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METHOD OF DETERMINATION OF THE MASS COMPOSITION OF RING CURRENT JONS

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16. Abstract

Examined herein is a method for individual registration of protons, and helium and oxygen ions, with energies E for a charge on the order of 100 kev/q in the ring currents of the earth's magnetosphere. The method is based on the various specific losses in energy by these ions in matter. The ion current, selected according to E/q, is passed through a solid target, after which identification of the masses is carried out, based on the energy losses in the target. The resolution of the spectrometer makes it possibly to reliably divide the flows of protons, and helium and oxygen ions.

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Examined herein is a method for individual registration of protons, and helium and oxygen ions, with energies E for a charge on the order of 100 kev/q in the ring currents of the earth's magnetosphere. The method is based on the various specific losses in energy by these ions in matter. The ion current, selected according to E/q, is passed through a solid target, after which identification of the masses is carried out, based on the energy losses in the target. The resolution of the spectrometer makes it possible to reliably divide the flows of protons, and helium and oxygen ions. /2*

A considerable portion of the earth's magnetosphere (from a cloud with L=3 right up to a magnetic pause) is filled with epithermal ions, the density of the kinetic energy of which, at the examined point, approaches the density of the energy of the geomagnetic field. These ions drift aroung the earth, forming ring currents, and have an appreciable diamagnetic effect on the geomagnetic field [1]. /3

Symmetrical and nonsymmetrical ring currents are distinguished. The symmetrical ring current forms ions with energies in the hundreds of kev. Ions with lesser energies form a nonsymmetrical ring current. Symmetrical ring currents exist constantly around the earth, while nonsymmetrical currents occur during geomagnetic perturbations, and disperse with characteristic times of several days. Ring currents are also detected in the magnetosphere of Jupiter [2]. Protons are usually the predominant component in the nonsymmetrical ring currents of the earth. However, in several experiments, flows of helium and oxygen ions were detected, which were comparable in intensity with the flows of hydrogen ions [3,4].

*Numbers in the margin indicate pagination in the foreign text.

The mass composition of symmetrical ring currents has practically not been studied. It is thought that symmetrical ring currents are formed, basically, by flows of protons [5], although it is impossible to preclude the substantial contribution from heavier particles [6,7].

It is evident that, without experimental study of the mass composition of the flows of particles which form the symmetrical ring current, it is impossible to determine just what is the basic source of the particles—solar wind or the earth's atmosphere, to evaluate the magnitude of the diamagnetic weakening of the geomagnetic field, or to study the nature of the temporary variations of the geomagnetic perturbations with time. /4

Given in the present study is a description of the method which makes it possible to identify the hydrogen and helium ions, and heavier ions, in a flow of charged particles with energies on the order of 100 kev/charge, owing to the varying specific energy losses in the substance with ions of varying atomic numbers.

Given in figure 1 are the specific energy losses of hydrogen, helium, and nitrogen ions in carbon. It is evident in the figure that, for ion energies exceeding 50-60 kev, the specific energy losses of the hydrogen, helium, and nitrogen ions differ appreciably. The specific energy losses by nitrogen ions are two times greater than the specific losses by hydrogen ions, even at an energy of 10 kev, with this difference increasing with an increase in the energy of the particles. The energy losses by nitrogen and oxygen ions are practically equal. More detailed information on the reaction of the particles with a solid substance are given in study [8].

Presented in figure 2 is a schematic of an instrument for mass analysis of a flow of ions. Ions with a fixed value of E/q are picked out of the ion flow 1 with the help of an electrostatic analyzer 2. After leaving the analyzer 2, the ions strike a target 3. The particles leaving the target are analyzed for their energies in the electrostatic analyzer 4, and registered by an open electron multiplier.

We will evaluate the effectiveness of registration of the ions and the resolution of the instrument.

