MASS-SPECTROMETRIC METHOD TO STUDY THE PROPERTIES OF HEAVY NUCLEI*

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There is considered a further development of the mass spectrometer MASHA to adapt the gas catcher technique to the mass spectrometric analysis. The ion-optical parameters of the new installation are calculated. These parameters were derived from the simulation of the compound nucleus fusion reaction $^{48}Ca+^{238}U\rightarrow^{286}112^{*}\rightarrow^{283}112+3n$. The applicability of this technique for production and investigation of both the SHE nuclei and the heavy neutron-rich nuclei created in the multinucleon transfer (MNT) collisions between ^{48}Ca, ^{86}Kr, and ^{136}Xe as projectiles and ^{208}Pb as a target is substantiated.

1. Introduction

The discovery of Super Heavy Elements (SHEs) with atomic numbers Z=113-118 as well as new neutron excess isotopes of the elements with Z=104-112 was one of the outstanding scientific results of the last decade [1]. Their synthesis stimulated works on the development of methods of their identification by means of the technique called Isotope Production On-Line (ISOL). Thereto, in FLNR there was designed and put into commissioning the mass spectrometer MASHA - Mass Analyzer of Super Heavy Atoms [2]. The uniqueness of this mass spectrometer consists in ability to measure "on-line" the masses of synthesized SHE isotopes with simultaneous detection of their alpha decays and the spontaneous fission. Technical details of the mass spectrometer combined with a hot catcher as well as the description of the test experiments aimed at measuring physical parameters of this hot-catcher+mass-spectrometer system were presented elsewhere [3].

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2. Incorporation of the gas catcher technique

2.1. *Gas catcher technique advantages*

For the mass separation the overall extraction efficiency and the delay time, which is the time between the ion production and ion delivery to the detection system, are very crucial parameters. Using the ECR ion source combined with the hot catcher enables to get the delay time of about some seconds. Besides, this assembly allows one to separate only volatile elements, thus, it is greatly sensitive to the chemical properties of the elements.

In this aspect the gas catcher technique widely used in the last years for production of radioactive beams turned out to be more promising [4, 5]. General advantages of the gas catcher technique are:

1. It does not suffer from the dependence on chemical properties of the nuclides whose beams are formed in the catcher.
2. It provides an essentially fast extraction time (τ~10ms).
3. It is possible to reach a high total efficiency ($\geq$ 20%) for nuclear reaction products with simultaneous formation of a low energy beam for further mass-spectrometric analysis.

The estimates made for obtaining transuranium ion beams at bombarding energies of 5–8 AMeV led to the following values of key parameters of the gas catcher:

- Gas cell dimensions – diameter =100 mm, length=210 mm.
- Buffer gas – high purity helium with a contamination level of $\leq$ 1ppb.
- Pressure – 100-200mbar.
- Extraction time $\leq$ 10ms.
- Transverse beam emittance $\leq 1\pi$·mm·mrad.
- Energy spread ~10^{-5}.

2.2. *Primary beam pre-separator*

The gas catcher technique has, nevertheless, essential limitations. The most important one is a relatively high ionization density produced by the primary beam in the gas catcher cell. This requires a separation of the reaction products from the primary beam. To achieve, e.g., an efficiency of about 20% the ion flux density in the catcher should not exceed 10^8 ion pairs/cm^3/s [6]. Hence, the gas catcher technique requires that the total intensity of the primary beam in the gas catcher volume of about one liter must not exceed ~10^5 s^{-1}. Moreover, taking into account a rather large entrance orifice of the gas catcher (its

diameter is usually 8-10cm), a possible pre-separator can have relatively moderate focusing properties. In case of the compound nuclear reactions these conditions could be fulfilled with a conventional gas-free electrostatic system.

2.3. *Evaporation-residue fusion reactions*

The compound nucleus reaction ^{48}Ca(234MeV)+^{238}U→^{286}112* →^{283}112+3n for synthesizing the ^{283}112 nuclide was chosen for simulation. The uranium tetra-fluoride UF_4 target deposited on a 0.75-mg/cm^2 titanium backing foil was taken for simulations. The target thicknesses of 0.2, 0.4, 0.6, and 0.8 mg/cm^2 were proposed. At simulation, the energy straggling and a small angle multiple scattering as well as the neutron evaporation were taking into account. The following phase space parameters were proposed for the cyclotron beam: 1) transverse emittances $\varepsilon_{X(Y)}$ = 10π mm-mrad; 2) kinetic energy spread σ(ΔT/T) = 0.25%; 3) beam spot on target 2r = 1.0cm.

