Possibilities of research for on-line mass separator with heavy ion reactions

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Abstract. Mass Analyser of Superheavy Atoms is ISOL – type setup created for direct mass measurement heavy ions. Hot catcher and ECR ion source combination allows effective formation of secondary beams of volatile elements. Powerful magnetic analysing system offers possibility to achieve mass resolution $M/\Delta M > 1000$ in the focal plane silicon strip detector. The efficiency, time characteristics and detection system properties are described. Two applications of setup in different fields of research are presented together with methodology of experiments and data analysis.

1. Introduction
To study the properties of nuclei at the limits of nucleon stability the most accurate separation of isotopes of exotic nuclei is needed. For this purpose, mass separators of heavy ions are widely used. One of them is the Mass Analyzer of Superheavy Atoms – MASHA, built in Flerov Laboratory of Nuclear Reactions (FLNR) at the Joint Institute for Nuclear Research (JINR) in Dubna, Russian Federation.

2. Separator characteristics
MASHA is the ISOL-type of setup consisting of target block with hot catcher, electron cyclotron resonance (ECR) ion source, ion – optical system of magnetic separator and focal plane with detectors (figure 1). Primary beam is delivered from U400M cyclotron (up to $\approx 500$ pA $^{48}$Ca). Exotic nuclei can be produced in nuclear reactions on thick or thin targets. Reaction products are thermalized in plate made of special fiber-like graphite heated up to 2000 °C by tantalum heater and transported into 2.45 GHz ECR ion source developed in FLNR\cite{1}. Reaction products are ionized to $1^+$ state and formatted into secondary beam with efficiency 84\% for $^{nat}$Xe (ionization efficiency is proportional to Z). Mass resolution for $^{nat}$Xe is $M/\Delta M = 1300$. For details of magnetic analyser properties see \cite{2}. Main part of focal plane detection system is the silicon multi-strip detector for alpha and fission fragments spectroscopy. Focal plane is divided into 192 strips with another 160 strips placed around in well-shape geometry, as can be seen on figure 2. Thickness of silicon strips is 300 $\mu$m with insensitive surface layer < 50 nm. Specifications can be found in \cite{3}. Secondary beam of 40 keV is unable to pass through dead layer, so there is no information about implantation of incoming ions.
Detector calibration is provided using $^{226}$Ra spectrometric source. Energy resolution is 25 keV for 5.5 MeV alpha particles. Due to thin TiO$_2$ foil covering source and detector dead layer, peak energy correction is needed. Monte Carlo simulation in GEANT 4 showed that alpha particles lose 32 – 68 keV on their way to sensitive volume depending on geometrical conditions. Experimentally measured energies of alpha particles in model experiments agreed with tabular values with uncertainty ± 5 keV. Simulation of geometrical efficiency for decay in focal plane showed that 92 – 95 % of alpha particles are registered in first decay, depending on the implantation point. Alpha decay of daughter nucleus has chance to be registered about 70 %. Signal from each strip has its own independent spectrometric tract. Time necessary for signal processing is < 5 µs depending on pulse height. Secondary beams of stable currents are detected by true copy of focal plane made of copper structure on glass fibre laminate (mainly used for measurement of noble gasses currents).

Time characteristics of particular separation processes were estimated from measurement of calibrated leaks of noble gasses into the ECR ion source and hot catcher chambers, experiments on $^{40}$Ar beam without target and by measuring decays of Hg isotopes created in reaction $^{144}$Sm ($^{40}$Ar, xn)$^{184}$Hg. Total time of separation for isotopes $^{179,181}$Hg was assessed to 1.8 ± 0.3 s (from creation in nuclear reaction to implantation in focal plane detector). Transport efficiency estimated from overall yield of 2n, 3n and 4n channel of this reaction is 7 ± 1.4 %. Procedure of those measurements can be found in [4].

3. Fields of research

Main purpose of MASHA separator is direct mass measurement of isotopes of superheavy elements (SHE) on the principle of ion trajectory bending in magnetic field. Yet known information about masses of SHE were estimated from systematic of alpha decay. MASHA’s aim is to confirm those data by method based on different principles. Isotopes of SHE will be synthetized in fusion-evaporation reactions of $^{48}$Ca projectiles with actinide targets. Decay of all SHE from $Z = 112$ to $Z = 118$ created in this hot fusion method were observed on another setup at the FLNR – Gas Filled Recoil Separator (GFRS) [5]. First proposed is mass measurement of isotope $^{283}$Cn created in reaction $^{238}$U($^{48}$Ca,3n)$^{280}$Cn.
Specific properties of hot catcher – ECR ion source combination allows to form secondary beams of volatile elements. Spectroscopic investigations of neutron shell closures \( N = 126, 152 \) can be performed on neutron-rich isotopes of radon and mercury. Their efficiency has been verified in model experiments [4]. Possibility of multi nucleon transfer reactions of \( ^{48}\text{Ca} \) with thick target \( ^{232}\text{Th} \) target in pyrolytic carbon matrix of catcher leads to production of neutron-rich isotopes of radon with \( A \leq 232 \). Estimated cross section for this reaction was evaluated using method described in [6] to predict the possibility to access the Rn isotopes reaching, even surpassing the presently known most neutron rich Rn isotopes. Isotopes \( ^{227}\text{Rn} - ^{232}\text{Rn} \) have from 3 to 5 \( \beta^- \) decays in chain before accessing the long lived alpha radioactive daughter. A GEANT 4 simulation was carried out to estimate possibility to measure decay of subjected isotopes by silicon detector. Since electrons are less ionizing particles than alphas, a 300 \( \mu \text{m} \) silicon thickness is not enough for complete stopping.

