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GENERAL EXPERIMENTAL  
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## A Magnesium Vapor Charge-Exchange Target for an Accelerator Mass Spectrometer

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**Abstract**—The target design and results of experiments aimed at stripping carbon ions in magnesium vapor are presented. It is proposed to substitute such a target for gas targets conventionally used in accelerator mass spectrometers, which will reduce the background ion charge exchange outside the target.

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### INTRODUCTION

An accelerator mass spectrometer (AMS) [1], which is under construction at the Siberian Branch of the Russian Academy of Sciences' Budker Institute of Nuclear Physics, will be used to measure the isotopic composition of substances. To be capable of detecting rare and cosmogeneous isotopes, the AMS must have a relative sensitivity of  $10^{-12}$ – $10^{-15}$  [2]. For example, the fraction of the carbon isotope with a mass of 14 amu in the carbon from a modern sample is  $\sim 10^{-12}$  with respect to  $^{12}\text{C}$ . To attain sensitivity as high as this, it is necessary that ion background due to atoms and molecules with close masses be suppressed. Background ions with various masses can surmount filters with magnetic and electric fields by interacting with the residual gas of the vacuum chamber. A tandem electrostatic accelerator has been selected as a basis for the AMS. In a system of this type, negative ions are initially accelerated to the potential of the high-voltage terminal. Ions are thereafter stripped to a positive charge and repeatedly accelerated to the ground potential. High requirements are specified for the stability of the thickness, the operating time, and the vacuum conditions of the charge-exchange target for the AMS. It should be noted that solid state targets cannot be used at a beam energy of  $\sim 1$  MeV, because they are rapidly destroyed by ion beams. Available AMSs include gas targets. A high vacuum in the accelerating tubes is maintained by a system of turbomolecular pumps located immediately in the high-voltage terminal.

The use of a target based on magnesium vapor offers a chance to substantially simplify the vacuum system in the AMS high-voltage terminal. The magnesium vapor pressure is  $< 10^{-10}$  Torr at room temperature [3]; therefore, there is no necessity in high-performance gas pumping system. In addition, the magnesium vapor pressure can be monitored and stabilized by controlling the temperature of the container with magnesium, thus

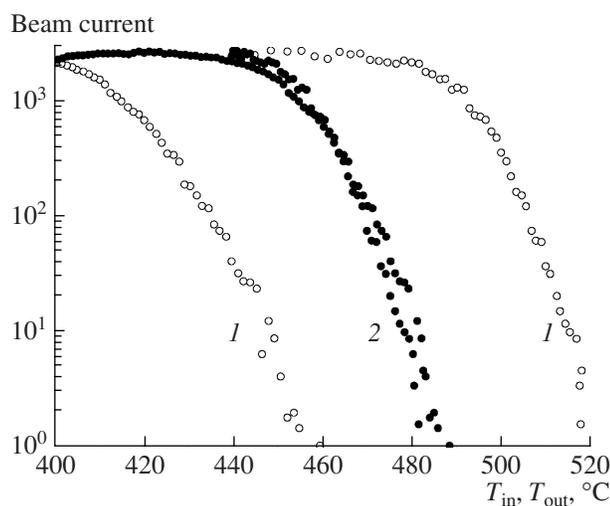
maintaining constant thickness of the target and simplifying optimization of the AMS operation. A similar magnesium target was used earlier for charge exchange of hydrogen ions [4] in the setup for studying electron cooling with a vacuum of  $10^{-11}$  Torr.

### DESCRIPTION OF THE MAGNESIUM VAPOR TARGET

The external appearance of the magnesium vapor target is shown in Fig. 1. The target consists of the central part heated to a temperature of  $\sim 500^\circ\text{C}$  and the side compartments held at a temperature of  $\sim 100^\circ\text{C}$  and used for condensation of magnesium vapor. The target is made of stainless steel. The stripping channel of the target has an inner diameter of 6 mm and a length of 30 cm. The flanges are welded to the target through bellows that prevent the tube from being deformed at temperature variations. A container with solid magnesium is situated in vacuum outside the channel. The magnesium target is heated when the electric current passes directly through the target body. As the container is heated, magnesium vapor penetrates through three 1-mm-diameter holes into the stripping channel. The magnesium vapor pressure in the stripping channel is lower than the magnesium saturated vapor pressure



Fig. 1. Magnesium vapor target.

