A CRYOGENIC GAS-FILLED ION STOPPING CELL AS AN INSTRUMENT FOR EXPERIMENTAL STUDY OF HEAVIEST NUCLEI

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Abstract – Mass measurement allows to determine the full binding energy of the nucleus – the integral characteristic of all atomic and nuclear forces which is the key for solving the fundamental physics problems, which includes nuclear physics, astrophysics, physics of fundamental interactions and symmetries, neutrino physics. High precision mass spectrometry could solve the problems of proton and neutron shells location in the nucleus (precision $\Delta M/M$~10^{-6}), the study the nuclei deformation phenomena, searching of so-called "halo-nuclei", the correct description of the heaviest elements formation during astrophysical r- and rp-processes of fast neutron and proton captures respectively (precision $\Delta M/M$~10^{-7}).

For this reason, a new facility for the high precision mass-spectrometry of heaviest nuclei is being built at the Flerov Laboratory of Nuclear Reactions, JINR, Dubna. It will include new target block, gas-filled separator for the reaction products, cryogenic gas-filled ion stopping cell ("Cryocell"), radio-frequency quadrupole transport system and the multi-reflection time-of-flight mass-spectrometer (MR-TOF-MS). This setup could provide mass measurements with the precision of about $\Delta M/M$~10^{-7}. "Cryocell" is one of the most crucial component of it. This is a powerful instrument for the fundamental research due to its high conversion coefficient of the fluxes of reaction products with heavy ions at energies 5-10 MeV/nucleon into low energy secondary beam and low extraction time. It could open the possibility to perform mass analysis of short-lived isotopes with the lifetime of 100 ms and more.

INTRODUCTION

One of the most important fundamental problems in nowadays nuclear physics, chemistry and astrophysics is the synthesis of superheavy elements and studying its properties. The main motive stimulating works in this field is the searching of so-called "Island of stability" [1], predicted by the shell model. According to this model, there should be an increased stability of nuclear matter near closed proton shells with the numbers 114 and neutron number 184. The study of nuclei properties near the N=126, 162, 184 neutron shell closures are of interest due to astrophysical investigations and understanding the nature of the nucleosynthesis processes. In the

FLNR, JINR, during last decades new elements with the numbers 113 (Nh), 114 (Fl), 115 (Mc), 116 (Lv), 117 (Ts) and 118 (Og) [2] were synthesized. Relatively high lifetimes of new nuclides open up the possibility of carrying out their direct mass-spectrometric identification using separation of complete fusion reaction products from gas volume – the ISOL [3] method. A creation of methodic allowing to identify and to study nuclei with the lifetime ≥30 ms with the separation efficiency of fusion reaction products ~50% opens the variety of investigation such nuclear characteristics as level structure, studying of rare types of decays (branching, transition to excited energy levels, isomeric states, etc.), low cross-section reaction channels, reactions of multi-nucleon transfer to synthesize the neutron reach isotopes of the heaviest elements.

The using of cryogenic gas cell as a method of separation of superheavy element nuclei limits experimental possibilities only in terms of separation time, which is ~30 ms and more. There are 31 from 45 known isotopes with $Z \geq 110$ which lifetime exceeds 30 ms available for analysis.

For such studies, a new facility for precise mass measurements is being developed in FLNR, JINR. A cryogenic gas-filled ion stopping cell is a most crucial unit of this facility on parameters of which depend an overall efficiency.

A CRYOGENIC GAS-FILLED ION STOPPING CELL

Gas catchers became widely spread in experimental nuclear physics. Powerful devices for the transforming high-energy newborn reaction products into the low energy beam suitable for analysis are the key components of all setup based on ISOL method. In comparison to solid ISOL method, it has several advantages due to its inert buffer gas filament and scrupulously constructed electrodes. First, it is not influenced from any physical and chemical environment properties. Secondly, there is no need in additional ionization. Thirdly, significantly shorter separation and extraction time in comparison to solid or liquid states ion catchers (~30-40 ms). Also, significantly higher conversion coefficient of the fluxes of reaction products with heavy ions at energies 5-10 MeV/nucleon into low energy secondary beam (≥ 70%). In addition, significantly lower temperature and energy derivation in comparison to classic method of solid ISOL and beam emittance (3π·mm·mrad).

It was based on an analogue, which works in GSI, Darmstadt [4], but has several improvements and upgrades.

