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ACCELERATION OF Xe IONS IN THE JINR TANDEM-CYCLOTRONS

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ABSTRACT

An accelerating system consisting of two 310-cm and 2-m cyclotrons is described with the help of which a Xe ion beam of an energy about 7 MeV/nucl and intensity 2×10^{10} part/sec is obtained.

INTRODUCTION

The most striking pages of nuclear physics of the past decade are primarily associated with the experimental study of nuclear reactions induced by heavy ions. Investigations along these lines have resulted in a number of important discoveries such as synthesis of a whole family of isotopes of new transuranium elements, proton radioactivity, spontaneous fission of nuclei from the isomeric state with anomalously short half-lives, production of a large number of neutron-rich nuclei and study of their properties, etc.

The success of these investigations is mainly due to the use of heavy ions from carbon to argon inclusively. However, to solve quite a number of problems beams of accelerated ions heavier than argon are recognized to be of much importance. One of the most exciting trends is the synthesis of transuranium elements in the region of the so-called new "islands of stability" which will allow one to verify, under laboratory conditions, the fundamental theoretical ideas about the nature of the nucleus. The experimental study of the properties of such nuclei can yield new valuable information on nuclear forces.

Therefore the problem of heavy-ion acceleration is being extensively developed, and in many laboratories of the world devices for obtaining ions like krypton, xenon and uranium are being designed and constructed.[1-3]

In the present report, an accelerating system consisting of two cyclotrons will be described. This system has been created at the Laboratory of Nuclear Reactions of the JINR and with the help of it accelerated xenon ions of an energy 7 MeV/nucl have been obtained.

POSSIBILITIES OF THE LNR CYCLOTRONS

At the Laboratory of Nuclear Reactions there are two heavy-ion 310-cm and 2-m cyclotrons. The 310-cm cyclotron permits to accelerate various ions up to an energy

$$E = 250\ Z^2/A\ \text{MeV}, \tag{1}$$

where Z and A are the charge and mass of an ion, respectively.[4] This accelerator is a classic cyclotron by means of which it is possible to accelerate ions to a full radius when the magnetic field level in the centre varies from 16.5 to 17.1 kG. The highest ion energy is 10 MeV/nucleon for particles with charge-to-mass ratio equal to 5. On the other hand, at this magnetic field level, the frequency range allows to accelerate ions with charge-to-mass ratio A/Z = 7. Thus, operating on 3rd harmonic, it is possible to obtain an external ion beam with A/Z = 15-21 and energy from 1.1-0.56 MeV/nucl, respectively.

The 2-m isochronous cyclotron is a modification of a class 1.5-m accelerator.[5] By increasing the average magnetic field from 17.5 to 20 kG and the full radius from 63 to 90 cm, we have succeeded in increasing the final energy by about a factor of 2.5. The ion energy presently reached in the 2-m cyclotron is

$$E = 150\ Z^2/A\ \text{MeV}. \tag{2}$$

Two 45° dees located in opposite valleys make it possible to accelerate ions with A/Z from 2.8 to 14.7 using harmonics from second to seventh inclusively. On the basis of the relations (1) and (2) it is not difficult to calculate the final ion energy for possible combinations of the two accelerators. The energy dependence of the equilibrium ion charge used in the calculations is taken from ref.6.

We have chosen an operating combination in which the 310-cm cyclotron is used as an injector and the 2-m one as a main accelerator. Such a tandem-cyclotron provides us with beams of Xe ions up to 7 MeV/nucl as well as beams of lighter elements like krypton, the energy of which can reach 9 MeV/nucleon.

VACUUM SYSTEM

One of the serious problems related to heavy-ion acceleration is ion losses due to the interaction with residual gas in the vacuum chamber. Fig. 1 presents the beam intensity as a function of pressure which is measured for $^{136}Xe^{9+}$ ions at the full radius of the 310-cm cyclotron (curve 1) and $^{136}Xe^{30+}$ ions in the 2-m cyclotron (curve 2). These curves are seen to obey the exponential law

$$I = I_0 \exp(-\alpha p), \tag{3}$$

where I_0 is the initial beam intensity, I the intensity at a pressure p, and α the coefficient which can be presented in the form

$$\alpha = \int_0^L \sigma d\ell = \bar{\sigma}L. \tag{4}$$

Here $\overline{\sigma}$ is the average charge exchange cross-section, L the ion path length which can be computed approximately by the formula

$$L = \frac{4\pi R_f N}{3} \tag{4}$$

where R_f is the full radius and N the total number of turns.

