ISBN: 978-3-95450-226-4 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2020-MOZZO01

PRODUCTION OF ^{48}Ca AND ^{48}Ti ION BEAMS AT THE DC-280 CYCLOTRON

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Abstract

The heaviest known elements (up to ^{118}Og) were synthesized at the U-400 cyclotron (FLNR JINR, Dubna) by using a beam of ^{48}Ca ions.

During the tests of the DC-280 cyclotron an intense beams of ^{48}Ca ions were produced.

For synthesis of the elements 119 and heavier, intense and stable beams of medium-mass elements are-required, such as ^{50}Ti and ^{54}Cr. Before starting the main experiments, we test the production of ^{48}Ti ion beam, which is less expensive than ^{50}Ti.

The article describes the method, technique, and experimental results on the production of ^{48}Ca and ^{48}Ti ion beam at the DC-280 cyclotron from the DECRIS-PM ion source.

INTRODUCTION

In last 20 years, at FLNR JINR the super-heavy elements up to 118 have been synthesized using the ^{48}Ca at the U-400 cyclotron.

For further progress in the synthesis of SHE the first in the world Factory of superheavy elements (SHE Factory) was created at the FLNR JINR in 2019 [1]. The main goals of the SHE Factory are experiments at the extremely low cross sections, such as synthesis of new SHE, new isotopes of SHE and study of decay properties of SHE. In addition, experiments requiring high statistics will be conducted, such as nuclear spectroscopy and the study of the chemical properties of SHE.

The factory includes the high-current DC-280 cyclotron and gas-filled separator DGFRS-2. The main parameters of the cyclotron are shown in the Table 1.

Table 1: The Main Parameters of DC-280

Ion sources	DECRIS-PM - 14 GHz
Injection energy	Up to 80 keV/Z
A/Z range	4÷7.5
Energy	4÷8 MeV/n
Magnetic field level	0.6÷1.3 T
K factor	280
Magnet weight	1000 t
Magnet power	300 kW
Dee voltage	2x130 kV
RF power consumption	2x30 kW
Flat-top dee voltage	2x14 kV
Deflector voltage	Up to 90 kV

The cyclotron is equipped with the all-permanent magnet ion source DECRIS-PM [2] (Fig. 1).

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To obtain the requested injection energy, the source is placed at a high-voltage platform. The requests for the ion source are the production of ions with low and medium masses (from He to Kr) such as ^{48}Ca and ^{50}Ti.

The first experiments at the SHE factory will be performed using ^{48}Ca+^{242,244}Pu and the ^{48}Ca+^{243}Am reactions. After completion of these experiments, it is planned to start the synthesis of new superheavy elements in reactions of ^{50}Ti and ^{54}Cr ions with ^{248}Cm, ^{249}Bk and $^{249\text{-}251}$Cf isotopes.

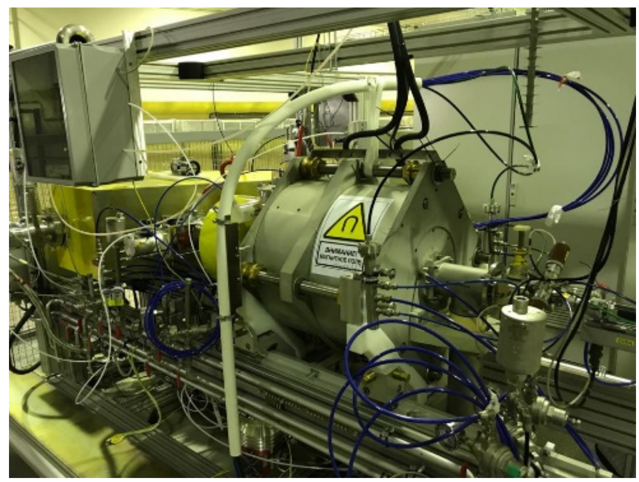

Figure 1: The DECRIS-PM on the high-voltage platform of the DC-280 cyclotron.

THE SOURCE DESIGN

Several different ion sources with permanent magnets are in operation, such as LAPECR2 [3], NANOGAN [4], BIE [5], and others. The sources of this type have the following advantages:

- Low power consumption.
- Low pressure in the water-cooling system.
- Easy tuning.

Disadvantages of these sources are the fixed and relatively small magnetic fields. Despite these disadvantages, the systems typically have a long service life-time.

The magnetic structure of DECRIS-PM consists of hexapole with 24-segments and five 36-segmented axial magnetic rings. The magnetic structure and axial magnetic field are shown in Fig. 2. In the middle part of the source the additional coil is installed for correction of B_{min} value in the range of ±0.075 T, with the maximum current in the coil of 300 A.

The source was tested on a test-bench before installing to the DC-280. The results for metal ions are shown in Table 2 [6].