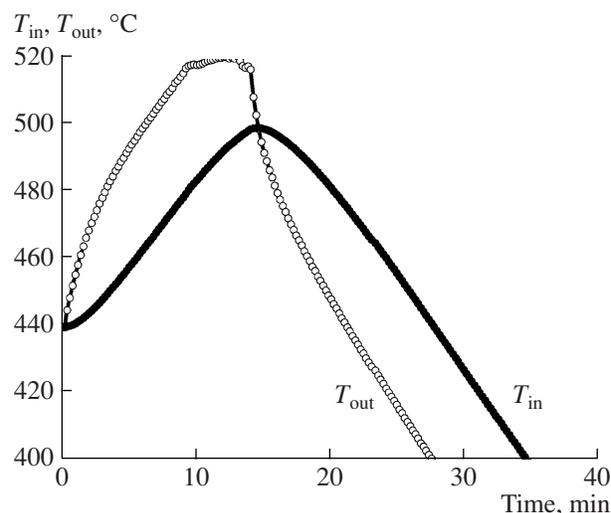


**Fig. 2.** The number of molecular ions with a mass of 14 amu that passed through the target vs. (1) the container and (2) magnesium temperatures.

inside the container due to the limited gas permeability of the holes. This prevents “overgrowth” of the channel with magnesium if the channel is insufficiently heated. To reduce the heat loss, the central part of the target was wrapped in an asbestos cloth, over which several layers of glass-fiber cloth and aluminum foil are wound. The temperature at the surface of the thermal insulation layer does not exceed 100°C. To increase the heat resistance, the central part of the target and the side compartments are connected by a labyrinth of three concentric tubes inserted one into the other. Thermocouples used to monitor the temperature are disposed along the housing of the target. The thermocouple located at the center of the target is used to stabilize the temperature of magnesium. Ceramic inserts are mounted at the edges of the target’s housing to ensure electric insulation; as a result, it is possible to monitor the charge of the beam incident on the target. The channel is adjusted by optimizing the passage of the ion beam through the stripping channel.

### EXPERIMENTAL RESULTS

The magnesium vapor target was installed in the high-voltage terminal of the accelerator mass spectrometer of the Siberian Branch of the Russian Academy of Sciences. The target is heated to the required temperatures for ~1 h. The power consumption is about 200 W. The temperature at the surface of the container with a magnesium sample can be monitored by readings of thermocouples; however, the vapor pressure is governed by the degree to which the magnesium itself is heated. In this target design, the magnesium vapor pressure is regulated by changing the container temperature. In the above-mentioned temperature range, the magnesium is heated, mainly due to heat conduction from the container walls. A change in the magnesium



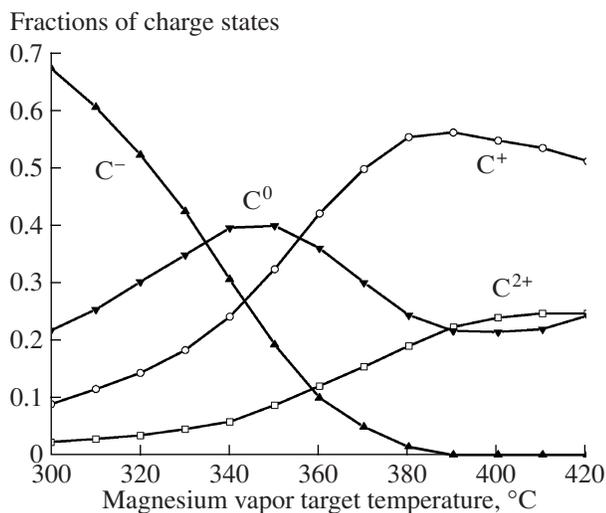
**Fig. 3.** Time dependence of the container temperature ( $T_{out}$ ) and the estimated magnesium temperature ( $T_{in}$ ).

temperature is proportional to the amount of supplied heat, i.e., to the differential temperature of the container and magnesium. The proportionality factor is expressed in terms of the quantity inverse of time; it characterizes the time delay of a change in the magnesium temperature relative to the container temperature:

$$\frac{dT_{in}}{dt} = (T_{out} - T_{in})/\tau, \quad (1)$$

where  $T_{out}$  is the container temperature,  $T_{in}$  is the magnesium temperature, and  $\tau$  is the delay time.