Experiments on Xe ion stripping by the residual gas of the vacuum chamber and the appropriate calculations have shown that the average charge exchange cross-section for $^{136}Xe^{+9}$ ions is 2×10^{-15} cm^2 and for $^{136}Xe^{+30}$ ions is 5.4×10^{-16} cm^2.

Six high-vacuum oil diffusion pumps with a total pumping speed of 12,000 litres/sec are available for removing gas from the 310-cm cyclotron. For an operating ion source with a gas flow of 0.5 cm^3/min the vacuum is 2×10^{-6} Torr. When accelerating Xe ions in the 2-m cyclotron no usual arc source is needed. Therefore, the vacuum conditions are essentially better, 5×10^{-7} Torr, when two oil diffusion pumps are used, each being capable of a speed of 4000 litres/sec.

BEAM TRANSPORT SYSTEM

A schematic view of the beam transport system is shown in Fig. 2. The beam is conducted along 70 m from the 310-cm accelerator to the 2-m accelerator. The system consists of five bending magnets adjusting the horizontal beam position, the total rotation angle of which being about 121°, two magnets adjusting the difference of the levels of the median planes of both cyclotrons, and seven pairs of quadrupoles. A magnet located at the input of the 2-m cyclotron permits to vary the entrance angle within ±2°, steering the beam straight to a stripper. To reduce defocusing effects of the fringing field of the 2-m cyclotron a radially-focusing iron magnetic channel is provided at the input of it.

Two first (in the beam direction) magnets and two pairs of quadrupoles were installed earlier and were exploited during some years in the external beam system of the 310-cm cyclotron. The remaining elements of the system, as well as a beam pipe 50 m long, were newly manufactured or mounted. The quadrupoles are placed along the beampipe at a distance of about 9-10 m from one another. Bending magnets and level-adjusting magnets are located at the places of intermediate foci. This permits use of magnets with small aperture, keeping at the same time a large acceptance of the transport system as a whole.

The median planes of both cyclotrons are at different height and are spaced from each other by 50 mm. The correction of this discrepancy is made by a pair of magnets, the distance between the centres of which is 2.5 m, one of the intermediate foci of the beam being placed in the middle of this distance. When tuning the transport system the sizes and intensity distribution of the beam are observed on a quartz plate by means of a TV set. This technique makes it possible to determine operating currents of all the focusing lenses and bending magnets and then to get beam transport efficiency about 70%. Significant losses in the beam pipe are due to stripping by the residual gas. Measurements show that at an operating pressure of 2×10^{-6} Torr these losses are about 30%.

ION INJECTION

High injection efficiency is assured by solving the two chief problems: choice of the sizes and the position of the stripper and focusing of the beam into it. The radial and azimuthal location of the stripper must be such that the centre of the orbits of ions with increased charges coincides with the centre of the 2-m cyclotron as exactly as possible.

The radial size of the stripper is defined by the condition that, after turning the stripper, ions should not fall into it. At $^{136}Xe^{9+}$ ion injection into the 2-m cyclotron, the radius gain per turn is 0.85 cm when ions are accelerated on the third harmonic for the dee voltage of 70 kV. Therefore the maximum radial size of the stripper is specified to be 0.9 cm. There are no so strict limitations on the vertical size of the stripper. It is equal to the aperture of the air gap, i.e. 2.8 cm.

The ion injection to the 2-m cyclotron is performed in such a manner that the ion trajectory before charge exchange passes at the place of location of the stripper along the tangent to the equilibrium orbits of the same ions after charge exchange. A schematical view of the ion injection is given in Fig. 3.

