \frac{R_0}{R^2} \frac{\varepsilon_0^2 \, d\varepsilon_0}{e^{\varepsilon_0/kT} - 1}, \tag{3}$$

where the constant ρ_0 is chosen so that the energy flux per cm^2/sec at a distance R_0 from the sun corresponds to the solar constant $\overline{K} = 0.15$ watts/cm^2. We have

$$\overline{K} = \frac{c\rho_0}{(kT)^3} \int_0^\infty \frac{\varepsilon_0^3 \, d\varepsilon_0}{e^{\varepsilon_0/kT} - 1} = c\rho_0 kT \cdot 3! \; \zeta(4), \tag{4}$$

where $\zeta(4)$ is the Riemann ζ function [$\zeta(4) = 1.082$], and c is the velocity of light. Hence, $\rho_0 = \overline{K}/ckT \cdot 3!\,\zeta(4) = 0.96 \times 10^7$ photons/cm^3.

Let us denote the effective cross section for the photodisintegration of a nucleus of type g by $\sigma_g(\epsilon)$, where ϵ is the photon energy in the coordinate system of the sun. The probability of photodisintegration of the nucleus before it reaches the earth can be written in the form

$$W_g(\gamma) = \int_\infty^0 dL \int_0^\infty \rho(\varepsilon_0) \sigma_g \left(2\gamma\varepsilon_0 \cos^2\frac{\alpha}{2}\right) 2\cos^2\frac{\alpha}{2} \, d\varepsilon_0, \tag{6}$$

where the factor $2\cos^2(\alpha/2)$ appears because of the head-on motion of the nucleus and of the photons. We assume the velocity of the nucleus to be equal to the velocity of light:

$$1 + \frac{v}{c}\cos\alpha \approx 2\cos^2\frac{\alpha}{2}.$$

In order to find the number of disintegrating nuclei, it is necessary to know the energy spectrum of the nuclei.

There are no data on the energy spectrum of nuclei of each type in the high-energy range. There is only information about the energy spectrum of all particles taken together, and the spectrum in the region of interest $E \approx 10^{16}$ ev can be approximated by a power law[2]

$$F(>E) = B(E/10^{16})^{-\varkappa}, \tag{7}$$

where $\kappa = 1.8$, and $B = 10^{-11}$ particles $cm^{-2} sec^{-1} sr^{-1}$ (reference 2).

We shall assume that the energy spectrum of various nuclei is of the same form. The fraction of nuclei of type g among all particles with an energy higher than a given value remains then constant in the energy range of interest. If we denote this fraction by δ_g, then, for the number of nuclei of type g having an energy higher than E, we obtain a formula analogous to Eq. (7) in which, instead of B, we have to write δ_g. In order to pass from the variable E to γ, we make a substitution in Eq. (7) according to the formula

$$E_g = A_g mc^2 \gamma,$$

where A_g is the atomic weight of the nucleus g. The integral spectrum of nuclei of the type g is then obtained in the form

$$F_g(>\gamma) = \frac{\delta_g B}{A_g^{\varkappa}} \left(\frac{mc^2\gamma}{10^{16}\,\text{ev}}\right)^{-\varkappa}, \tag{8}$$

and the differential spectrum is

$$F_g(\gamma)\, d\gamma = B_g \gamma^{-(\varkappa+1)} \, d\gamma; \tag{9}$$

where $\kappa = 1.8$, and $B_g = 2 \times 10^{-11} \delta_g (10^7/A_g)^{1.8}$ particles $cm^{-2} sec^{-1} sr^{-1}$. Multiplying Eq. (6) by Eq. (7) and integrating over $d\gamma$, we obtain the total number of disintegrations of nuclei of type g occurring per unit time [using Eq. (2)]:

$$N_g = \frac{2B_g R_0 \rho_0}{\sin\lambda\,(kT)^3} \int_0^\lambda d\alpha \int_0^\infty d\varepsilon_0 \int_{\varepsilon'}^\infty \frac{\varepsilon_0^2}{\exp(\varepsilon_0/kT) - 1} \sigma\left(2\gamma\varepsilon_0 \cos^2\frac{\alpha}{2}\right)$$
$$\times \gamma^{-(\varkappa+1)} \cos^2\frac{\alpha}{2} \, d\gamma, \tag{10}$$

where ϵ_g is the threshold energy for the photonuclear reaction on nuclei of type g, and $\epsilon' = \epsilon_g / 2\epsilon_0 \cos^2(\alpha/2)$.