The effectiveness of registration of the ions striking the target is equal to

$$\alpha(E) = K(E) \cdot \varphi(E, d, \theta_0)\, \alpha_+ . \qquad (I)$$

Here, K(E) is the portion of the positively-charged particles in the flow, leaving the target with a thickness d, $\phi(E,d,\Theta_0)$ is the portion of particles having struck at an aperture angle Θ_0 of the second electrostatic analyzer after scattering at the target, and α_+ is the effectiveness of registration of the ions by the secondary multiplier. For simplicity, we will assume that $\alpha_+=1$. /5

The charge equilibrium in the flow of particles emanating from the layer of the substance is established in the last 5-6 atomic layers. It depends weakly on the material of the target, and is basically determined by the energy of the particles at the outlet from the target [9-11].

Given in figure 3 is the relationship of the number of positively-charged particles to the total number of particles in the flow H^+, He^+, N^+ after passage of the layer of the solid substance. It is evident that, for hydrogen ions with an energy of 100 kev, $K(E)\approx 80\%$; for helium $K(E)\approx 40\%$, and for nitrogen $K(E)\approx 30\%$.

The magnitude of $\phi(E,d,\Theta_0)$ is determined by the scattering capability of the target, with respect to the bombarding particles. For ions with small energies (E<25 kev/nucleon), the angular distribution of the particles after passage of the layer of the substance with a thickness d is determined by the expression [8]:

$$f(\Theta, d, E) = \frac{I}{4\pi} \cdot \frac{1-e^{-2p}}{(I+e^{-2p}-2e^{-p}\cos\Theta)^{3/2}}, \qquad (2)$$

where p is determined by the relationship

$$p = \frac{2{,}05 \cdot Z_1 \cdot Z_2 \quad e^2 \, a(M_1+M_2)}{N_2 \, \bar{E}}. \qquad (3)$$

Here, Z_1, M_1 and Z_2, M_2 are the atomic number and mass of the bombarding particle and the atoms of the target, respectively, N is the number of atoms of the target per unit of volume, e is the elementary charge, $a=0.46 \cdot 10^{-8}(Z_1^{1/2}+Z_2^{1/2})^{-2/3}$ cm is the Thomas-Fermi radius of screening, $\bar{E}$ is the average energy of a particle moving to the target, and Θ is the angle of scattering in the system of the center of inertia.

If the angle of scattering is small, then formula (2) may be utilized for evaluations for particles with energies E<100-200 kev/charge as well.

Utilizing formula (3), we find:

$$\varphi(E, d, \Theta_0) = \int_0^{2\pi} d\varphi \int_0^{(M_1+M_2)\Theta_0/M_2} f(\Theta, d, E) \sin\Theta \, d\Theta =$$
$$= \frac{1}{2}\left[1+e^{p}\right]\left\{1-\left[1+\frac{4e^{-p}}{(1-e^{-p})^2} \cdot \sin^2\left(\frac{M_1+M_2}{M_2}\right)\frac{\Theta_0}{2}\right]\right\}^{-\frac{1}{2}} \qquad (4)$$

(the factor in front of Θ_0 in the upper limit of integration is determined by the transformation of the angle Θ from the system of the center of intertia to Θ_0, reckoned in a laboratory system of coordinates. The evaluations show that, for a target with a thickness of 20 mkg·cm^{-2}, $\Theta_{1/2}$ is the angle of scattering in the laboratory system of coordinates, corresponding to a decrease in the intensity by 2 times, and is 1° for protons, 1.5° for He^+ ions, /6 and 6° for N^+, at an energy of 140 kev. The resolution of such an instrument is determined by the energy dispersion in the flow of ions having passed the target, and the energy resolution of the electrostatic analyzers. Unfortunately, it is not possible, at the present time, to accurately calculate the dispersion of the energy distribution of the ions after passage of the layer of the substance [12-13], and, therefore, we will conduct the disucssion of the instrument's resolution after describing the experimental data.

Given in figure 4 are the energy distributions of the hydrogen, helium, and nitrogen ions with an initial energy of 140 kev, having passed a carbon target with a thickness of 6.25 mkg/cm^2. The resolution of the analyzer, in this case, was no worse than 1000, and, therefore, the form of the energy distributions was completely determined by the dispersion of the energy losses of the ions in the target. It is evident from the figure that this method makes it possible to distinguish the signals which correspond to ions of various masses.