To determine the delay time, we investigated breakup of molecular ions (the ion energy was 250 keV). A beam of negative molecular ions with a mass of 14 amu was injected, and the current of ions with a mass of 14 amu in the charge state of 2+ was measured at the exit from the AMS. Molecular ions with a charge of 2+ break up as they interact with the target; in this case, the intensity of the beam of such ions decreases with an increase in the target thickness according to an exponential law. Molecular ions with a mass of 14 amu consist of carbon and hydrogen atoms:  $^{12}\text{CH}_2$  and  $^{13}\text{CH}$ . Note that negative ions of nitrogen are unstable and, therefore, do not contribute to the beam intensity with a mass of 14 amu. Figure 2 shows the dependence of the number of molecular ions on the temperature of the target container (curve 1). The upper segment of the curve corresponds to target heating, and the lower segment is associated with cooling. The time dependence of the target container temperature is presented in Fig. 3. From the stationary state with a temperature of 440°C, the target is heated to 520°C for ~10 min. The temperature is maintained constant over 5 min. Heating is thereafter ceased, and the target starts cooling. The time it takes to cool the container is determined by the external thermal insulation; in our case,



**Fig. 4.** Dependence of different charge states of 400-keV carbon ions on the target temperature.

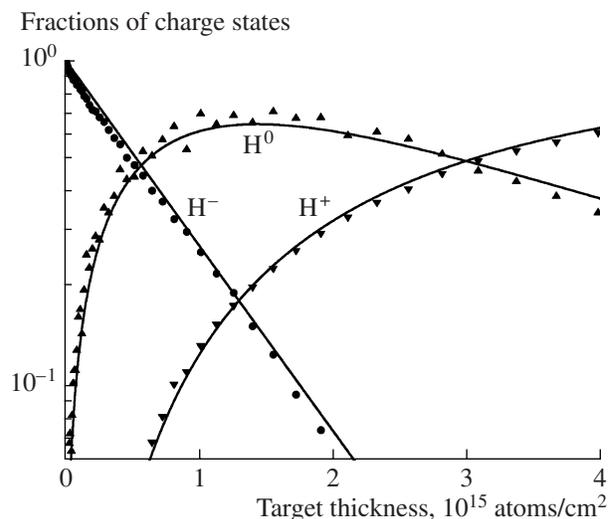
the target housing is cooled to 440°C for ~15 min. From Fig. 2, it is apparent that the dependence of the number of molecular ions on the container temperature has a hysteresis. It is clear that this dependence is determined by the characteristic delay time between the temperatures of the magnesium and the housing. The dependence of the target pressure on the magnesium temperature is independent of the history of heating. When searching for a numerical solution to Eq. (1),

$$T_{in\ k+1} = T_{in\ k} + (T_{out\ k} - T_{in\ k})(t_{k+1} - t_k)/\tau, \quad (2)$$

for the experimental heating curve and different values of  $\tau$ , we will find that the hysteresis disappears at delay time  $\tau = 430$  s. The resultant time dependences of the number of molecular ions and the magnesium temperature are presented in Figs. 2 (curve 2) and 3. Note that the delay time for heating of magnesium is independent of the heating cycle and is governed by the target design. Various experiments on interactions of ion beams with the target's atoms showed that the delay time could be considered as invariable. Thus, the possibility has been demonstrated of using the target in processes in which the target thickness must be varied with time.

Figure 4 presents the measured charge-state composition of the ion (carbon) beam versus the target temperature. This dependence corresponds to passage of 400-keV negative carbon ions through a magnesium target. It is apparent that, after certain temperatures are attained, the ion charge state distribution is almost constant. The equilibrium distribution is characteristic of any target type. Further heating of the target is useless, since it causes the beam emittance to increase by scattering.