4. Events registration

When the magnetic fields inside separator magnets are set to requested values, secondary beam ions are focused to mass spots in the focal plane. Masses of radioactive nuclei are identified by their alpha decay in corresponding strips. In the experiments where a good statistics can be achieved, exact atomic mass up to \( 10^5 \text{ a.m.u.} \) can be assessed from the mass peak position on the focal plane.

Neutron-rich Rn isotopes emit beta particles with maximum energy up to 5 MeV. Beta particles are less ionizing than alphas, so their track in silicon is longer resulting to incomplete energy deposition of particle in sensitive volume. Simulations in GEANT 4 showed that energy spectrum of beta particles in silicon block of 14 x 14 x 0.3 mm dimensions is strongly deformed, with most probable energy deposition about 120 keV and maximum about 1 MeV (figure 3a). Corresponding track length achieves most probable value about 340 \( \mu \text{m} \) (figure 3b). In lower part of spectrum noise-like background consisting of x-rays occurs. While x-ray part of spectrum takes place in low energies, \( \beta^- \) part of spectrum starts to rise above 60 keV. Since beta decays cannot be identified from energy spectrum, crucial parameter is probability of observing all \( \beta^- \) particles from one decay chain with suitable energies. Isotopes of interest are primary the heaviest with \( A = 229 - 232 \). All of them have at least 4\( \beta^- \) in decay chain before accessing long living alpha emitters. Probabilities are shown in table 1.

| Isotope  | \( ^{227}\text{Rn} \) | \( ^{229}\text{Rn} \) | \( ^{230}\text{Rn} \) | \( ^{231}\text{Rn} \) | \( ^{232}\text{Rn} \) |
|----------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Beta particles in coincidence | 3\( \beta^- \) | 4\( \beta^- \) | 4\( \beta^- \) | 4\( \beta^- \) | 4\( \beta^- \) |
| Event detection probability [%] | 0.654 | 0.187 | 0.149 | 0.223 | 0.2 |

**Figure 3a:** Energy spectra of electrons in silicon – simulation.

**Figure 3b:** Track lengths of electrons in silicon – simulation.
5. Monte Carlo simulations of particle registering processes

Monte Carlo simulations in GEANT 4 were performed on the software suite Geant4 9.6 patch01 on RedHat Scientific Linux 5.8 platform for VMware [7]. Detector construction represents 352 silicon strips with exactly the same dimensions as real detector. Thickness of strips was 300 µm and on the surfaces of all detector planes were added a 50 nm thick plate of silicon representing insensitive layer. During a simulation of particle track, data collection algorithm stores the data from the strip with the biggest energy deposition. All materials used in construction of setup are used from GEANT4 internal database. Low energy electromagnetic physics was simulated employing PENELOPE model (penetration and energy loss of positrons and electrons) including processes of atomic relaxation and de-excitation (XRF, Auger, PIXE). Particles were created using GEANT4 General Particle Source. Energy calibration correction were performed by comparison of $^{226}$Ra atoms decay with zero initial kinetic energy in point source and isotropic point source emitting alpha particles of defined energy, both covered by 100 nm layer of titanium dioxide. Geometrical efficiency was estimated by comparison of beam of 100% alpha decaying self-defined isotope in point source directing into various points on focal plane and also by isotropic point source of alpha particles lying 10 nm under surface of dead layer of well-shaped detector (only efficiency for first decay).

Adapted decay chains radon isotopes were used in simulation of radon isotopes decay instead of GEANT 4 radioactive decay database. Tabular values [8] were used and all isotopes were set to 100% single β emitters. Energy spectrum was acquired from implantation of 40 keV ions in beam of 5 mm radius standard deviation of beam position profile $\sigma_r = 0.5$ mm, pointing to geometrical centre of track detector volume. Information about energy spectra of all single isotopes in decay chains together with all particle track lengths and corresponding energies per track were stored. In the case of $^{231}$Rn only 4 β decays were simulated, while coincidence detection probability for 5 β tracks is $3.5 \times 10^{-4}$ and half-life of $^{231}$Th is 25.5 hours. Searching for only 4 β tracks raised this probability by one order of magnitude. In the simulations with multi-strip detector $10^7$ primary events were created and to understand processes β particles registration the statistics was $10^6$ primary events.

6. Conclusion

Experiments with calibrated noble gas leaks and experiments with $^{40}$Ar beam showed that MASHA separator has 7 ± 1.4 % transport efficiency and 1.8 ± 0.3 s separation time for mercury isotopes. Mass resolution is $M/\Delta M = 1300$ for natural xenon isotopes. MASHA is prepared for mass measurement of $^{283}$Cn synthetized in reaction $^{238}$U($^{48}$Ca,3n)$^{283}$Cn. Monte Carlo simulations in GEANT 4 outlined possibilities for measurement of neutron rich Rn isotopes decay by compact silicon tracking device. Characterization of registration processes inside tracking detector together with probabilities of detecting 4β event and geometrical properties of well-shaped silicon strip focal detector together with its energy calibration correction were evaluated.

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