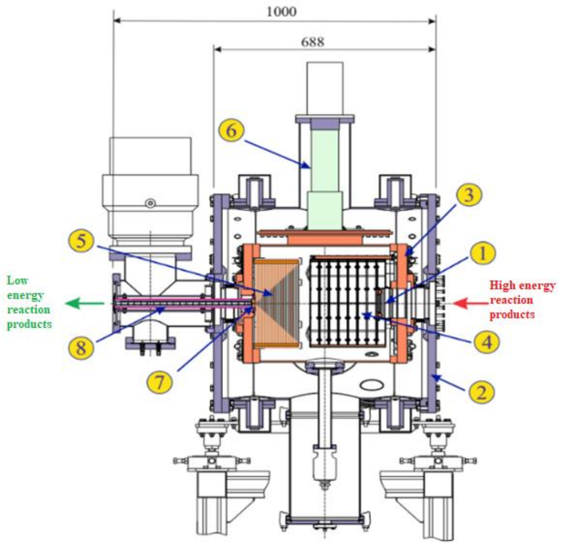

Figure 1. An axial cut of cryogenic gas-filled stopping cell.

The concept is very simple. An outer chamber (2) serves as a heat insulator for the inner "cold" chamber (3), which is a working one. Cryorefrigerator (6) for cooling down the inner vessel to the temperatures below 40 K. Evaporation residue of fusion reactions passing an entrance window (1) containing nickel or titanium foil of the thickness referring to ions to lose about 90% of its initial energy, stops inside the inner vessel filled with the buffer gas – helium of the highest purity (with impurity level 100 ppb – 10^{-7} at/at) – and serves as a stopper. The reaction products afterwards are being picked up with the gas flow (~1 Torr·l/s) and leading to the exit nozzle with the diameter 0.6 mm (7). Another force, which leads to the exit, is electrostatic uniform gradient, generated by multielectrode DC cage (4). An alternative RF field, generated by RF funnel (5), do not let the ions hit the walls and electrodes, providing a repulsive force. A superposition of all forces makes products move to the exit freely to the transport system, RF quadrupole (8), where the neutral gas is being pumped with the help of turbomolecular pump, but the ions lead to the analyzation block.

TESTING OF THE CRYOCELL SYSTEMS

Cryogenic tests of the cell were performed with the help of thermoresistors. It was mounted on copper plating of the inner chamber, flexible heat conductors, and on both flanges. The entire chamber was covered with a copper layer with the thickness of 2 mm. This minimized the temperature gradient between different parts. Every metal part of the outer chamber was wrapped with vacuum thermal insulation to minimize the heat load gained from radiant heat. The result could be seen on a Figure 2.

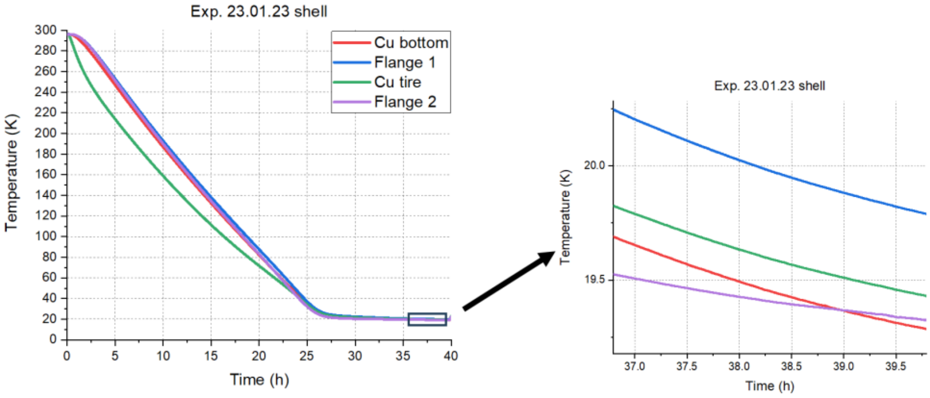

Figure 2. The latest cooling down test.

The minimum temperature reached 20 K within 30±5 hours, which means about 50 Watts of heat load and is very enough. Buffer gas also being cooled down preliminary before inlet and after the chamber filling temperature rose not more than 2-3 K.

