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NUCLEAR EXPERIMENT TECHNIQUE

Measuring the Current of a Beam of Argon Ions Accompanying a Beam of Protons in a Tandem Accelerator with Vacuum Insulation

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Abstract—In electrostatic tandem charged particle accelerators, gas stripping targets are used to convert negative ions into positive ones. Partial ionization of the gas by ions leads to the formation of an undesirable beam of stripping gas ions in the accelerating channels. In this work, the current of a beam of argon ions produced in a tandem accelerator with vacuum insulation was measured by mass spectroscopy. It is shown that the current of argon ions is 2000 times smaller than the current of the proton beam. The reliability of the measurements is provided by visualization of an argon ion beam on the surface of a lithium target and is also confirmed by an experiment with increased gas injection and an estimate of the possible contribution of the proton beam. It is shown that such a small value of the argon ion current does not pose a danger either as a source of additional heating of a lithium target, or as an additional load of a high-voltage power supply, and therefore does not require the previously proposed means for its suppression.

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Charged particle accelerators are widely used in scientific research, medicine, and other applications. Tandem accelerators are high-voltage electrostatic accelerators in which the high-voltage potential is used twice: first to accelerate negative ions, and then, after changing the polarity of their charge in the high-voltage terminal, to accelerate positive ions. Thin foils are used for the conversion of the ion charge, or, at a higher ion current, gas stripping targets similar to the argon target in the tandem accelerator of the Budker Institute of Nuclear Physics of the Siberian Branch of the Russian Academy of Sciences. The stripping gas target provides effective stripping of the negative ion beam; however, its use leads to the formation of an undesirable beam of argon ions, which are formed in the stripping target as a result of argon ionization by the ion beam and penetrate into the accelerating channel.

The aim of this work was to measure the current of an argon ion beam in a tandem accelerator with vacuum insulation.

THE EXPERIMENTAL SCHEME

The studies were carried out at the accelerator neutron source of the Budker Institute of Nuclear Physics SB RAS (Novosibirsk, Russia). The source diagram is shown in Fig. 1 and its detailed description was given in [1]. A tandem accelerator with vacuum insulation was used to obtain a stationary proton beam with an energy of 0.6 to 2.3 MeV and a current of 0.3 to 10 mA, that is, a tandem accelerator of charged particles with an original design of electrodes. In it, unlike traditional accelerators, there are no accelerating tubes; the high-voltage electrode and electrodes with an intermediate potential are embedded in each other and fixed on a single feedthrough insulator, as shown in Fig. 1. This configuration of the accelerator made it possible to improve the high-voltage strength of the accelerating gaps and, as a consequence, to increase the proton current.

One of the main elements of the tandem accelerator is the stripping target *4* placed inside the high-voltage terminal. It provides the conversion of negative hydrogen ions to protons with a high efficiency, usually at the level of 95%. The target is a 400-mm long cooled cylindrical copper tube with an inner hole

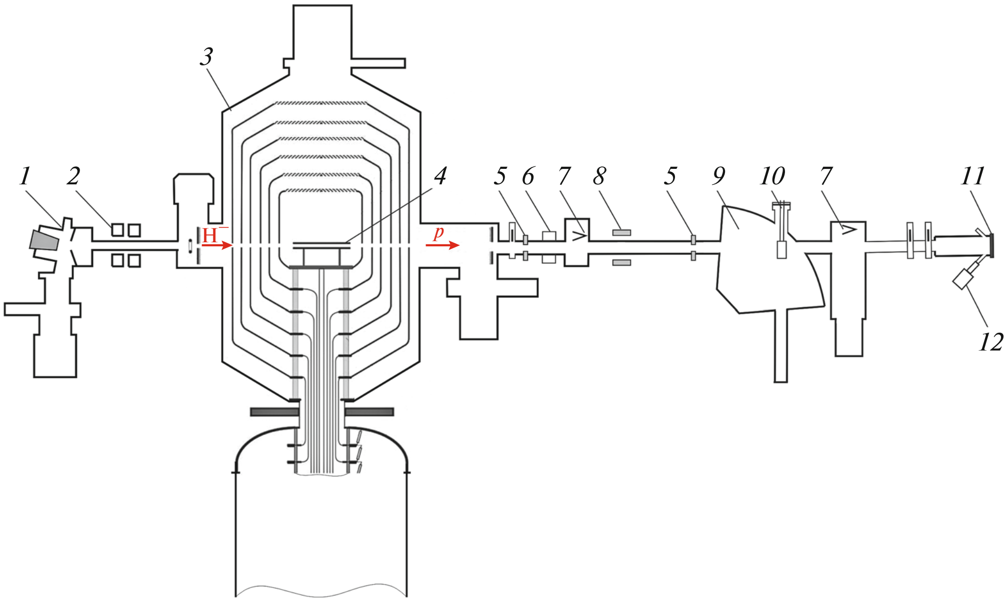

Fig. 1. A diagram of an accelerator based source of epithermal neutrons. *1*, a source of negative hydrogen ions; *2*, magnetic lens; *3*, vacuum-insulated tandem accelerator; *4*, gas stripping target; *5*, cooled diaphragm; *6*, contactless current sensor Bergoz (France); *7*, introduced Faraday cylinders; *8*, corrector; *9*, bending magnet; *10*, cooled beam receiver with a diaphragm; *11*, lithium target; *12*, Hikvision video camera (China).