The ion trajectories are calculated by means of a computer. It is found that the stripper should be located in one of the free "east" or "west" valleys of the cyclotron since it is impossible to place it in the hill. The calculations performed allow also to select the position of the stripper such that the total beam bending angle is minimum along the whole transport line for the purpose of reducing the value of BR product for all the bending magnets. This is just achieved when placing the stripper in the "west" valley of the 2-m cyclotron.

The calculations are carried out for variable ion charges after charge exchange for the purpose of defining operating positions of the stripper. A necessary matching of the positions of the stripper for ions with different charges is reached by varying the azimuthal and radial positions of the stripper and the injection angle. The latter changes by means of a steering magnet at the input of the 2-m cyclotron.

In the first ion injection experiments one has failed in focusing the beam at the place of location of the stripper because of radial defocusing effects at the input of the 2-m cyclotron. To overcome this trouble a steel magnetic channel 35 cm long with an aperture of 5cm for the beam focusing in the radial direction (the channel aperture is $3.5 \times 5\ cm^2$) is mounted. The experiments have shown that the beam transport efficiency is about 30% for a stripper of dimensions $0.9 \times 2.8\ cm^2$.

This efficiency is due to the loss of a portion of the beam at the input of the 2-m cyclotron dee since the vertical aperture of the dee is as small as 3 cm and the vertical size of the beam is 5 cm on the intercept of the trajectory.

The sizes and the intensity distribution of the beam to be injected are detected by the luminescence of a CsI crystal mounted on the "west" probe. This probe has a sliding carriage with an ion collector, a luminophor crystal and a stripper installed on it.

TIME MATCHING OF BUNCHES

In any resonance accelerator the ion beam has a definite microscopic structure created by rf accelerating voltage. There arises the problem of matching bunches emerging from the first accelerator with the time intervals during which these bunches can be trapped by the second accelerator. To this end, the ratio of the accelerating voltage frequencies of both cyclotrons should be an integer, i.e.

$$\frac{\omega_{rf_I}}{\omega_{rf_{II}}} = \frac{n_1 Z_1 B_1}{n_2 Z_2 B_2} \qquad (6)$$

where Z_1 and Z_2 are the ion charges before and after stripping, B_1 and B_2 are the magnetic fields of the accelerator-injector and the main accelerator, n_1 and n_2 the numbers of harmonics. If the magnetic field levels are fixed or changed insignificantly, as in our case, this ratio may be an integer only for fixed ion charges. When accelerating Xe ions, both cyclotrons operate on third harmonic. This choice is defined by the cavity wave-length range for the 310-cm cyclotron and by the energy gain per turn for the 2-m one.

An exact synchronization for both rf generators is reached for the following ion combinations:

$$Xe^{8+} \rightarrow Xe^{26+},\ Xe^{8+} \rightarrow Xe^{27+},\ Xe^{9+} \rightarrow Xe^{30+},\ Xe^{9+} \rightarrow Xe^{29+}$$

and is facilitated in the following way. A signal coming from the rf generator of the 310-cm cyclotron passes through a phase shifter. The signal phase at the output of the phase shifter varies between 0 and 360°. Then the signal is given to a resonant circuit tuned to second harmonic of the rf generator frequency. When the 2-m cyclotron operates on third harmonic of the ion rotation frequency the second harmonic of the rf signal is given at the input of a first power amplifier stage where it is doubled and after being amplified in subsequent stages enters the cyclotron resonator.

Synchronization of the frequency and the accelerating voltage phase allows to increase the beam intensity by a factor of 3 compared with the operation mode in which the oscillator of the 2-m cyclotron is excited by its own driving oscillator.

STRIPPING

The ion charge after stripping is known to depend on the ion energy, material of which the stripper is manufactured, and its thickness. At the same ion energy (about 1 MeV/nucleon) the charge of an ion passing through a solid stripper is higher by 30% compared with a gaseous stripper. Therefore, solid strippers are found to be more effective. In designing the JINR tandem-cyclotron it was decided to use a solid stripper for which the equilibrium Xe ion charge and the distribution of ions over charges near equilibrium one were measured on the 310-cm cyclotron.