Given in figure 5 are the dependences of the energy losses (ΔE), the total width at half the height of the energy distribution in the flow of ions after passage of the target ($\Delta E_{1/2}$), and the effectiveness of registration $\alpha(E)$ of hydrogen, helium, and nitrogen ions on the thickness of the carbon target d for the energy E=140 kev.

It is evident from the figure that, with an increase in the thickness of the target, the difference in energy losses by the ions of various masses increases, the magnitude of $\Delta E_{1/2}$ increases, and the effectiveness of registration of the ions decreases.

The final magnitude of the resolution of the analyzers leads to an additional expansion of the energy distribution of the ions.

Let γ_1 and γ_2 be the dispersion of the first and second ana- /7 lyzers, respectively. Then, the total width at half the maximum of the energy distribution of the flow of ions, after passage of the first analyzer, is equal to $\gamma_1 E_1$, where E_1 is the energy which corresponds to the maximum in this distribution. A similar condition is also recorded for the second analyzer.

The conditions of resolution of the signals from the ions of two different masses, which we will assign the number 1 and 2, are recorded in the following form:

$$\frac{1}{2}\left[\Delta E_{1/2}(1) + \Delta E_{1/2}(2) + 2\gamma_1 E + \gamma_2 E_1 + \gamma_2 E_2\right] \leq |\Delta E(1) - \Delta E(2)| \quad (5)$$

It follows from the data in figures 4 and 5, and formula (5), that the resolution of each analyzer (with the condition that $\gamma_1 = \gamma_2$ and E=140 kev) should be at least 150 for a carbon target with a thickness of 20 mkg·cm^{-2}, for distinguishing signals from hydrogen and helium ions. A subsequent increase in the thickness of the target is inadvisable, because of the decrease in the effectiveness of registration of the ions (see fig. 5). A resolution equal to 12 is sufficient for picking out the heavy ions O^+ from the light ions H^+ and He^+. We will evaluate the possibility of the use of the described procedure for the possibility of registration of the ions of the ring current. The geometric factor of the instrument with a cylindrical analyzer is equal to

$$\Gamma = \frac{S\gamma E}{4\pi}\int_0^{2\pi}\int_0^{\Theta_0} \sin\Theta \, d\Theta \, d\varphi \simeq \frac{S\Theta_0^2 \gamma E}{4}. \quad (6)$$

The number of ions reaching the receiver of the instrument is equal to:

$$N = \frac{d\varphi}{dE} \cdot \Gamma \cdot \alpha(E), \quad (7)$$

where $\frac{d\varphi}{dE}$ is the differential flow of particles of the ring current. Expression (7) is written with the assumption that the measurements of the number of particles emanating from the target is accomplished by scanning, according to energies, by the second analyzer. For evaluation of the sensitivity of the dual electrostatic analyzer with cylindrical plates in the area of the ring currents, we adopt S of the detector as equal to 0.5 cm^2, $\gamma_1=\gamma_2=0.03$, /8 which corresponds to $\theta\sim 0.05$ (3°) [14], d=20 $mkg\cdot cm^{-2}$, and $\frac{d\varphi}{dE}=3\cdot 10^5 \exp\left(\frac{E - 100\ kev}{200\ kev}\right)$ $cm^{-2}\ sec^{-1}\ ster^{-1}\ kev^{-1}$ is the anticipated differential flow of protons in the area of the ring current [15, 16]. For these values, $N_{H^+}\sim 3\cdot 10^2$ $imp.sec^{-1}$. This magnitude is insufficient for ensuring a broad range of registration of the intensity of the protons.

The sensitivity of the instrument may be increased through the utilization of spherical electrostatic analyzers [8], with the very same resolution $\gamma=0.03$, because of an increase in the angle along the direction of the plates up to $\sim$1 rad, i.e., by 20 times, as compared with the cylindrical analyzer, which corresponds to $N_{H^+}\sim 6\cdot 10^3$ $imp.sec^{-1}$.

