EXPERIMENTS ON ACCELERATION OF α PARTICLES BY THE COLLECTIVE METHOD

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Results are reported of experiments on acceleration of ions by the collective method. An electron ring (major radius R = 6 cm and cross-section radius a ~ 0.1 cm) was accelerated in a falling magnetic field with a gradient of 10 G/cm. In a length of 40 cm, doubly charged helium ions captured into the ring received an energy W ~ 30 MeV. The number of electrons was $(5-8) \times 10^{12}$, and the number of accelerated ions $N_\alpha \sim 5 \times 10^9$. The results of the experiment agree with theory.

In 1956 V. I. Veksler[1] pointed out the possibility of accomplishing new methods of acceleration utilizing collective interactions. During the last few years these ideas have been successfully developed both theoretically and experimentally, first in the USSR[2] and later in other countries.

In order to accelerate protons or heavy ions by the new method it is necessary to create a dense electron bunch. In the collective ion accelerator model at the Joint Institute for Nuclear Research a ring of electrons rotating in a magnetic field was chosen as the bunch. A LIU-3000 induction linear accelerator is used for injection of electrons. A 100-A, 1.5 MeV beam is injected into the weak-focusing field of the electron ring compressor chamber ("adhesator") at a radius of 40 cm in the median plane. Turning on pulsed fields assures that the beam misses its injector and subsequently undergoes adiabatic compression to a radius of 6 cm. In the first revolutions the beam has an elliptical cross section with semiaxes $a_r \sim 1.6$ cm in the radial direction and $a_z = 1.2$ cm in the axial direction. During the adiabatic compression a decrease in the transverse dimensions of the beam occurs.[3]

Calculations show that, if we take into account the change of the betatron oscillation frequency associated with capture of ions from the helium medium in which the compression occurs, for a pressure $P = 10^{-7}$ mm Hg in the final stage of compression the ring has a cross section of dimensions ~1 mm. Measurements of the radial dimension of the ring were made at an acceleration distance of 20 cm and showed that $2a_r \sim 2$ mm.

Figure 1 shows the coil system of the compressor chamber and the magnetic field produced by this system. As can be seen, to extract and accelerate the beam it is necessary to adiabatically deform the magnetic mirror—to destroy its symmetry in such a way that the bunch will experience an expulsive force in the z direction. For this purpose, coils 4, 5, and 6 are shunted by means of spark gap 9 at a certain moment. As a result there is produced in the compressor chamber a magnetic field (see Fig. 1b) whose gradient in the axial direction produces the necessary accelerating force.

The problem of containing the ions in the electron ring during acceleration places definite requirements on the magnetic field gradient.[4] Control of the gradient is achieved by choice of the time of turning on spark gap 9 and solenoid 7. Measurement of the local values of the gradient with high accuracy is difficult. Therefore in acceleration of the ring the average magnetic field gradient in a 40-cm acceleration region was maintained equal to ~10 G/cm. With this field gradient, the acceleration of a ring with $(5-8) \times 10^{12}$ electrons was less than the limiting acceleration and permitted acceleration of doubly charged α particles to an energy ~30 MeV.

According to theory the effective accelerating field acting on an ion located in the potential well is

$$E_{\text{eff}} = keN_e i / \pi Ra, \tag{1}$$

where N_e is the total number of electrons in the ring, e is the electronic charge, i is the ionization multiplicity, R is the major radius of the ring, a is the cross-sectional radius of the ring, and k is a param-

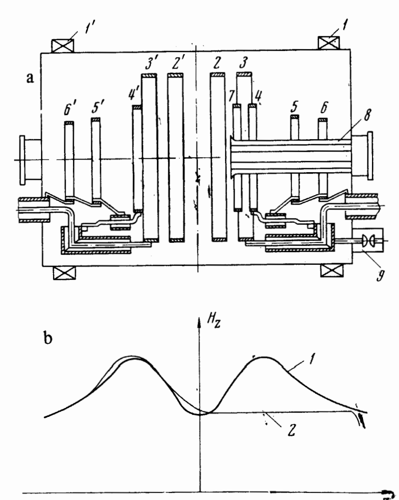

FIG. 1. a—Diagram of electron ring compressor: 1–7—Windings for producing magnetic field, 8—focusing tube, 9—spark gap; the dashed line shows the beam cross section at the initial moment of time. b—Magnetic field distribution: 1—at the moment of maximum compression of the ring, 2—at the moment of extraction of the ring.