2.4. *Electrostatic pre-separator*

A schematic view and main ion-optical parameters of the elements of the pre-separator are given in Figure 1. The transverse space distributions of ^{283}112 and ^{48}Ca at the entrance orifice of the gas catcher are plotted in Figure 2. Transmissions of the system for ^{283}112 are listed in Tables 1.

Besides rescattering of the primary beam on the walls of the vacuum chamber another interfering process is the elastic scattering of ^{48}Ca from ^{238}U loading the gas catcher working area with lower energy ions.

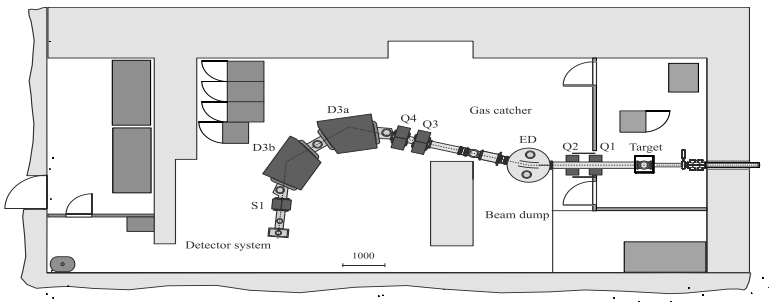

Figure 1. Schematic view of the electrostatic pre-separator and the modified version of the mass spectrometer MASHA: Q1-Q2 – magnetic quadrupoles (L_{eff}=35cm, 2r=20cm, G_{max}=8T/m); ED – cylindrical electrostatic deflector (effective electrode length=47.8cm, bending radius=182.6cm, electrode gap=15cm, U_{max}=±200kV); other elements D3a,D3b(magnetic dipoles), Q3-Q4(magnetic quadrupoles), and S1(magnetic sextupole) are elements of the existing installation.

Fortunately, the contribution of the letter process is quite strongly suppressed due to a small ±100mrad angular acceptance of the separator. The beam rescattering can be eliminated down to an acceptable level with an appropriate collimator system at the entrance to the pre-separator.

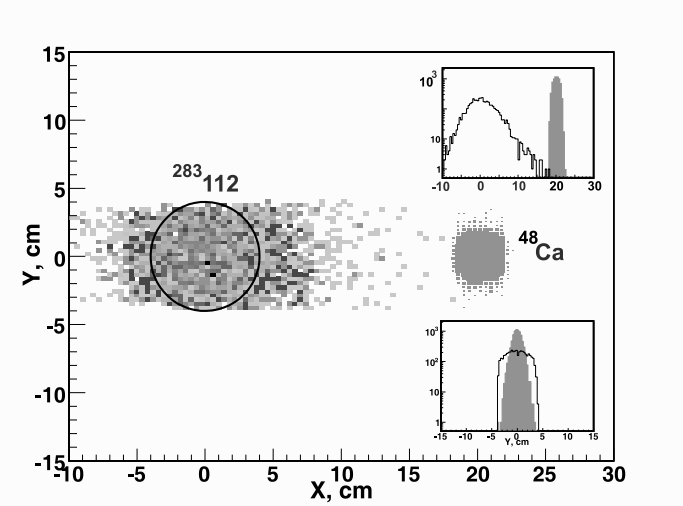

Figure 2. Transverse space distributions of $^{283}112$ and ^{48}Ca at the entrance orifice of the gas catcher for the UF_4 target with a thickness of 0.4 mg/cm^2. The solid line circle is the gas catcher orifice.

Table 1. Transmission of $^{283}112$ from the physics target to the entrance orifice of the gas catcher. The diameter of the gas catcher entrance orifice was chosen to be 8 cm. The working aperture of the quadrupole magnetic lenses was proposed to be 2r = 18.4 cm. The beam size to be acceptable for the electrostatic deflector was taken as $\Delta r \times \Delta y = 9 \times 10$ cm^2.

UF_4 target thickness, mg/cm^2	Eρ, MV	Electric field, kV/cm	Bρ, T-m	Transmission, %
	$^{283}112(^{48}Ca)$		$^{283}112(^{48}Ca)$	
0.2	4.189(26.924)	22.95	0.8532(0.9046)	52
0.4	4.070(26.727)	22.30	0.8512(0.9018)	42
0.6	3.954(26.525)	22.66	0.8493(0.8986)	37
0.8	3.839(26.339)	21.04	0.8477(0.8960)	32

2.5. *Modification of the mass spectrometer MASHA*

To match the gas catcher system with the mass spectrometer MASHA the ion-optical scheme of the latter was slightly modified (Figure 1). Now the spectrometer consists of a doublet of the magnetic quadrupoles Q3-Q4, two magnetic dipoles D3a-D3b, and the magnetic sextupole lens S1 (see Fig.1). The quadrupoles Q3-Q4 are the same type as Q3 in the existing spectrometer. The

distances between the elements were kept as ones in the original version of the mass spectrometer except from the object plane F2 to Q3 and from S1 to the focal plane F3. The vertically bending electrostatic deflector was removed. The ion-optical parameters of the modified version of the mass spectrometer MASHA are listed in Table 2.