The switch to quarter-toroid electrostatic analyzers [8] makes it possible to increase the sensitivity of the instrument because of the increase in the ratio of the areas S $\frac{S_{in}}{S_{out}}$ by R_0/d times, which, with $\gamma=0.03$, corresponds to $\frac{S_{in}}{S_{out}}\sim 20$, which, as compared with the spherical analyzer, gives $N_{H^+}\sim 20\cdot 6\cdot 10^3\approx 10^5$ imp./sec. These evaluations of sensitivity for values of $R_0\sim 10$ cm, with $\gamma=0.03$, determine the width of the gap between the plates $d\sim 2\gamma R_0=0.6$ cm, which corresponds to the maximum field strength between the plates $U_0=\frac{2}{10}\cdot\frac{150}{0.6}=50$ kv/cm for E=150 kev, which is much less than that observed in laboratory measurements of the limits: 100 kv/mm [17].

A subsequent increase in the sensitivity of the instrument by 2-3 times may be accomplished through replacement of the toroid analyzer on the plates, in the form of a body of rotation of a logarithmic spiral [8]. For intensities of He^+ and O^+ ions on the order of 1% of H^+, the rates of calculations from them, with regard for scattering in the target, will be $N_{He^+} \sim 2 \cdot 10^3$ imp/sec and $N_{O^+} \sim 5 \cdot 10^2$ imp/sec, respectively.

The given rates of calculation exceed the inherent background of the type KEU detector. However, the presence of energy particles in the area of ring currents, which penetrate through the shield at 1 g/cm^2, increases the level of the background readings. At the equator, with L=3, the flow of penetrating protons with E>25 Mev, and electrons with E>2 Mev, may reach 10^2 cm^{-2}sec^{-1}. A reduction in the rate of calculation by two orders of magnitude may be ensured by a detector shield with a thickness of up to 5 g cm^{-2}. /9

The background of the KEU, from the braking radiation of the flow of electrons j_e with E>500 kev (j_e=10^7 cm^{-2}sec^{-1} at the equator with L=3.5) may reach 10^2 cm^{-2}sec^{-1} [18].

A reduction in this background by two orders of magnitude requires either shielding of the saturated detector of the KEU type with lead up to 1 cm thick, or the utilization of an unsaturated detector of the PPD type, with discrimination of the readings from the braking radiation.

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Captions for Figures

Fig. 1 - Dependence of specific energy losses by H^+, He^+, and N^+ ions in a carbon target.

Fig. 2 - Principle of construction of analyzer according to masses, for ion energies on the order of 100 kev/charge.

1 - beam of nonselected ions

2 - first electrostatic analyzer for picking out ions with equal E/q

3 - solid carbon target

4 - second electrostatic analyzer for selection of ions having experience different losses in the target

5 - ion detector

Fig. 3 - Portion of H^+, He^+, and N^+ ions in the beam having passed through the carbon target with a thickness of 6.25 mkg cm^{-2}, in the energy interval 10-200 kev.

Fig. 4 - Energy distributions of H^+, He^+ and N^+ ions with an initial energy of 140 kev, having passed through the carbon target with a thickness of 6.25 mkg/cm^{-2}.

Fig. 5 - Dependences on thickness of the target of:

ΔE - losses of energy by the ions, kev

$\Delta E_{1/2}$ - total width of the circuit at half the altitude after the target, kev

$\alpha(E)$ - effectiveness of registration of hydrogen, helium, and nitrogen ions