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Table 2: Results of the DECRIS-PM Tests

Q	5^+	7^+	8^+	9^+	10^+	11^+	12^+
^{24}Mg	450	140	40	15			
^{40}Ca				220		158	58
^{50}Ti				90	72	60	23
^{56}Fe				85	80	55	

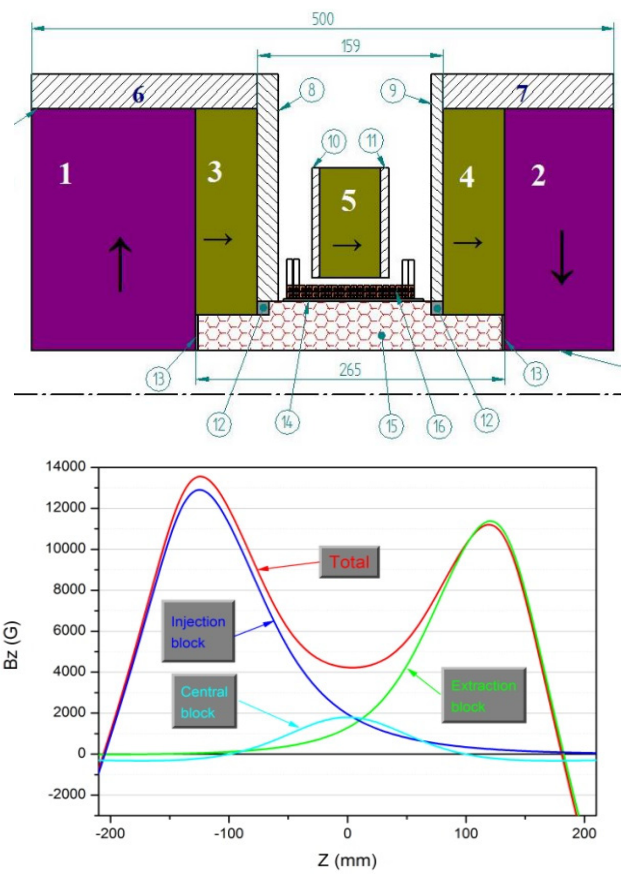

Figure 2: (Top) Magnetic structure of DECRIS-PM: 1÷5 – PM rings; 6, 7 – soft iron rings; 8÷11 – soft iron plates, 12÷14 – auxiliary elements, 15 – hexapole, 16 – coil. (Bottom) Axial magnetic field.

PRODUCTION OF ^{48}Ca BEAM

Production of Ca ions is performed by injecting the calcium vapors into the source chamber from the electrically heated micro-oven installed at the injection side of the source and shifted from the center to the radius of 23-mm.

The oven has a length of 50 mm and the outer diameter of 6 mm. The body of the oven is made of stainless steel; the crucible is made of tantalum. Working diagram for the oven is shown in the Fig.3. The red quadrangle shows the temperature range for the required vapor pressure; the average vapor pressure for calcium in this area is 2.3×10^{-3} Torr.

The crucible is filled with Ca at the stand-alone installation by using the calcium oxide reduction with aluminum in vacuum:

$$3CaO+2Al \rightarrow 3^{48}Ca+Al_2O_3 \quad (1)$$

The required temperature for the reaction is around 1300 °C. In the process of reduction, pure calcium is condensed inside the crucible. The evaporation system is shown in Fig. 4.

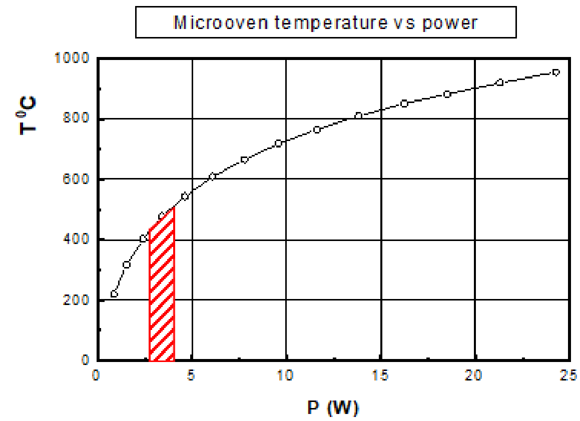

Figure 3: Working diagram of the oven.

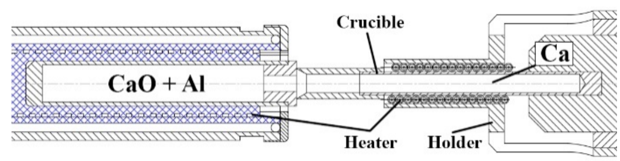

Figure 4: Calcium evaporation system.

The inner volume of the crucible (Fig. 5) is 88 mm^3 that corresponds to 130 mg of calcium. However, the irregular deposition during reduction from the initial volume into the crucible gives a smaller volume of the substance. The crucible is stored in a vacuum container to avoid re-oxidation.

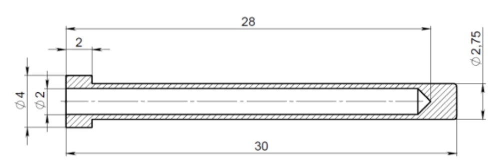

Figure 5: Crucible.