diameter of 16 mm [1]. The interaction of a hydrogen ion beam with a gas target leads to its partial ionization, and a weakly ionized plasma is formed inside the stripping tube. Since electrons are more mobile than argon ions, the plasma assumes a positive potential to maintain quasineutrality. Under the action of the positive potential, part of the argon ions leaves the stripping tube, enters the accelerating channel, and forms a beam of argon ions. Simple estimates of the argon ion current give values from commensurate to negligible in comparison with the proton current. It is difficult to reliably estimate the magnitude of the argon ion current due to the inhomogeneity of the converted beam and secondary plasma along the target, the possibility of the development of beam-plasma instability, the penetration of the electric field of the accelerating gaps into the high-voltage terminal, and many other parameters that are not reliably known.

To suppress the penetration of argon ions into the accelerating gaps, it was proposed to place metal rings under a negative or positive potential in front of and after the stripping target, or to deflect the ion beam by a magnetic field inside the high-voltage terminal [2].

The formation of an argon ion beam was indicated by two experimental facts. First, the secondary ion current flowing along the periphery towards the accelerated beam of negative hydrogen ions was previously measured with a ring detector [3]. It is possible that argon ions escaping from the stripping target also contribute to this current. However, it is more likely that the main contribution to this current is made by the positive ions formed in the accelerator gaps as a result of the ionization of the residual or stripping gas by the hydrogen ion beam. In this case, positive ions are formed mainly in the first accelerating gap due to its length and high ionization cross section at a relatively low velocity of negative hydrogen ions. Second, when studying the radiation blistering of metals upon implantation of protons with an energy of 2 MeV [4], an earlier formation of blisters of a smaller than expected size from the implantation of protons was observed. This effect was explained by the presence of a beam of argon ions with an energy of 1 MeV; these penetrate the metal to a shallower depth than protons and can deform a metal surface faster with smaller blisters.

MEASUREMENT RESULTS AND DISCUSSION

The measurements were carried out at a proton beam current of 760 ± 10 μA, an energy of 1.850 ± 0.002 MeV, and a transverse beam size of approximately 1 cm.

The method of mass spectroscopy was used to measure the argon ion current. Inside the bending magnet *9* (see Fig. 1) a cooled diaphragm was inserted *10* with a 5 × 20 mm slot. Since the mass of an argon ion is 40 times greater than the mass of a proton and the kinetic energy is two times lower, the Larmor radius of an ion in a magnetic field is $\sqrt{20}$ times less than the Larmor radius of the proton and the bending magnet will deflect argon ions by an angle $\sqrt{20}$ times smaller than the angle of deflection of protons. The

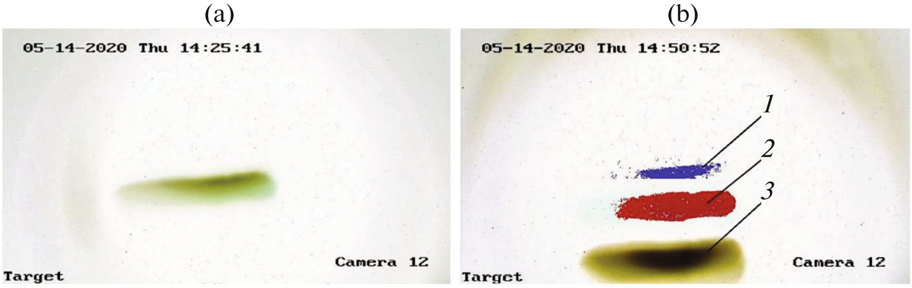

Fig. 2. Images from a video camera looking at the surface of a lithium target at a bending magnet current of (a) 0 and (b) 14 A. *1*, glow caused by neutrals (hydrogen atoms); *2*, argon ions; *3*, protons.

separation of the ion beam components is clearly visible on the surface of a lithium target, when the interaction of ions with lithium leads to luminescence recorded by a video camera *12* [5]. Figure 2 shows two examples of a video camera image: without a magnetic field and with a magnetic field. It can be seen that turning on the magnetic field divides the beam into three components: the flux of neutrals *1*, the argon ion beam *2,* and the proton beam *3.*

The scenario for measuring the argon ion current consisted in placing the diaphragm below the axis of the accelerator, directing the argon ion beam into the diaphragm opening with the magnetic field of the bending magnet, and deflecting the proton beam below, as shown in Fig. 3. In fact, at a current of 68.5 A in the bending magnet coil, only a beam of argon ions passes through the diaphragm, which, upon hitting the lithium target, causes a characteristic luminescence recorded by a video camera. According to Fig. 4, at a current of 10 A in the bending magnet coil, an argon beam and a proton beam are visually visible on the surface of a lithium target, while at a current of 68.5 A, there is no proton beam; only beams of argon and neutral ions are visible.