eter. The parameter k depends on the density distribution inside the ring and can vary from 1 to $\frac{1}{2}$ for different distribution functions. The total energy W of doubly charged α particles for an acceleration length L will be

$$W = E_{\text{eff}} L. \tag{2}$$

Thus, according to theoretical estimates the energy for various k values and the N_e values chosen is W = 19.2–52.6 MeV.

For a Gaussian distribution of electrons the theory gives for the α-particle energy 19.2–32 MeV. Comparison of these values with experiment provides the possibility of confirming that the electron density distribution in the ring is close to Gaussian.

As follows from calculations in accordance with Ivanov et al.,[4] the ratio of the number of accelerated α particles to the number initially captured into the potential well of the ring is 30%. This is explained by the fact that the target hit by the accelerated ring loaded with α particles is located in a region of strong falloff of the magnetic field. Directly in front of the target is placed a flag on which the electron component is precipitated. However, because of the nonuniformity of precipitation of the electron ring, a smearing of the α-particle energy occurs in the high-energy direction.

In order to detect the α-particle beam and determine its main characteristics, we used the method of measuring the activity induced in a copper target. This activity is the result of interaction of the accelerated α particles with the nuclei Cu^{63} and Cu^{65}. The principal nuclear reactions occurring in the copper are the following:

$$Cu^{63}(\alpha, n)Ga^{66},\ T_{1/2} = 9{,}4\ \text{h};\quad Cu^{63}(\alpha, 2n)Ga^{65},\ T_{1/2} = 15\ \text{min};$$
$$Cu^{65}(\alpha, n)Ga^{68},\ T_{1/2} = 70\ \text{min};\quad Cu^{65}(\alpha, 2n)Ga^{67},\ T_{1/2} = 78\ \text{h}$$

The most convenient isotope for detection of the γ radiation is Ga^{66}, whose γ spectrum contains two intense lines at 511 and 1040 keV. Since the measurements were carried out 4–5 hours after the bombardment, the contribution from other reaction channels to the 511-keV line will be insignificant as the result of the small half-lives of Ga^{68} and Ga^{65}.[5]

A side reaction in copper is the interaction of the electron bremsstrahlung with Cu^{63} and Cu^{65}. The threshold for the photonuclear reaction $Cu^{65}(\gamma, n)$ is 11 MeV. In order to evaluate the effect of the yield of isotopes from this reaction, we carried out a bombardment of a copper target with the electron ring at the moment of its maximum compression. The activity was absent in the γ spectrum from this target in the energy range of interest. In this way, by measuring the γ spectra from the copper foil, we can judge the energy and number of the α particles incident on the target.

Estimates were made of the efficienty for detection of α particles by means of the isotope Ga^{66}. They showed that it is possible to detect α-particle fluxes with a number of particles $N_\alpha > 5 \times 10^8$ and energy $E_\alpha > 10$ MeV.

In determining the parameters of the α-particle beam we placed targets at a distance z = 40 cm from the median plane. The target was prepared as a set of five copper and five aluminum foils in alternate order. The thickness of a copper foil was 12 mg/cm^2 and an aluminum foil 5.4 mg/cm^2. Four to five hours after the bombardment, the activities of the copper foils were measured by means of a scintillation spectrometer whose principal characteristics—the γ-ray detection efficiency as a function of energy and the calibration curve—are shown in Figs. 2 and 3.

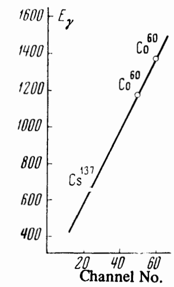

FIG. 2. Spectrometer calibration curve.

