PRODUCTION AND ACCELERATION OF TITANIUM-50 ION BEAM AT THE U-400 CYCLOTRON*

S. Bogomolov, A. Bondarchenko, I. Kalagin, K. Kuzmenkov, A. Lebedev, V. Lebedev, V. Loginov, R. Vaganov, JINR, Dubna, Moscow Region, Russia
Z. Asfari, B.JP. Gall, H. Faure, M. Filliger, IPHC, Strasbourg Cedex 2, France

Abstract

The production of Ti-50 ion beam with ECR ion source using MIVOC method is described. The experiments were performed at the test bench with the natural and enriched compounds of titanium $(CH_3)_5C_5Ti(CH_3)_3$. The compounds were synthesized in collaboration with IPHC (Strasbourg) group. In the experiments at the test bench the beam currents of Ti^{5+} - 80 μA and Ti^{11+} - 70 μA were achieved at different settings of the source. After successful tests two 3 weeks runs with Ti-50 beam were performed at the U-400 cyclotron for the experiments on spectroscopy of super heavy elements. The intensity of the injected beam of $^{50}Ti^{5+}$ was about of 50÷60 μA, during experiment the source have shown stable operation. The compound consumption rate was determined to be about of 2.4 mg/h, corresponding to ^{50}Ti consumption of 0.52 mg/h.

INTRODUCTION

In recent years, the reactions ^{48}Ca with ^{238}U, $^{242,244}Pu$, ^{243}Am, ^{245}Cm and ^{249}Cf were used to synthesize new super heavy elements with Z = 114-116 and 118. In the frame of these experiments a technique for producing of metallic ^{48}Ca was developed, optimization of operation mode of ECR ion source was performed in such a way that the necessary intensity of $^{48}Ca^{5+}$ ions was achieved with maximum efficiency ionization [1]. The methods of collection and recovery of expensive isotope also were developed. The complex of these studies made it possible to conduct long-term experiments on the synthesis of super heavy elements with high efficiency using of the working substance.

The most heavy target, with which it is possible to carry out experiments on the synthesis of super heavy elements in heavy-ion reactions is ^{249}Cf, so further progress in the area of the elements with Z > 118 requires the production of intense beams of accelerated neutron-enriched isotopes such as ^{50}Ti, ^{58}Fe, ^{64}Ni and others. The use of each new isotope for production of the accelerated beam requires investigations directed on optimization of the ECR source operation mode and development of technique for material feed into the source.

Several methods for production of ions of solids from ECR sources have been developed. Solid material can be evaporated by resistor or inductive oven, which is inserted into source chamber [2,3].

Refractory metals can be sputtered by plasma ions [4] or inserted into the plasma and heated by energetic plasma electrons ("insertion technique") [5,6].

The other possibility for production of ions of solids is the feeding of the plasma with an organometallic compound through the Metal Ions from VOlatile Compounds (MIVOC) method [7].

PRODUCTION OF TITANIUM ION BEAM

The experiments on production of Ti ion beams were carried out at many laboratories with the use of different methods.

The production of Ti ion beams by evaporation from the resistor oven was studied at GSI [8]. The evaporation of pure titanium requires the temperature between 1750 °C and 1800 °C. During the experiments with HTO more than 50 eμA of $^{50}Ti^{8+}$ were produced with high level of beam stability. The oven life time of 6 days was obtained.

The experiments on production of Ti ion beams by evaporation from the induction oven were carried out at ANL [9]. The beam of $^{50}Ti^{12+}$ with the intensity of 5.5 eμA was produced during seven days.

The MIVOC method was first adopted for production of Ti ion beam by JYFL group [10]. Commercially available $(CH_3)_5C_5Ti(CH_3)_3$ compound was used as a working substance. In the case of $^{48}Ti^{11+}$ ion beam the intensity of 45 eμA was produced.

The consumption of the compound was measured to be 47 mg giving the value of 0.22 mg/h for the consumption of titanium. The ion beam was very stable during the period of 282 h. So, from the point of view beam intensity, stability, reliability and material consumption the MIVOC method seems very promising for providing ^{50}Ti ion beam for long term (several months of non-stop operation) experiments on synthesis of super heavy elements.

The compound is sensitive to air, moisture, temperature and light that needs cautious handling when loading the material for use. The synthesis of this compound is rather complicated especially with the use of enriched titanium which is available in a small, about 1 g, quantity.