The integration yields

$$N_g = 2B_g \rho_0 R_0 (2kT/\varepsilon_g)^{\varkappa} (2+\varkappa)!\, \zeta(3+\varkappa)\, f(\lambda, \varkappa)\, I_g \tag{11}$$

[for the chosen value of $\kappa = 1.8$, $\zeta(3+\kappa) = 1.04$], where

$$I_g = \int_1^\infty \sigma_g(y\varepsilon_g)\, y^{-(\varkappa+1)}\, dy, \qquad (12)$$

where $y = \epsilon/\epsilon_g$ and the function $\sigma_g(y\epsilon_g)$ can be well approximated by the expression

$$\sigma_g(y\varepsilon_g) = c_g(y-1)\, e^{-a_g(y-1)}. \qquad (13)$$

The constants a_g and c_g are found from the experimental data on the energy dependence of the effective cross section for the photonuclear reaction[3-11]

$$a_g = 1/(y_m - 1), \qquad (14)$$

$$c_g = e a_g \sigma_{max}, \qquad (15)$$

σ_{max} is the value of the maximum effective cross section attained for $y = y_m$.

As a result of integration (12), we obtain the differences of complete and incomplete gamma functions, which is very inconvenient for calculation, as it is necessary to take the values of these functions with a large number of signs. One can, however, derive an approximate expression for I_g which is more convenient for making calculations if we substitute an exponential function $\exp[-\sqrt{\kappa(\kappa-1)}\,(y-1)]$ for the power function $y^{-(\kappa+1)}$ under the integral. For such a substitution, the solution coincides with the exact one for $a \gg 1$ and $a_g \ll 1$, while, for $a_g \approx 1$, the value of I_g will be negligibly higher.

As a result, we obtain

$$I_g \approx c_g / [a_g + \sqrt{\varkappa(\varkappa-1)}]^2. \qquad (16)$$

The function $f(\lambda, \kappa)$ [see Eq. (11)] depends little on κ and, therefore, in computing the values of this function, we set $2(1+\kappa) = 5$ for simplicity, and obtain

$$f(\lambda) = (1/\sin\lambda)\left\{\tfrac{5}{4}\sin\tfrac{1}{2}\lambda + \tfrac{5}{24}\sin\tfrac{3}{2}\lambda + \tfrac{1}{40}\sin\tfrac{5}{2}\lambda\right\}, \qquad (17)$$

$f(\lambda) \to 1$ for $\lambda \to 0$; $0.9 < f(\lambda) < 1$ in the range $0 < \lambda < \pi/2$; $f(\lambda) \to 16/15(\pi - \lambda)$ for $\lambda \to \pi$. Substituting Eq. (16) and also the numerical values of the corresponding constants (see Table I) into Eq. (11), we find that the number of particles produced in photodisintegrations of nuclei of type g per hour over an area of 1 km² and within an angle of 1 sr is

$$N_g = 3.9\,\delta_g \left(\frac{10^7\,\text{ev}}{\varepsilon_g}\right)^{1.8} \frac{10^{24} C_g}{(a_g + 1.2)^2}\, f(\lambda). \qquad (18)$$

The numbers obtained show that the expected effect amounts to a quantity of the order of $10^{-4}\,\text{hr}^{-1}\,\text{km}^{-2}\,\text{sr}^{-1}$, and does not depend greatly on the atomic weight of the nuclei.

The real value differs from the calculated one apparently by not more than one order of magnitude. The contribution of other photonuclear reactions will increase the effect by not more than a factor of 3 to 5. The increase in the number of detected showers when the sun is near the zenith is found to be negligible. In fact, the angular dependence $f(\lambda)$ of the disintegration probability increases with decreasing angle $\pi - \lambda$ only slowly during the passage of particles near the sun:

$$f(\lambda) \approx 1/(\pi - \lambda). \qquad (19)$$

This leads to the fact that the disintegration probability, averaged over the angle of 1 sr along the direction pointing towards the sun, is greater than for angles $\lambda \approx 0$ by only a factor of 3.5. Averaging over one day will give a coefficient differing little from one.