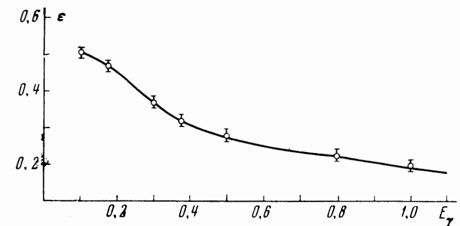

FIG. 3. Spectrometer detection-efficiency curve.

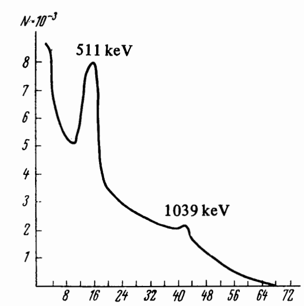

FIG. 4. γ-ray spectrum from bombardment of copper target.

Figure 4 shows the complete γ spectrum obtained in the measurements. It contains two lines with energies 511 and 1040 keV. The half-life of this activity was measured (see Fig. 5) and turned out to be $T_{1/2}$ = 9 hours.

In order to measure the energy, the activity was measured as a function of the number of the copper layer. The results are shown in Fig. 6. It can be seen that the maximum yield occurs in the fourth copper foil. By means of the data in Refs. 6 and 7 and irradiations of the same stack of foils in the U-200 cyclotron of the Nuclear Reactions Laboratory we estimated the energy

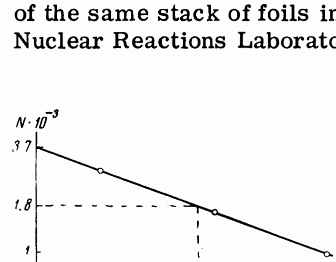

FIG. 5. Copper foil activity as a function of time from the end of the bombardment to the beginning of the measurement.

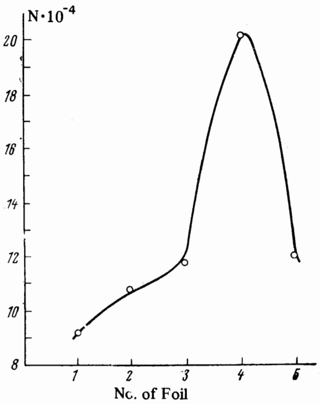

FIG. 6. Activity as a function of copper foil number.

of the incident α particles. The estimate gave a value $E_\alpha = 29 \pm 6$ MeV. The error in determination of the energy is due to the uncertainty in measurement of the thickness of the copper foils, which amounts to 10%, and the inaccuracy in determination of the location of the maximum in the excitation function.

Knowing the α-particle energy, we can determine from the yield of the isotope in the fourth foil the integrated flux of incident α particles according to the formula

$$N_\alpha = N_0 / \sigma(\alpha, n) N_{\text{nuc}} \qquad (3)$$

where N_{nuc} is the number of target nuclei per cm^2, N_0 is the number of active Ga^{66} nuclei at the initial moment of time;

$$N_0 = \frac{S_p e^{\lambda t_d}}{\varkappa \varepsilon (1 - e^{-\lambda t_m})}, \qquad (4)$$

S_p is the area under the photopeak, κ is the absolute quantum yield, ϵ is the γ-ray detection efficiency, t_d is the time from the end of the bombardment to the beginning of the measurement, t_m is the measurement time, and λ is the Ga^{66} decay constant.

The calculations give a value of integrated α-particle flux $N_\alpha \approx 5 \times 10^9$. The error in determination of the number of α particles is determined mainly by the uncertainty in measurement of the α-particle energy—20%—and the thickness of the copper target—10%. Thus, the α-particle flux is determined as

$$N_\alpha = (5 \pm 1.5) \cdot 10^9.$$

These experiments have shown the presence of accelerated α particles and thus have uniquely proved the possibility in principle of collective acceleration.

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