Test Experiments

First time the ^{50}Ti ion beam was accelerated at the U-400 cyclotron in 2005. The task was to provide about of 30 enA of ^{50}Ti beam at the target for experiments on the fission physics. Due to the moderate requirements for the intensity it was decided to use $TiCl_4$ which has a vapor pressure of about 10 torr at room temperature that is sufficient for feeding of the ECR source with working substance. The natural $TiCl_4$ (5.2 % of ^{50}Ti) was used. The glass ampule with $TiCl_4$ was connected to the standard

*Work supported by Russian Foundation for Basic Research under grant number 13-02-12011

ISBN 978-3-95450-158-8

piezoelectric leak valve, which is used when the source is operating with gases. The intensity of ^{50}Ti ion beam, extracted from the cyclotron constitutes about 200 enA, the source was running stable during two weeks.

But the use of $TiCl_4$ do not provide the intensity required for the experiments on the synthesis of super heavy elements.

Taking into account the problems with synthesis and handling of $(CH_3)_5C_5Ti(CH_3)_3$ we decided to try to find the other compounds, suitable for MIVOC method. The titanium isopropoxide ($Ti\{OCH(CH_3)_2\}_4$) and cyclopentadienyl cycloheptatrienyl titanium ($C_5H_5TiC_7H_7$) were tested, but no noticeable titanium current were observed, just a few microamperes of Ti^{5+}. The ($C_5H_5TiC_7H_7$) compound was later used at IMP [11] with LAPECR2 source for production of titanium ions by oven method. During the test, 24 eμA of Ti^{11+} has been achieved with 250 W 14.5 GHz microwave power.

After that the experiments on production of titanium beam with oven method at the DECRIS-2 [12] source were performed. The titanium tetrafluoride (TiF_4) was used as working substance. TiF_4 is colorless crystals with melting point of 426° C, and the temperature about of 50÷80° C is required to provide the vapor pressure sufficient for the source operation. In this temperature range it is difficult to control the oven temperature due to the additional heating of the oven by u.h.f. and plasma [13]. To decrease the material flux into the source chamber the oven with a thin long channel, 15 mm in length and 1 mm in diameter, was used. The oven was inserted into the source axially and its position was adjusted remotely. More or less stable mode of the source operation was possible to achieve at the intensity level of $^{48}Ti^{6+}$ about of 10÷20 eμA, with the increase of the material feed the discharge became unstable.

The next step was the production of titanium ions by insertion method. The experiments were also performed with the DECRIS-2 ion source. The titanium rod with diameter of 3 mm was axially inserted into the source chamber through the bias tube. The position of the rod can be adjusted remotely. Helium was used as a support gas. The evaporation rate is dependent on microwave power, helium pressure and position of the rod.

Figure 1 shows typical spectrum of titanium ions produced at the microwave power of about 140 W with the source tuning on Ti^{5+}. The intensity is quite suitable, but the long term stability of the beam was not achieved. Without source tuning during one hour the beam intensity was varied in the range of 30% and then discharge became uncontrollable or the beam intensity droped to zero.

Our further activity in the production of titanium ion beam was related with MIVOC method and (trimethyl)pentamethyl-cyclopentadienyltitanium compound.

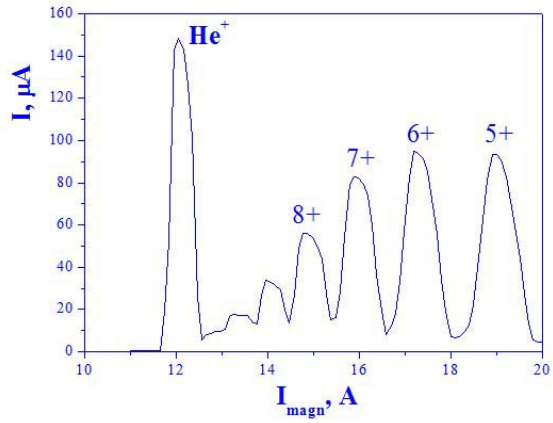

Figure 1: Ti ion spectrum produced by rod insertion from the DECRIS-2 ion source.

The commercially available compound produced by Sigma-Aldrich company [14] was tested with DECRIS-4 [15] and DECRIS-2 sources. The sources were optimized for production of Ti^{5+}, similar results were produced with both sources and figure 2 shows the spectrum of Ti ions, produced from DECRIS-4 source at the microwave power of 34 W.