The approximation made in the calculation because of the exchange of the true sun spectrum for the black-body spectrum with temperature $T = 5800°K$ does not lead to an appreciable error, since the relative contribution of different regions of the solar spectrum to the photodisintegration process is very close to the relative contribution of these regions to the energy flux of solar emission. The contribution of the different spectral regions is shown in Fig. 2: the dotted line 1 shows the contribution to the energy flux, and the curve 2 shows the contribution to the number of photodisintegrations. The maxima of both curves lie in the visible part of the spectrum. The greatest uncertainty in the calculation of the number of disintegrations is due to the constant B which appears

TABLE I

	ε_g, Mev	ε_m, Mev	σ, mb	a_g	C_g, mb	N_g, $\text{km}^{-2}\text{hr}^{-1}\text{sr}^{-1}$
He^4	20.5	24	1.3	5.9	20.8	$0.4\cdot10^{-4}$
C^{12}	19.5	21.3	13	11.1	397	$0.6\cdot10^{-4}$
N^{14}	17.5	22.5	16	3.6	113	$0.7\cdot10^{-4}$
O^{16}	19.0	22.5	8	5.25	127	$0.3\cdot10^{-4}$
Fe^{56}	13.0	17.7	75	2.8	570	$0.6\cdot10^{-4}$

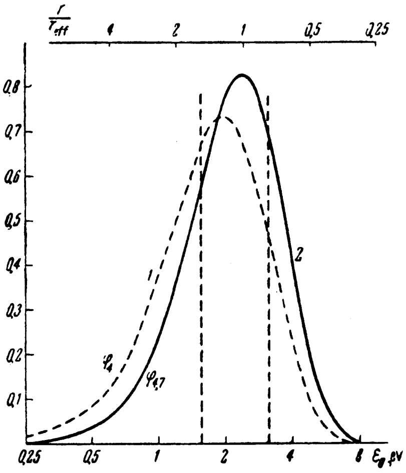

FIG. 2. Curve 1 — energy-flux distribution of the solar spectrum; curve 2 — contribution of photons of different energies to the photonuclear process, and also the energy distribubution of nuclei undergoing photodisintegrations. The x axis at the bottom of the figure represents the energy of photons in ev (vertical dotted lines enclose the optical region of the spectrum). The top scale of the x axis refers to curve 2, and represents the energy of the nuclei expressed in units of $\gamma/\gamma_{\text{eff}}$ ($\gamma = E/Mc^2$). The y axis represents the corresponding values of the functions in arbitrary units.

in the expression of the energy spectrum of cosmic rays. If an error by a factor of 2 is made in the estimate of the total energy of EAS, on the basis of which the primary-particle spectrum is normalized, then this leads to an error in the constant B by approximately a factor of 4.

In the detection of correlated showers, the effective solid angle for the observation may amount to 2 or 3 sr.

Taking all these factors into account, one can expect, for an array with an effective area of 1 km^2, a number of detected photodisintegrations equal to 10^{-4} to 10^{-3} per hour, provided that a considerable percentage of ultra-high-energy cosmic-ray particles consists not of protons but of more complex atomic nuclei.

ENERGY DISTRIBUTION OF DISINTEGRATING NUCLEI

For the majority of nuclei, the energy dependence of the effective photodisintegration cross section has the shape of a narrow resonance curve. Because of this, and also because of the sharply decreasing form of the energy spectrum of cosmic rays, a considerable contribution to the number of photodisintegrations, determined by the integral $I_\sigma(12)$, is made only by a very narrow range of values of y close to $y = 1$. If, for an estimate of the distribution with respect to γ, we set $y = y_m$ = const, we obtain the condition

$$2\gamma\varepsilon_0 \cos^2(\alpha/2)/\varepsilon_T = y_m \approx 1. \qquad (20)$$

Hence, it follows for $\cos^2(\alpha/2) = \text{const}$ that $d\ln\gamma = -d\ln\epsilon_0$. Therefore, the distribution of the nuclei undergoing photodisintegration with respect to γ should be represented by the same curve as the distribution of the contribution of various regions of the solar spectrum, if the x axis represents $\ln\epsilon_0$ or $-\ln\gamma$. Thus, curve 2 in Fig. 2 shows also the approximate energy spectrum of nuclei undergoing photodisintegration. The values of γ_{eff} corresponding to the maximum of curve 2 are given in Table II for the case $\cos^2(\alpha/2) = 1$. Evidently, for other values of α, we have

$$\gamma_{\text{eff}}(\alpha) = \gamma_{\text{eff}}(\alpha = 0)/\cos^2(\alpha/2). \qquad (21)$$