The mass analysis of residual gas was performed for room and cryogenic temperature using special quadrupole mass-analyzer PrismaPro QMG 250 from Pfeiffer Vacuum. This test is one of the most crucial tests, showing the abundance of gases inside the working chamber. Due to the method of gas-state ISOL is very vulnerable to ultra-pure hygiene, it is obligatory to know which components were frozen away and what percentage of undesirable admixtures are inside the working vessel.

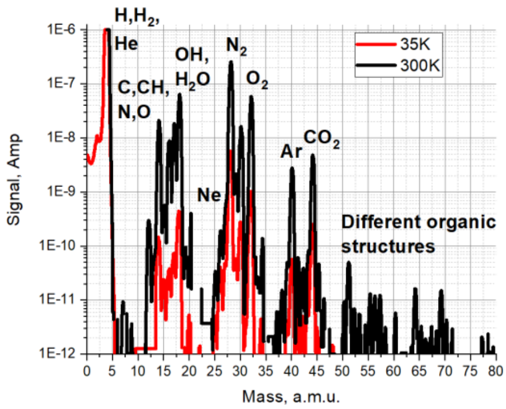

Figure 3. Mass scan of air admixtures of room temperature (black) and cryogenic (red).

The need of the cooling down process is obvious. This showed that all the main gases admixtures of air were freezed away. It was dropped down on more than 2 orders – legit for the most uncomfortable gases for vacuum and ions – nitrogen, oxygen, carbon dioxide, argon and water. All of them have boiling and melting points higher than reached temperature. Below this temperature, there is only hydrogen, neon and helium. Helium already is being used as the buffer gas, and here we see overflow in signal. The abundance of hydrogen and neon is so small, so it is not taken in account. Organic structures is being freezed away totally.

The tests of resonant circuits for RF based modules – the multielectrode RF funnel and transport quadrupole system were carried A transformer coils were made to rock the contour. It should fit the required parameters: about 1 MHz in resonance for both, 180 Volts at secondary coil, minimum power consumption and the matching to primary coil income impedance 50 Ohm. Good *Q*-factor is also important. As a result, a resonance was found at 996 kHz. Power consumption was less than half Watt, which lead heating a cold flange not more than 5 degrees.

In the nearest plan is to perform a complex test to determine an overall efficiency by method of inner source. The method is well known and standard one for these kinds of tests. A Th emanation is located at the entrance of cell and voltage is applied to it. Feedback nuclei is flown away, stopping in the cell, and moving to the exit nozzle by the electrostatical, RF forces and with gas flow. Passing the transport system, it sits on a metallized thin foil, and in the latter, there is a detector, which shows the alpha spectra of daughter nuclei in all decay chain. By this method, we could see and test all the systems of gas catcher and transport system and determine the total efficiency and extraction time for this ISOL unit.

CONCLUSION

In FLNR, JINR, a base for a new setup of precise mass measurements is being built. A facility might locate at one of the physical cabins of a new accelerator complex U-400R. The most crucial unit – a cryogenic gas-filled ion stopping cell was designed, manufactured and constructed. The pumping and cryogenic cooling tests already performed; these systems are fully functional. The temperature of the inner chamber reached 20 K within 30±5 hours and the differences between different parts were less than 1 K. This means that thermal load by radiation does not exceed 50 W from all the walls of the outer chamber. The tests of quantitative and qualitative compounds with the help of the QMG250 quadrupole mass analyzer were also performed and had shown the exclusion of all the gases inside the air mixture. The tests of the RF components were carried out with success. In the nearest future a complex test of the Cryocell unit with the emanation source to determine the overall efficiency and extraction time will be performed.

REFERENCES

1. *U. Mosel, W. Greiner.* On the Stability of Superheavy Nuclei against Fission // Z. Physik. 1969. Vol. 222. Pp. 261-282.
2. *Oganessian Yu.Ts., Utyonkov V.K., Lobanov Yu.V. et al.* Synthesis of the isotopes of elements 118 and 116 in the ^{249}Cf and ^{245}Cm+^{48}Ca fusion reactions // Phys. Rev. C. 2006. V. 74.044602.
3. *Kofoed-Hansen O., Nielsen K.O.* Short-lived krypton isotopes and their daughter substances // Phys. Rev. 1951. V. 82. P. 96
4. *Droese C., Eliseev S., Blaum K., Block M. et al.* The cryogenic gas stopping cell of SHIPTRAP // Nuclear Instruments and Methods in Physics Research B 338 (2014) 126–138.