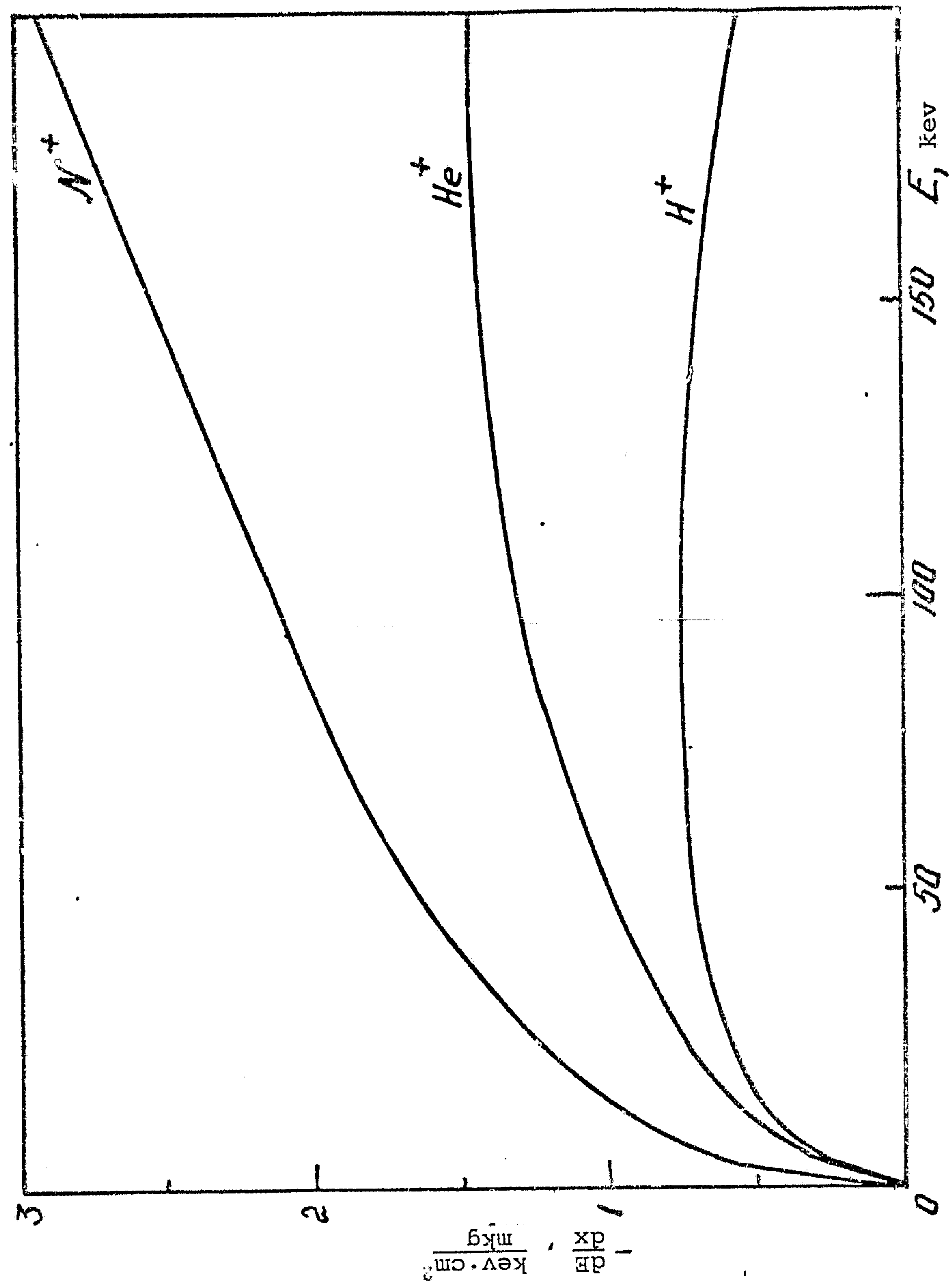

FIG. 1

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OF POOR QUALITY

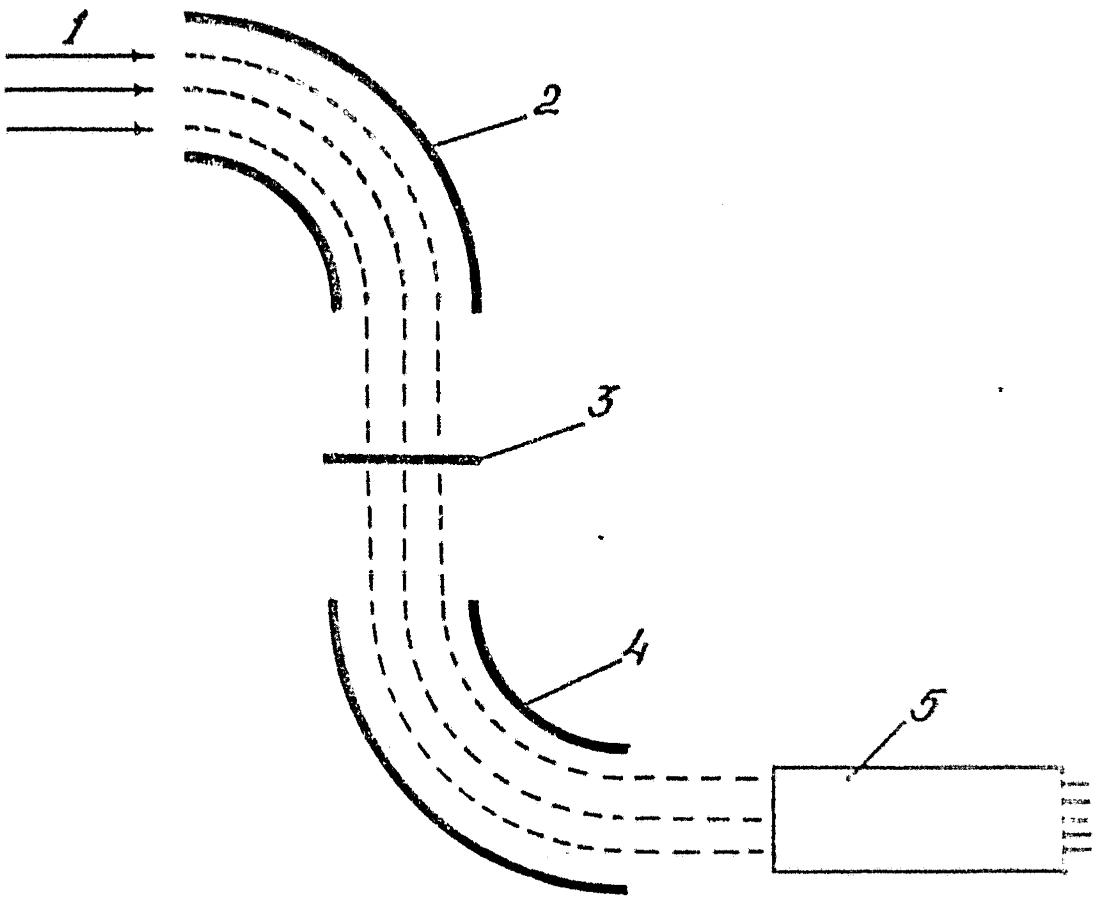