To make this measurement the $^{132}Xe^{8+}$ ion beam was accelerated to an energy of 0.9 MeV/nucleon on third harmonic of the ion rotation frequency.[7] The external beam of these ions was focused into a gold stripper 380 $\mu g/cm^2$ thick, and the ion charge after stripping was analysed by means of a magnetic separator. In the focal plane of this separator the ion beam was detected by a solid-state detector, the results being recorded by a multichannel analyser. Varying the magnetic field of the separator, the detector was struck by ions with different charges.

The charge distribution of ions is plotted in Fig. 4. The largest fraction of ions, amounting to about 13% of the incident beam, is seen to have Z=27, the intensity of the ion beam with Z=24 and 29 being only half the intensity of the beam with equilibrium charge. This allows to accelerate stripped Xe ions with charges from 24 to 29 in the 2-m cyclotron thereby the final energy by about a factor of 1.5 for the constant value of the cyclotron magnetic field.

Similar stripping experiments are made with an aluminium foil 130 $\mu g/cm^2$ thick. Within the experimental accuracy, no noticeable changes in the magnitude of the equilibrium charge have been detected. When passing through a substance, the ion undergoes, in addition to stripping, scattering on the stripper atoms. The scattering angle is estimated to be in good agreement with experiment by the following formula[8]

$$\langle\theta^2\rangle^{\frac{1}{2}} = \left(\frac{Z_2(Z_2+1)}{A_2}\right)^{\frac{1}{2}} \frac{Z_1\sqrt{t}}{2E} \qquad (7)$$

where $\langle\theta^2\rangle^{\frac{1}{2}}$ is the mean-square scattering angle (mrad), t the thickness of the stripper with charge Z_2 and mass A_2, Z_1 and E are the charge and energy (MeV) of an incident ion.

As is seen from the formula, the beam divergency reduces strongly with increasing ion energy. However, for low energies the scattering angle is rather large. So, for the 150 MeV ^{136}Xe ions the scattering angle is 5.5 mrad for an aluminium stripper 130 $\mu g/cm^2$ thick and

2.1 mrad for a graphite stripper 40 μg/cm^2 thick. The large value of the scattering angle leads to a noticeable increase of the emittance. The calculations show that in the case of the aluminium stripper the vertical beam emittance increases from 8π to 21.4π mm.mrad in the case of the graphite stripper, only to 11π mm.mrad for the beam height equal to 8 mm. This fact results in a decrease of the beam intensity.

EXPERIMENTS ON Xe ION ACCELERATION

In earlier experiments on Xe ion acceleration in the 2-m cyclotron aluminium foils 0.5μ thick each are used. To increase thermal radiation of these foils a thin graphite layer is deposited onto them. When the injected beam intensity reaches 2×10^{11} part/sec the duty life of the foil is 30 hours.[9] After a focusing magnetic channel has been installed at the entrance of the 2-m cyclotron, the beam intensity becomes higher and a graphite stripper 40-50 μg/cm^2 thick is used, instead of the aluminium one. The foils of dimension 9×15 mm^2 are mounted on metallic frames spaced uniformly along the circle of a vertical disc 90 mm in diameter. The constantly moving disc allows to decrease essentially the heat load of the stripper. At an intensity of 7×10^{11} part/sec the temperature of the fixed graphite stripper is found to be about 1000°K, which can be seen visually by foil luminescence under the beam. Under these conditions the duty life of the stripper is 10-15 hours. The disc with foils is mounted on a probe which is displaced radially and azimuthally by a remote handling. The probe is introduced into the chamber through a vacuum lock so that the time of replacement of the disc is a few minutes. The use of graphite foils increases the beam intensity by about a factor of 4 because for them the mean-square scattering angle is small enough.

A beam of accelerated $^{132}Xe^{27+}$ ions with an intensity of about 10^8 part/sec and an energy of 6 MeV/nucl was first obtained in August 1971.