A significant part of the metal vapors evaporated from the oven condenses on the walls of the source chamber and only a small part leaves the source as an ion beam [6]. To prevent deposition of atoms on the water-cooled walls of the chamber, we use a hot tantalum screen. It is placed inside the source with a minimum contact with the surface of the chamber, which reduces heat transfer in the system. During the source operation, the screen is heated by the plasma electrons and microwaves, which contributes to the additional evaporation of the atoms from the surface. As the result, the higher is the injected microwave power, the higher is the temperature of the screen. The injected microwave power of 500 W provides the screen temperature of 550 °C, which is quite enough for the evaporation of calcium from the screen surface [7].

As a support gas, light gases such oxygen and helium are used. The best result for required charge state (Ca^{10+}) is achieved with helium (Fig. 6).

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The total operational time with injection of the calcium beam is currently ~1600 hours; the average consumption for the entire working time is 0.7 mg/h at the average intensity of 8 pμA for Ca^{10+}. The average efficiency of the total Ca ion extraction is 16%, for the Ca^{10+}, this value is 5%, excluding regeneration. The dependence of consumption on the ion beam current of Ca^{10+} is almost linear.

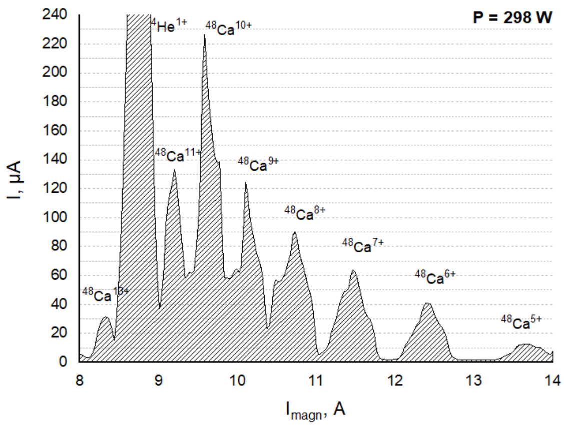

Figure 6: The ^{48}Ca ion spectrum, optimized for Ca^{10+}.

PRODUCTION OF ^{48}Ti BEAM

Operational temperatures of our micro-oven do not allow to use the evaporation technique to produce ^{48}Ti ion beams. Thus, to obtain a stable and high-intensity titanium beam we use the MIVOC method. This method is based on use of organometallic compounds that have a relatively high vapor pressure (10^{-3} Torr) at the room temperature.[8] The vapor pressure is sufficient to operate the source providing the high conductivity of the vapor supply channels. We tried to work with different systems of the gas feeding. The best results were achieved with the gas-regulating valve EVR 116 [9]; it has a smooth adjustment of the gas supply and sufficient gas conductivity, which eliminates clogging of the valve openings by the deposited compound.

The working substance is placed in a glass container (Fig. 7) and after pre-pumping, the glass flask breaks inside the metal casing, which prevents air from entering. The vapor pressure of the substance at the room temperature is sufficient to produce an ion beam without a support gas.

Figure 7: Container with $(CH_3)_5C_5Ti(CH_3)_3$.

The source is equipped with a half-millimeter thick stainless-steel liner to facilitate cleaning of the chamber from carbon contamination. It is a necessary because the change of operating modes should be done in a short period of time. The recently measured charge state distribution of the extracted ion currents for titanium ions is shown in Fig.8. The working time with the titanium beam currently corresponds to ~240 hours on a DC-280 cyclotron. The average efficiency of ion source for ^{48}Ti is 20 %, for the Ti^{7+} this value is 5%.

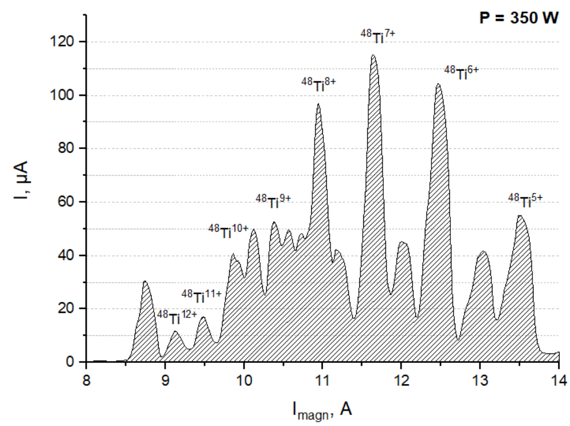

Figure 8: The ^{48}Ti ion spectrum, optimized for Ti^{7+}.

CONCLUSION

During the work was obtained ^{48}Ca and ^{48}Ti. Calcium beam was accelerated, the average efficiency from the ion source to output from the cyclotron is 50%. The average consumption for the Calcium-48 is 0.7 mg/h, for Titanium-48 is 0.55-0.65 mg/h.

ACKNOWLEDGMENT

This work was supported by the Russian Foundation for Basic Research under grant № 20-52-53026/20.

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