Table 2. Main ion-optical parameters of the modified version of the mass spectrometer MASHA.

Maximum energy	keV	40
Maximum magnetic rigidity	T-m	0.5
Mass acceptance	%	±2.8
Angular acceptance (in both transverse planes)	mrad	±14.0
Diameter of the object orifice F2	mm	1.0
Focal plane F3:		
– horizontal linear magnification	-	-0.8
– vertical linear magnification	-	-4.0
– linear mass dispersion	mm/%(ΔM/M)	-20.0
– mass resolution $(M/\Delta M)_{FWHM}$	-	3000
($\Delta E/E=2\times10^{-5}$ and $\varepsilon_{X(Y)}=0.2\pi$ mm-mrad)		

3. Application for studying multinucleon transfer (MNT) reactions

3.1. *MNT reaction features*

In the past two decades, it was realized that the multinucleon transfer processes could be successfully used for producing the neutron-rich nuclei with $Z \leq 40$. In the experiments with stable light projectiles (e.g. Ca, Ti, Ni, Se, Zr) and heavy targets (e.g. Pb, U) turned out to be possible to produce the projectile-like neutron-rich fragments in the vicinity of Ti [7], Ni [8,9], Ca [10], Se [11], and Zr [12] at the bombarding energies close to the Coulomb barrier. Herein, the main production mechanism, leading mainly to formation neutron-deficit target-like nuclei, was a multiple process of the neutron pickup on and proton stripping from the projectile. To move the process toward the higher production rate of the neutron-rich target-like nuclei, the heavier neutron-rich projectiles seem to be more suitable.

In this connection, a perspective of application of the mass spectrometer MASHA for production of the neutron-rich nuclei located near the neutron shell N = 126 was studied. The cross sections of isotope production of the elements of Rn (Z=86), At (Z=85), Po(Z=84), Pb(Z=82), Hg(Z=80), Au(Z=79), and Pt(Z=78) were calculated proposing the MNT reaction mechanism between ^{48}Ca, ^{86}Kr, and ^{136}Xe as projectiles with energies in the range from 6.0 to 7.5 AMeV, and ^{208}Pb as a target installed just in front of the entrance window of the gas catcher. The primary beams of high enough intensities of

such heavy ions seem to be available, at least for ^{48}Ca and ^{86}Kr, from the U400M cyclotron.

Table 3. Laboratory system exit channel energies as well as intensities of the ^{48}Ca,^{86}Kr, and ^{136}Xe projectiles ($E_{ejectile}$, $I_{ejectile}$), and ^{208}Pb target nuclei (E_{recoil}, I_{recoil}) elastically scattered into the angular range of θ_{Lab} = 30° – 70 at different entrance channel energies (E_{proj}). A ^{208}Pb target thickness of 0.5 mg/cm^2 and a projectile intensity of I_{proj} =10 pnA were assumed in calculations.

Reaction: I_{proj}=10pnA, t_{target}=0.5mg/cm^2	E_{proj}, MeV	$E_{ejectile}$, MeV	$I_{ejectile}$, pps	E_{recoil}, MeV	I_{recoil}, pps
^{48}Ca + ^{208}Pb	305	260 – 286	$3.6\cdot10^5$	22 – 45	$2.8\cdot10^5$
	325	283 – 304	$2.7\cdot10^5$	23 – 41	$2.1\cdot10^5$
	350	312 – 327	$2.0\cdot10^5$	24 – 36	$1.3\cdot10^5$
^{86}Kr + ^{208}Pb	515	360 – 460	$4.6\cdot10^5$	50 – 150	$5.3\cdot10^5$
	560	430 – 500	$3.4\cdot10^5$	54 – 130	$4.0\cdot10^5$
	600	490 – 540	$2.2\cdot10^5$	58 – 110	$2.7\cdot10^5$
^{136}Xe + ^{208}Pb	885	620 – 740	$2.6\cdot10^5$	100 – 265	$5.2\cdot10^5$
	950	724 – 795	$1.5\cdot10^5$	105 – 230	$3.8\cdot10^5$
	1020	820 – 850	$7.0\cdot10^4$	115 – 200	$2.7\cdot10^5$

The isotope production cross sections corresponding to the maximum available energies of the projectiles are shown in Fig.14. The calculations were made with the program GRAZING [13-15] implying the grazing angle mechanism of the MNT reactions. The flux of the isotopes consists, mainly, of high energy projectile nuclei and low energy target ones. A major contribution to the flux gives the elastic scattering.