A Xe ion beam with Z=8 was accelerated on the 310-cm cyclotron. The rf generators of both accelerators operated without synchronization. After a focusing magnetic channel has been installed at the input of the 2-m cyclotron and a synchronization system for rf generators had been arranged, the beam intensity became essentially higher. At present the maximum intensity is $2 \cdot 10^{10}$ part/sec. Ta, Bi and U targets were bombarded by ions of the heaviest Xe isotope - 136. The first experiments showed that the $^{136}Xe^{27+}$ energy is insufficient. Therefore, it was further necessary to accelerate ions with Z=30. In order to produce ions with such a charge and synchronize accelerating voltage we passed in the 310-cm cyclotron from acceleration of ions with Z=8 to that with Z=9. The number of ions with Z=9 produced in the ion source is by a factor of 4 smaller than the number of ions with Z=8. However, when going to the acceleration of $^{136}Xe^{9+}$ ions the beam intensity in the 310-cm cyclotron remained actually unaffected, compared with the $^{132}Xe^{8+}$ beam intensity, since in the former case xenon was enriched with isotope 136 and in the latter one a natural xenon was used (26.9% of ^{132}Xe).

The experiments on Xe ion acceleration and the long-term operation of the tandem-cyclotron showed that with a careful tuning of all the elements of the accelerating and transport systems the total efficiency of it reaches 2%.

The efficiency of the transport system is 70% and the main losses are due to stripping at residual gas atoms of the ion pipe. About 50% of the beam to be injected into the cyclotron is lost on the edges of the dees. As was already mentioned, after stripping only 13% of ions have the charge with which they undergo further acceleration. The growth of the beam emittance at the stripping due to ion scattering by the stripper results also in beam losses which are estimated to be 20-30%. Finally, a portion of the beam is lost in the 2-m cyclotron due to stripping at residual gas atoms of the vacuum chamber. At a vacuum of 5×10^{-7} Torr these losses are about 50%.

CONCLUSION

For the combination of the 310-cm and 2-m cyclotrons xenon is an extreme particle, the energy of which is sufficient to overcome the Coulomb barrier at heavy targets. However, after reconstructing the 310-cm cyclotron to a 4-m one[10] there will appear a possibility of accelerating U ions.

The reconstruction will provide an increase of the final energy from 250 to 625 Z^2/A MeV. Then the U^{12+} ions will possess an energy higher than 1.5 MeV/nucleon at the final radius of the 4-m cyclotron, which will be sufficient for obtaining U^{50+} ions after stripping. These ions can then be accelerated in the 2-m cyclotron to an energy of 7 MeV/nucl.

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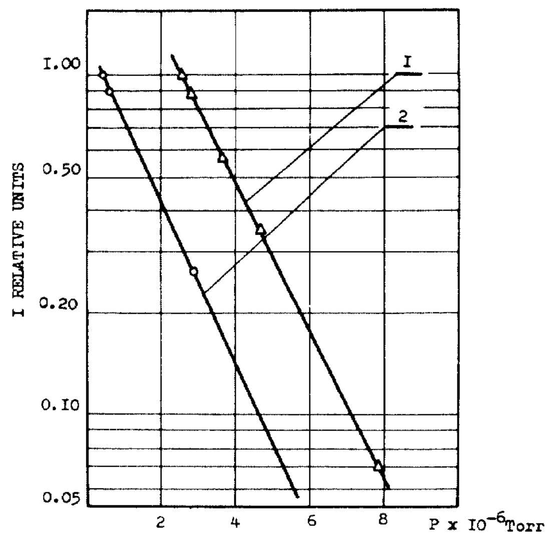

Fig. 1. Beam intensity as a function of the pressure in the vacuum chamber. Curve 1 for $^{136}Xe^{9+}$, E = 1.1 MeV/nucl Curve 2 for $^{136}Xe^{30+}$, E = 7 MeV/nucl.