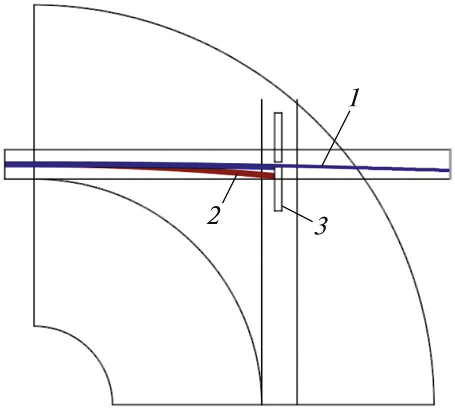

Fig. 3. The result of modeling the trajectory of an argon ion beam (*1*) and a proton beam (*2*) in a bending magnet with a current in the magnet coil of 68.5 A. Cooled diaphragm *3* was placed 12 mm below the axis of the accelerator.

In this mode, at a current of 68.5 A, the current of charged particles passing through a hole in the diaphragm and hitting the surface of the lithium target was measured; it was 150 ± 70 nA. The current is measured by an ohmic voltage divider connected to the target unit (*11* in Fig. 1), electrically isolated from the facility. Without the visualization of an argon ion beam by its luminescence on the surface of a lithium target, such a small value of the recorded current could be mistakenly considered as noise.

The result we obtained was unexpected, since it was previously assumed that the current of argon ions is of course less than the current of protons, but not by very much. Since the maximum proton current that passed through the slit of the diaphragm is 286 ± 3 μA, then,

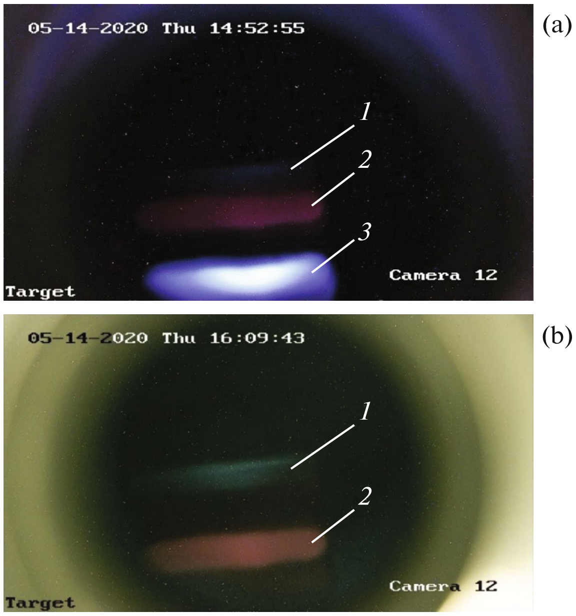

Fig. 4. Images from a video camera looking at the surface of a lithium target: (a), with a current in the bending magnet coil of 10 A; (b), 68.5 A. *1*, a beam of neutral atoms; *2*, an argon beam; *3*, a beam of protons.

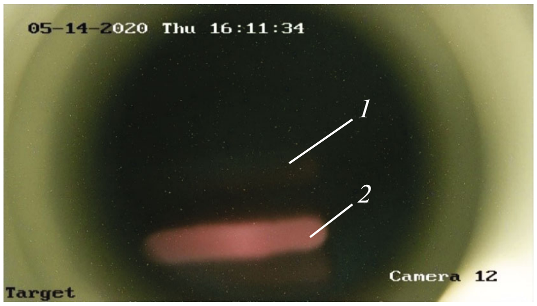

Fig. 5. The argon beam glow (*1*) and a beam of neutral atoms (*2*) caused by the luminescence of the target lithium layer upon a twofold increase in the argon flow in the stripping target.

assuming the sizes of the beams of argon ions and protons to be equal, we obtain that the current of argon ions is 2000 times less than the proton current. This result is the main result of this study.

At such a value, the argon ion beam current does not pose a danger either as a source of additional heating of the lithium target, or as an additional load of a high-voltage power source, and therefore does not require means for its suppression.

We will confirm the reliability of this result by an additional experiment and evaluation.