FIG. 2

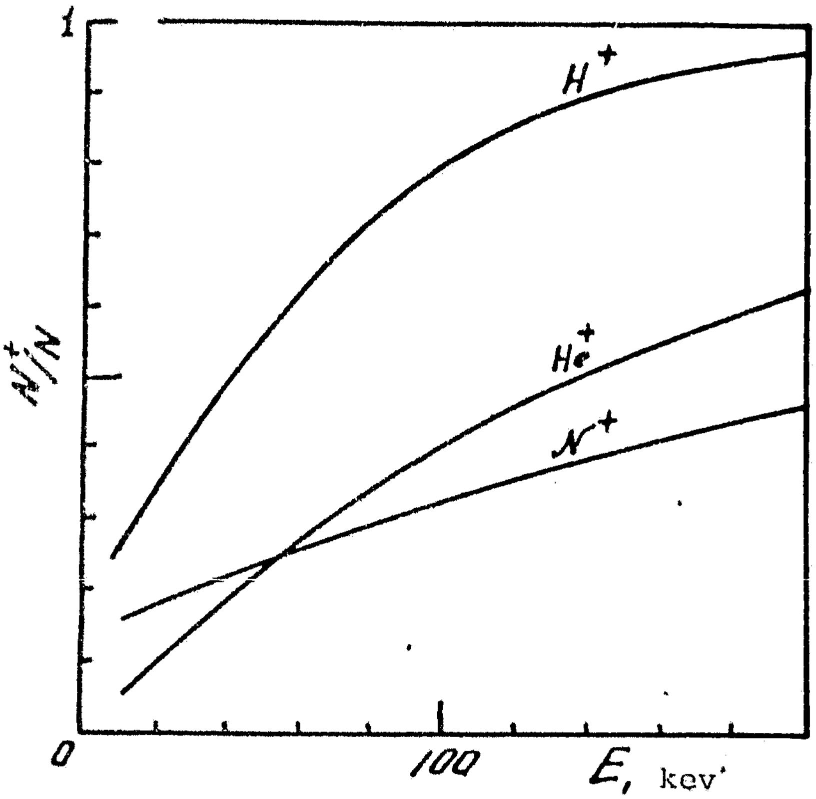
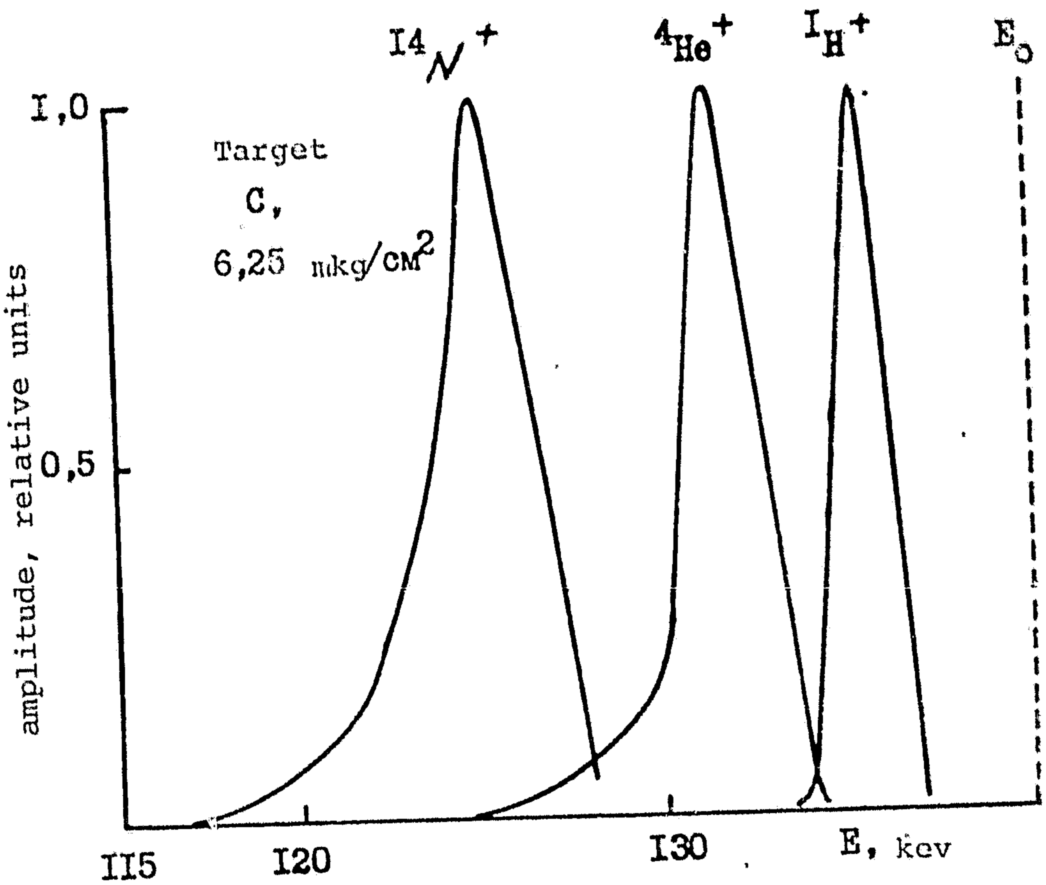
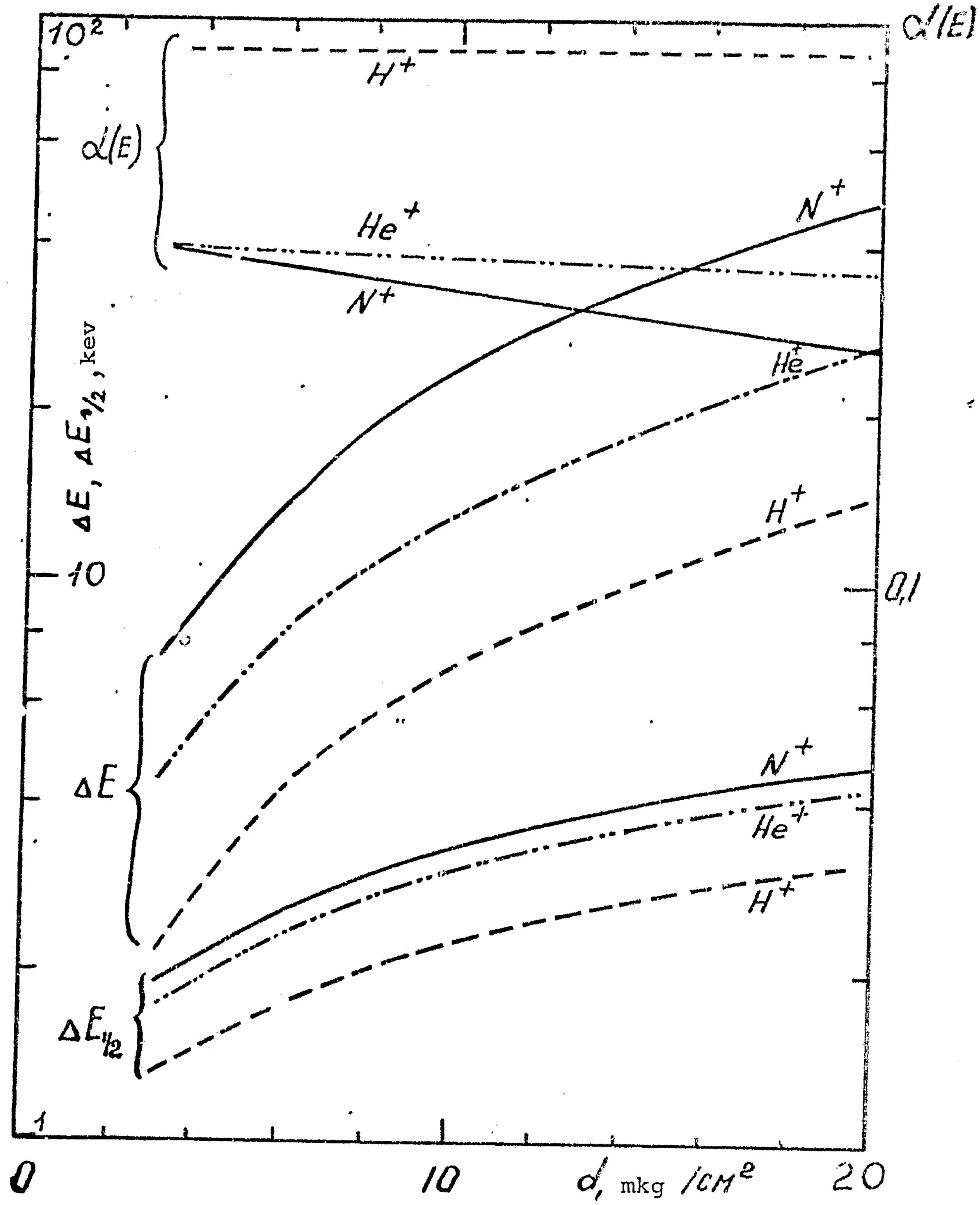


FIG. 3



I4N+
4He+
IH+
E0
I,0
0,5
Target
C,
6,25 mkg/cm2
amplitude, relative units
II5
I20
I30
E, kev

FIG. 4



10^2
$\alpha(E)$
H^+
$\alpha(E)$
He^+
N^+
N^+
He^+
H^+
$\Delta E, \Delta E_{1/2}$, kev
10
0,1
ΔE
N^+
He^+
H^+
$\Delta E_{1/2}$
1
0
10
d, mkg /cm²
20

FIG. 5