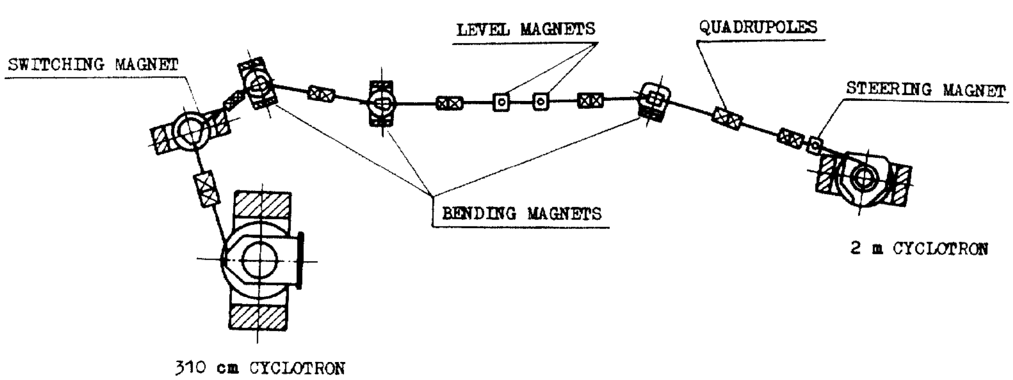

Fig. 2. A schematic view of the beam transport system between the two cyclotrons.

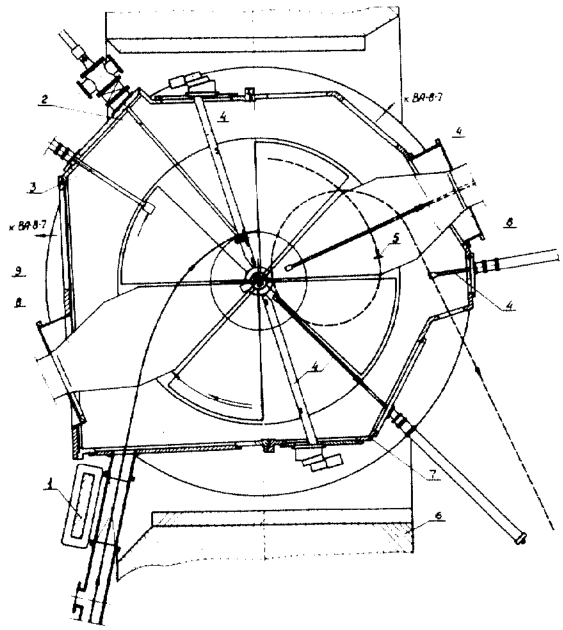

Fig. 3. A scheme of ion injection into the 2-m cyclotron: 1) adjusting magnet for beam injection, 2) probe with stripping, 3) physical probe, 4) current probes, 5) extraction foil, 6) yoke, 7) vacuum chamber, 8) dees, 9) sectors.

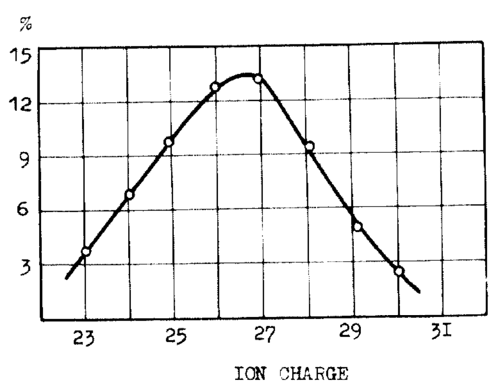

Fig. 4. Measured charge distribution of Xe ions of an energy 0.9 MeV/nucl for stripping on a gold foil 380 μg/cm^2 thin.

DISCUSSION

WEGNER: How much beam loss do you have in the beam transport between the two accelerators?

OGANESIAN: How much? 30%. The total efficiency is about 70%, and the losses are about 30%.

WEGNER: Is that in the transport?

OGANESIAN: Yes, in the 70 m long beam pipe. We think this is only dependent on the stripping in this line.

MALLORY: Do you run your machine synchronously? By synchronous, I mean the RF systems are in phase.

OGANESIAN: Yes.

CLARK: Are you doing experiments with the internal beam and do you plan to extract that beam?

OGANESIAN: For the physicists' experiments at present we use only the internal beam. With this beam the physicists began the program for discovering new transuranium elements. But maybe in the near future we will try to extract this beam. In extracting it we expect to use two methods: an electrostatic deflector and stripping methods. We use these methods in the 2 m machine when it is operated independently.