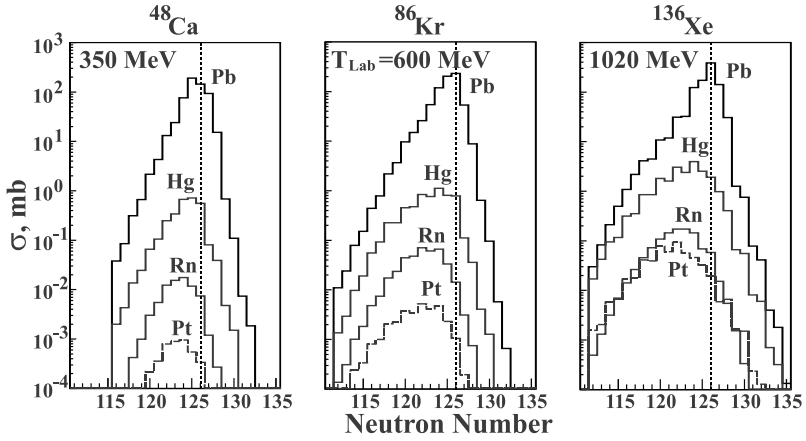

Figure 10. Target-like nuclide production cross sections (after neutron evaporation) for the MNT reactions of ^{48}Ca(^{86}Kr,^{136}Xe)+^{208}Pb at laboratory system projectile energies of 350MeV, 600MeV, and 1020MeV (GRAZING calculations), respectively.

Estimations (Table 3) showed that the intensities of the entrance channel nuclei elastically scattered into the angular range of θ_{Lab}=30°–70° would be about a factor of 10^5pps provided the target thickness t(^{208}Pb)=0.5mg/cm^2 and the projectile intensity I_{proj}=10 pnA. Such irradiation level of the gas catcher working area by the primary beam and the target recoil nuclei seems to be acceptable. At these conditions, the yields of the fragments in the MNT processes with a cross section of σ_{MNT}=10 μb would be $Y_{MNT}\approx$1 pps.

3.2. *Transport line to deliver primary beams up to the gas catcher*

To adopt the mass spectrometer MASHA to study the MNT reactions the primary beams must be delivered just up to the gas catcher. The electric rigidities of these beams are of an order of magnitude higher than ones of the compound nucleus evaporation residuals. An easiest way to deliver the primary beams is to provide a mechanical replacement of the electrostatic deflector (ED in Figure 1) by a dipole magnet (L_{eff}=47.8cm, R_{bend}=182.6cm, $\Delta\Phi_{bend}$=15°, pole tip gap=15cm, B_{max}=0.65T). Thereto, in the most rigid case, ^{136}Xe projectile, the maximum magnetic rigidity of the transport line is about Bρ=1.2 T-m.

The dump of the primary beams and both the projectile-like and target-like fragments, elastically scattered into the angular range of 0-30°, must be implemented with an appropriate collimator system.

4. Conclusion

The proposed modification of the mass spectrometer MASHA will significantly enhance the effectiveness of production and investigation of both superheavy elements (Z>110) synthesized in the compound nuclear fusion reactions, e.g. ^{48}Ca+^{238}U→^{286}112* →^{283}112+3n, and heavy neutron-rich nuclei, e.g. the ones near the doubly magic ^{208}Pb (Z=82) produced in the multinucleon transfer collisions. In this connection, the adaptation of the gas catcher technique is a key element to achieve:

1. A possibility to investigate the nuclei with lifetimes as short as some tens of milliseconds.
2. A high production efficiency of superheavy elements by using relatively thick targets. In the tested reaction of synthesis of the compound nucleus evaporation residual ^{283}112 the yield of about 0.4 nuclei/day could be anticipated assuming the ^{238}U target thickness of 0.8 mg/cm^2, the intensity of the ^{48}Ca beam of 1 pμA, the production cross section of σ_{3n}=2.5 pb [16], and the efficiencies of the pre-separator and gas catcher of 30% and 50%, respectively.

3. A sensitivity of about 0.1μb for the production of heavy neutron-rich nuclei around the neutron shell N=126.
4. A very small phase space of beams of the nuclei which are of interest for investigation – a transverse emittance of $\varepsilon \leq 1\pi \cdot$mm·mrad and an energy spread of $\Delta E/E \sim 10^{-5}$.

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