For this purpose, we will double the frequency of opening the valve that supplies argon to the stripping target. A larger supply of stripping gas, as it should, leads to an increase in the argon ion current to 670 ± 150 nA and more intense luminescence, which can be seen from a comparison of the images in Figs. 4b and Fig. 5. As well, a larger gas supply leads to better stripping of the beam of negative hydrogen ions, which entails a decrease in the neutral flux, as can be seen from a comparison of the images in Figs. 4b and 5. We note that a two-fold increase in the supply of argon to the stripping target leads to an almost four-fold increase in the argon ion current, which is possible, since the outflow of ions from the stripping target depends on many processes and parameters. Even in this case, the argon ion beam current is very small compared to the proton current.

Let us estimate the contribution of protons to the measured value 150 ± 70 nA. To do this, it is necessary to determine the profile of the proton beam, which is a difficult task, taking the high power of the proton beam into account. Prior to this study, only one measurement of the proton beam profile was carried out in a rather exotic way, that is, by the propagation of the blister formation boundary with an increase in the fluence of protons implanted into copper [4]. The transverse size of the proton beam was estimated at 1 cm; this value was taken into account when developing diagnostics for measuring the argon ion current.

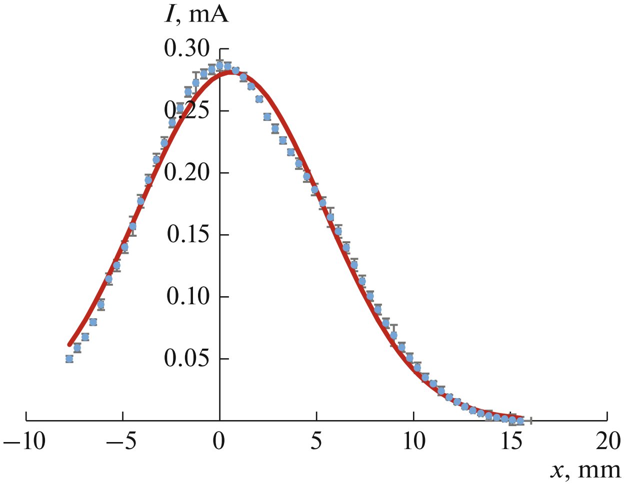

Fig. 6. The dependence of the beam current of protons passing through the slit on their deflection at the beam receiver (points with errors) and the Gaussian distribution approximating the dependence (solid line).

By changing the current of the bending magnet coil, we can scan the beam of charged particles. The measurement result, which is actually the result of chord measurements of the proton beam, is shown in Fig. 6. Here, the abscissa shows the transverse displacement recalculated for protons. Let us fit the Gaussian distribution into the measured dependence of the proton current on the magnetic field. Extrapolating the inscribed Gaussian distribution to a coordinate of 28 mm, which corresponds to a current of 68.5 A in the bending magnet coil, we obtain that protons can contribute 19 nA to the measured value of 150 ± 70 nA. In reality, this contribution is much smaller, since at the periphery, the proton current density decreases faster than the Gaussian distribution, which can be seen in Fig. 6. This is due to the strong focusing of the negative hydrogen ion beam into the accelerator, the action of the spatial charge [6], and the small size of the holes in the accelerating electrodes of the accelerator. Some difference between the current profile and the Gaussian distribution in the paraxial region of the proton beam, which was previously discovered [4] and is not fundamental to the result, is due to the distortion of the electric field in the accelerator due to the misalignment of the electrodes and imperfection of their shape.

Chord measurements of the proton beam profile make it possible to reconstruct its profile. Assuming the distribution to be Gaussian:

$$j(r) = \frac{j_0}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-x_0)^2}{2\sigma^2}},$$

using the least squares method, we find that the standard deviation σ = 4.8 mm, the displacement x0 =

0.61 mm, and the width of the proton beam at a height of 1/e is equal to 13 mm.

CONCLUSIONS

The Budker Institute of Nuclear Physics of the SB RAS operates a tandem accelerator with vacuum insulation, in which a gaseous argon stripping target is used to strip a beam of negative hydrogen ions into protons. The interaction of the ion beam with the stripping gas leads to partial ionization of argon, penetration of argon ions into the accelerating channel, and the formation of an accelerated beam of argon ions accompanying the proton beam.

The magnitude of the argon ion beam current was measured by mass spectroscopy using a bending magnet and a cooled diaphragm; it is 2000 times smaller than the proton beam current. The reliability of the measurement is provided by visualization of an argon ion beam on the surface of a lithium target, as confirmed by an experiment with increased gas injection and an estimate of the possible contribution of the proton beam. Such a small value of the current of the argon ion beam poses no danger either as an additional heating of the lithium target or as an additional load of a high-voltage power supply and therefore does not require the previously proposed suppression means.

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