TABLE II

	γ_{eff}	E_{eff}, ev
He^4	$5.1\cdot10^6$	$2\cdot10^{16}$
C^{12}	$4.5\cdot10^6$	$5.4\cdot10^{16}$
N^{14}	$4.7\cdot10^6$	$6.6\cdot10^{16}$
O^{16}	$4.6\cdot10^6$	$7.3\cdot10^{16}$
Fe^{56}	$3.5\cdot10^6$	$2\cdot10^{17}$

For $\lambda \neq 0$, the trajectory of the nucleus moving towards the earth is characterized by various values of α and, therefore, for an estimate of the distribution with respect to γ, it is reasonable to introduce the quantity $[\cos^2(\alpha/2)]_{1/2}$ corresponding to an angle $\alpha_{1/2}$ such that[12]

$$\int_0^{\alpha_{1/2}} \left(\cos\frac{\alpha}{2}\right)^{2(1+\varkappa)} d\alpha = \frac{1}{2}\int_0^{\lambda} \left(\cos\frac{\alpha}{2}\right)^{2(1+\varkappa)} d\alpha. \qquad (22)$$

We give here the values of $[\cos^2(\alpha/2)]_{1/2}$ for various values of λ:

λ: 0 $\pi/4$ $\pi/2$ $3\pi/4$

$[\cos^2(\alpha/2)]_{1/2}$: 1 0.97 0.9 0,84

ESTIMATE OF THE DETECTION PROBABILITY OF CORRELATED SHOWERS AS A FUNCTION OF THE DISTANCE BETWEEN THE CORES

The distance between a photonucleon and a nucleus is, at the earth, equal to

$$r = \theta L, \qquad (23)$$

where θ is the angle between the directions of the nucleon and of the nucleus in the coordinate system of the earth.

We shall assume that the distribution of the fragments in the coordinate system of the nucleus is isotropic, so that the probability of emission of a particle within an angle θ_c, $\theta_c + d\theta_c$ is given by the formula

$$W(\theta_c)\,d\theta_c = \tfrac{1}{2}\sin\theta\,d\theta_c, \qquad (24)$$

where θ_c is the angle, in the coordinate system of the nucleus, between the direction of emission of a particle and the direction of motion of the nucleus towards the earth before the decay. For a velocity of emission of the nucleon and nucleus equal to βc, the angular distribution in the coordinate system of the earth can be written in the form

$$W(\theta)\,d\theta = \gamma^2\theta\,d\theta/\beta^2\sqrt{1-(\gamma\theta/\beta)^2} \quad \text{for } \theta \leqslant \beta/\gamma,$$
$$W(\theta) = 0 \quad \text{for } \theta > \beta/\gamma, \qquad (25)$$

since

$$\theta \approx (\beta/\gamma)\sin\theta_c \quad \text{for } \beta \leqslant 1.$$

For simplicity, let us assume henceforth that in photodisintegration the nuclei are always emitted from the nucleus at the same velocity. The lateral distribution function $\rho(r)$ in its differential form is given by the equation

$$d\rho(r) = \frac{W(\theta)\,d\theta}{2\pi L^2\theta\,d\theta} = \frac{1}{2\pi(L\beta/\gamma)}\frac{1}{\sqrt{1-(\gamma r/\beta L)^2}}\,dN, \qquad (26)$$

where dN is the number of nuclei undergoing disintegration at a distance L, L + dL from the earth, corresponding to the integrand (10). It is very difficult to carry out an accurate integration of this expression. The problem is, however, simplified if we take into account that, for the nuclei undergoing disintegration, the range of important values of γ is small (see Fig. 2). Therefore, in integrating the expression (26) over γ (or over y), it is permissible, in the factor standing before dN, to set $y = y_{\text{eff}}$, the value of which can be obtained from Eq. (21) on the basis of Table II and the values of $[\cos^2(\alpha/2)]_{1/2}$ for various values of λ. To obtain the lateral distribution it is now only necessary to perform an integration over dL, i.e., over $d\alpha$; this presents no difficulties.