The experience gained in using the magnesium target shows that the magnesium vapor pressure decreases



**Fig. 5.** Dependence of the charge state composition of 70-keV hydrogen ions on the thickness of the magnesium vapor target.

in the course of time at a fixed container temperature. Thus, after one-year operation, the container temperature was increased by 50°C in order to obtain the same target thickness. The target thickness is monitored by the effect of ion beam interaction with magnesium atoms. The characteristic degradation time of the target is rather long; therefore, there is no necessity of monitoring this process during a measurement run of the accelerator mass spectrometer. In our case, the decrease in the vapor pressure is likely to be caused by oxidation of the magnesium surface.

The absolute value of the target thickness can be estimated by stripping hydrogen ions with known cross sections of charge exchange with magnesium vapor [5]. From the known cross section, one can calculate the charge distribution of hydrogen ions passing through the magnesium vapor target and compare these values to experimental data obtained with a particular target sample. To do this, a beam of negative hydrogen ions with an energy of 70 keV was used. The results of this comparison are shown in Fig. 5, where solid lines correspond to the results of calculation and dots present the experimental data. For the experimental data, the target thickness is calculated from well-known temperature–pressure relations [3] with subsequent scaling used to ensure the best fit to the theoretical data. To accomplish this, the vapor density was lowered by a factor of 5 with respect to the tabulated pressure of saturated vapor.

Magnesium deposits on surrounding lower-temperature surfaces; therefore, the target vapor is concentrated directly inside the target, which reduces background charge exchange of ions under investigation, except for the first heating of the target after a vacuum is attained in the system. The first heating of the target is followed by gas release; in this case, the degassing time is 2–3 h. Subsequent cycles of target heating do

not result in an apparent deterioration of the vacuum conditions at an operating vacuum of  $10^{-6}$ – $10^{-7}$  Torr.

As the magnesium vapor target is heated, some magnesium penetrates into the accelerating tube of the electrostatic tandem. Under the operating conditions, the target thickness is  $5 \times 10^{15}$  atoms/cm<sup>2</sup>. We did not succeed in finding reliable data on the free path of magnesium in magnesium vapor; however, at a preset concentration, the particle range for all gases mentioned in the handbook [6] exceeds the radius of the channel in the used target. At a range ratio such as this, particle collisions affect the gas conductivity of the channels only slightly [7]. To estimate the amount of magnesium penetrating into the accelerating tube, passing of test particles through the magnesium target was simulated. The particle direction after its interaction with the wall of the target channel was assumed to vary in a random manner with a cosine distribution of the probability that the particle beam will depart from the normal to the surface. A similar distribution according to the particle direction corresponded to the initial conditions of the simulation. Particles were injected at the center of the tube from its surface and had no distribution according to the initial coordinates. It was assumed that the particle velocity is constant and corresponds to the mean value for atomic magnesium at a temperature of 500°C. The magnesium consumption obtained by simulation is 5.4 g for 200 h (this time approximates the number of work hours per month). To limit the ingress of magnesium into the accelerating tube, a 7-mm-diameter diaphragm is located at a distance of 140 mm from the exit of the target's stripping channel. Of the 10000 test particles, 27 passed through this diaphragm, which corresponded to the ingress of ~15 mg of magnesium (the consumption being 5.4 g) into the accelerating tube per month.

It is known that penetration of metal into the accelerating tube may reduce the electric strength of the vacuum gaps; however, well-defined criteria for estimating this process are still absent. No decrease in the electrostatic strength of the tubes was observed over two years of various experiments at the tandem accelerator in the operating mode when a 250-kV voltage was applied to

the high-voltage terminal and the operating conditions of the magnesium vapor target were close to the rated values. It should be noted that the ion beam used in the experiments passed through an electrostatic filter in the high-voltage terminal, i.e., the operating conditions were sensitive to the stability of the voltage applied to the high-voltage terminal.

## CONCLUSIONS

The results of our experiments demonstrate the possibility of using the magnesium vapor target in accelerator mass spectrometers. The target parameters needed for stripping a carbon ion beam have been obtained. The target does not deteriorate the vacuum beyond its housing, which favors the decrease in the number of background ions in measurements of low isotope concentrations at low ion energies.

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