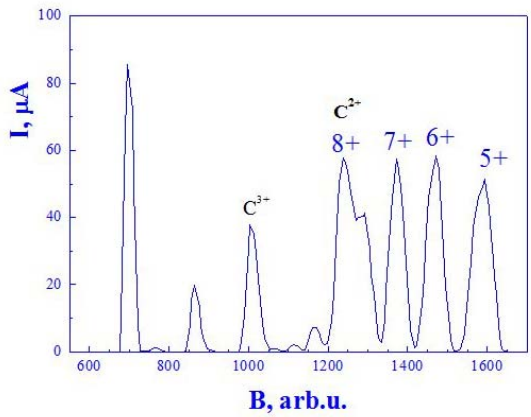

Figure 2: Ti ion spectrum produced by MIVOC method from the DECRIS-4 ion source.

Next step was the test of compound, produced by DALCHEM company [16]. The main feature is that the compound is provided in a welded glass ampules, that makes the handling of the compound much more easier - it is not necessary to use the argon filled glove box, the ampule can be destroyed under the vacuum in a specially designed MIVOC chamber. The tests were performed with the modified ECR4M [17] source at the test bench. Figure 3 shows the spectrum of titanium ions with the source tuning on Ti^{5+}. In all experiments no support gas and no control of MIVOC chamber temperature were used. The operation of the sources was stable and reproducible.

ISBN 978-3-95450-158-8

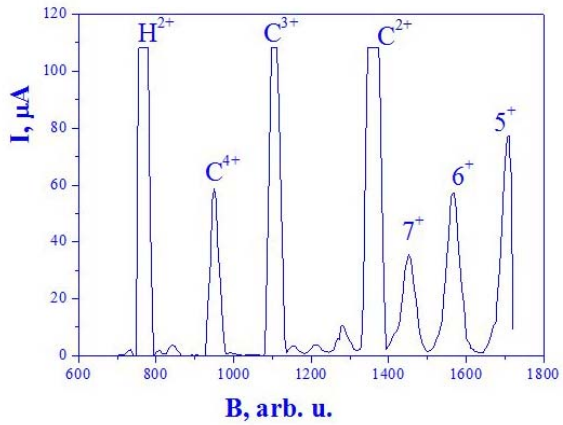

Figure 3: Ti ion spectrum, produced by MIVOC method from the ECR4M source at microwave power of 20 W.

Production of Titanium-50 Ion Beams

The development of titanium-50 beam production was performed in the frame of collaboration between IPHC (Strasbourg, France) and JINR.

After several years of chemistry developments at IPHC the $C_5(CH_3)_5Ti(CH_3)_3$ compound was synthesized using 92.57 % enriched ^{50}Ti. A two step chemistry was done starting from $TiCl_4$ going to $C_5(CH_3)_5Ti(CH_3)_3$ through an intermediate $C_5(CH_3)_5TiCl_3$ organic compound with quite high efficiency.

First MIVOC isotopicaly enriched beam was developed and tested in 2011 at the University of Jyväskylä. After optimization, up to 19.4 eμA of titanium-50 in charge state 11^+ could be extracted from the JYFL 14 GHz ECRIS2 ion source [18,19].

The compound from natural titanium, synthesized at IPHC, was also tested at GANIL [20]. An intensity of 20 eμA for $^{48}Ti^{10+}$ was maintained for 4 days, with regulation the temperature of the MIVOC chamber. The consumption of 1.5 mg/h for the MIVOC compound has been deduced, i.e. 0.23 mg/h for ^{48}Ti.

During 2012÷2013 years several samples of $(CH_3)_5C_5Ti(CH_3)_3$ compound synthesized at IPHC were tested at the FLNR test bench. The main problem was the long time transportation of the samples from IPHC to JINR that leads to destroying of the compound, and very pure currents of titanium were produced. After that it was decided to perform the final step of synthesis at FLNR chemistry laboratory.

First natural material synthesized at FLNR by IPHC group was tested in October 2013 with ECR4M ion source at test bench. After optimization, very stable ^{48}Ti beams were produced with intensities up to 70 eμA for the 11^+ charge state (6.2 pμA) and 75 eμA for the 5^+ charge state (15.0 pμA). Figure 4 shows the charge state distribution of ^{48}Ti ion beam with source settings for optimum production of $^{48}Ti^{11+}$.