The probability of observation of shower cores at different distances from each other is shown in Fig. 3. Curve 1 was calculaed for $\lambda = 0$, and curve 2 for $\lambda = 3\pi/4$.

To determine the value of r_0 it is necessary to estimate the velocity of photonucleons β. For light nuclei, the majority of photonucleons will be due to a direct photoeffect, so that the energy of a photonucleon is given by the formula

$$E_n = \varepsilon_T(y_{\text{eff}} - 1), \qquad \beta_{\text{eff}} = \sqrt{2E_n/mc^2}. \qquad (27)$$

The values of β_{eff} calculated from this formula for all nuclei are close to $\beta = 0.07$. Hence, the

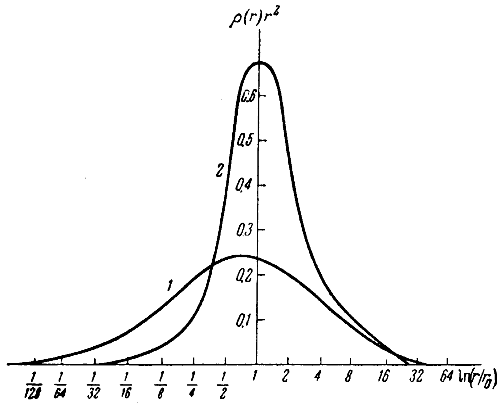

FIG. 3. Graph of the detection probability of shower cores at various distances from each other; x axis represents $\ln(r/r_0)$ and the y axis $\rho(r)r^2$ in arbitrary units.

value r_0 ($\lambda = 0$), according to Eq. (26) and the values of γ_{eff} given in the table, is of the order of r_0 ($\lambda = 0$) = 2 km. It is evident that our calculation leads to an overestimate in the value of r_0, since not all photonucleons are due to the direct photoeffect.

Special experiments for the detection of correlated showers have not been carried out. However, during the observation of EAS in 1950 at an altitude of 3860 m,[13] a case was detected which is of considerable interest. High-density showers were recorded at two extreme points 1 km apart while at the central point the detected shower-particle flux density was found to be extremely small. The probability of a chance passage of two independent showers of corresponding densities within the resolving time of the array (6 μsec) can be estimated as being 10^{-4} during the whole period of observation of 1000 hours. An analogous event was observed in 1951 by Éĭdus et al.[14] at sea level. Further experiments with suitable arrays can yield important information on this subject.

[1] G. T. Zatsepin, Dokl. Akad. Nauk SSSR **80**, 577 (1951).

[2] K. Greisen, Progress in Cosmic Ray Physics (North-Holland Publishing Co., Amsterdam, 1956) Vol. III (Russ. Transl. IIL, 1958).

[3] T. H. Stix, Phys. Rev. **95**, 782 (1954).

[4] B. H. Flowers and F. Mandle, Proc. Roy. Soc. **A206**, 131 (1951).

[5] Ferguson, Halpern, Nathans, and Jergin, Phys. Rev. **95**, 777 (1954).

[6] V. O. Nicolai and E. L. Goldwasser, Bull. Am. Phys. Soc. **29**, 18 (1954).

[7] R. Nathans and J. Halpern, Phys. Rev. **92**, 940 (1953).

[8] V. Weisskopf, Phys. Rev. **52**, 295 (1946).

[9] Montalbetti, Ratz, and Gordemberg, Phys. Rev. **91**, 659 (1953).
[10] E. G. Fuller, Phys. Rev. **96**, 106 (1954).
[11] A. N. Gorbunov and V. M. Spiridonov, JETP **33**, 21 (1957), Soviet Phys. JETP **6**, 16 (1958).
[12] A. A. Gershun, Usp. Fiz. Nauk **46**, 388 (1952).
[13] Antonov, Vavilov, Zatsepin, Kutuzov, Skvortsov, and Khristiansen, JETP **32**, 227 (1957), Soviet Phys. JETP **5**, 172 (1957).
[14] Éĭdus, Adamovich, Ivanovskaya, Nikolaev, and Dulyankina, JETP **23**, 440 (1952).

Translated by H. Kasha
239