Following these very promising results, a 92.57 % enriched compound was synthesized and tested with ECR4M test bench. Under similar conditions up to 80 eμA of $^{50}Ti^{5+}$ beam was extracted, corresponding to 16.0 pμA. Figure 5 shows the charge state distribution of ^{50}Ti ion beam with source settings for optimum production of $^{50}Ti^{5+}$.

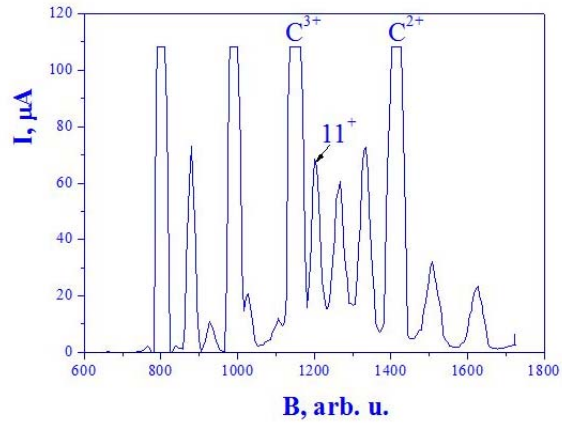

Figure 4 : Ti ion spectrum, produced by MIVOC method from the ECR4M source at microwave power of 300 W.

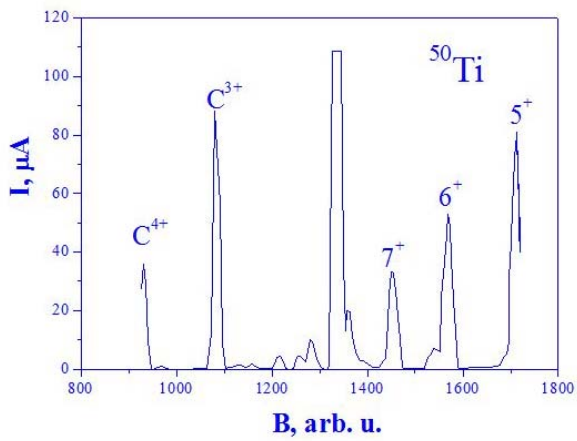

Figure 5 : ^{50}Ti ion spectrum, produced by MIVOC method from the ECR4M source at microwave power of 30 W.

This beam was then produced with the DECRIS-2m [21] source and accelerated at the U400 cyclotron. A very stable and intense 55 eμA beam was injected at 5^+ charge state (11.0 pμA) in the cyclotron. Chopped after extraction, transport to the targed a 0,490 pμA was used on target for several weeks in October-November 2013. This beam was very stable with wery low, about of 0.6 mge/h titanium consumption.

Next run with titanium-50 ion beam was performed at the U-400 cyclotron during April-May 2014. By then the DECRIS-2m source at the U-400 cyclotron was replaced by ECR4M source. During three weeks the intensity of $^{50}Ti^{5+}$ beam was maintained at the level of 55÷62 eμA. The material consumption was similar to the previous run with DECRIS-2m ion source.

ISBN 978-3-95450-158-8

CONCLUSION

During last years significant progress was achieved in production of intanse multiply charged ion beams of titanium from ECR ion sources. Table 1 summarise the results of titanium ion beam production at different Laboratories by MIVOC (JYFL, GANIL, FLNR) and oven (GSI, ANL, IMP) methods.

Table 1: Intensity (eμA) of Titanium Ion Beams Produced at Different Laboratories by MIVOC and Oven Methods

	JYFL	GANIL	FLNR	GSI	ANL	IMP
$^{48}Ti^{5+}$			79			
$^{48}Ti^{10+}$		20				
$^{48}Ti^{11+}$	45		68			24
$^{50}Ti^{5+}$			82			
$^{50}Ti^{8+}$				50		
$^{50}Ti^{11+}$	20					
$^{50}Ti^{12+}$					5.5	

The MIVOC method was successfully used for production and acceleration of titanium-50 ion beam at the U-400 cyclotron. This method provides intense beams with long term stability, and is quite promising for experiments on synthesis of super heavy elements.

ACKNOWLEDGMENT

This work was supported by Russian Foundation for Basic Research under Grant number 13-02-12011.

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ISBN 978-3-95450-158-8