Isotope distribution of iridium in the interaction of 47MeV/nucleon ¹²C with ¹⁹⁷Au

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Abstract Thick gold targets were bombarded with 47 MeV/nucleon ${}^{12}C$ ions and the radioactive isotopes of iridium and platinum were produced through the multi-nucleon transfer reactions. The production cross-sections of iridium isotopes in the reactions have been determined by a combination of radiochemical separation and off-line γ -ray spectroscopy technique. The obtained Ir isotope distribution was compared with those obtained in other experiment as well as calculated by the statistical model.

Keywords Iridium, Isotope distribution, Multi-nucleon transfer reaction, Neutron-rich isotope **CLC numbers** 0674. 233⁺, 0571. 41⁺3

1 Introduction

In the studies of interactions of lighter heavy ions with nuclei at non-relativistic energies, Dubna group declared that the deep inelastic transfer reaction was an effective way of producing neutron-rich isotopes.^[1-4] At a later time, it was found that the other two reaction mechanisms: fission and fragmentation could also produce neutron-rich isotopes. The fission is mainly used to synthesize the medium-mass neutron-rich nuclides,^[5,6] while the fragmentation reactions are more suitable for the production of heavy neutron-rich isotopes.^[7,8]

During the last twenty years, many new neutron-rich isotopes have successfully been synthesized and identified by using the multi-nucleon transfer reactions. In a series of experiments at the GSI on-line mass-separator, more than twenty new neutron-rich isotopes as the products of the multi-nucleon-transfer reactions have been identified. Some of them are in the regions of heavy lanthanide and of actinide.^[9,10] In the past decade, five new neutron-rich isotopes with mass number $A \ge 170$ have been successfully synthesized and identified via the same reaction mode in the interactions of heavy neutron-rich target nuclei with lighter heavy ions at the intermediate energies at IMP.^[11-13] The results relating to the above reactions convincingly prove the multi-nucleon transfer reactions taking place between heavy ion projectiles and neutron-rich target nuclei have played an important role in the synthesis of the unknown neutron-rich heavy isotopes which cannot be produced in high energy neutron or proton induced reactions.

A large number of investigations on mass, charge as well as isotope distribution in the low or high energy nuclei collisions have been reported. But there is only a little published radiochemical work in the intermediate energy region. Although some of similar experimental investigations have been made, the experimental data of production cross sections on target-like productions, especially neutron-rich, heavy target-like products produced by the multi- nucleon-transfer reactions are still scarce up to now. It is still necessary to precisely measure the formation cross sections of heavy target residues, because the formation cross sections for heavy neutron-rich isotopes produced in the exotic multi-nucleon transfer reactions at intermediate energies is of extreme importance for synthesis of the unknown heavy neutron-rich isotopes.

Supported by the National Natural Science Foundation of China (10075063), Major State Basic Research Development Program under Contract Number (G2000077400) and the Chinese Academy of Sciences.

Received date: 2004-01-09

The charge distributions of the target-like products were usually considered the same as that of the reaction products in other mass regions in order to gain the independent yields of the target-like products. So the isotopic distribution gained by such method cannot really reveal the shapes of the isotopic distribution for the target-like products. Furthermore, the transfer process in which how the majority of neutrons are transferred to the target nuclei is still not clearly understood. The present experiment was carried out for extending the study of the isotope distributions of the target-like products and for finding the reaction channels suitable for producing new neutron-rich isotopes with $A \ge 170$.

2 **Experimental**

2.1 Irradiation and chemical separation

The experiments were performed at the Heavy Ion Research Facility at Lanzhou (HIRFL) in the Institute of Modern Physics (IMP). The gold targets consisting of three pieces of gold foils (99.99% purity) were irradiated with 47 MeV/nucleon ¹²C ions having an average intensity of about 10 enA. A target assembly includes the foil facing the beam with a thickness of 90 mg/cm², the midway piece of 90 mg/cm², and the last piece of 453 mg/cm². The beam current was measured with an electrometer. The radioactive isotopes of iridium and platinum were produced as target-like products through the multi-nucleon transfer reactions. After irradiation, the middle gold foil was subjected directly to y-ray spectroscopy measurement and the other two pieces were radiochemically separated in order to gain the chemical yields of Ir and Pt. The Au foils were dissolved in aqua regia. The iridium and platinum were separated 1.5 h after the end of irradiation from the reaction products using the chemical procedure described in Reference [14]. In the final step, the γ solid radioactive sources of iridium and platinum (metal powder) were prepared for γ spectroscopy, respectively. The chemical yields of iridium and platinum were determined from γ -ray intensities of the iridium or platinum isotopes in the gold foil subjected directly to y-ray spectroscopy measurement and the chemically separated fractions.

2.2 Radioactivity measurements and data analysis

The γ -activities of both Ir and Pt sample were measured with an HPGe detector in a multi-spectrum mode. The detector has a resolution of 2.3 keV (FWHM) for 1332 keV gamma ray of ⁶⁰Co. The detective efficiency of the detector was determined with a ¹⁵²Eu standard source. Measurements for long-lived Ir isotopes lasted about 5 months. The data were stored on the magnetic disks with a PC-CAMAC Multi-Parameter Data Acquisition System.

The measured γ -ray spectral data were analyzed by employing a set of computer programs. The radioisotopes of Pt and Ir in each sample were identified by half-lives, specific energies and, if necessary, relative intensities of their gamma rays. The production cross sections were calculated from target thickness, end-bombardment activities, variations of beam intensity during the irradiation as well as chemical yields. The cross sections for the majority of Ir isotopes are cumulative except for those of ¹⁹⁰Ir, ¹⁹²Ir and ¹⁹⁴Ir isotopes. On the basis of experimental data, the correction of Ir activities for the precursor decays during the irradiation and before the chemical separation were made by utilizing a computer program to obtain the independent yields of Ir isotopes. The details of data analysis have been described in Reference [15].

3 Results and discussion

The cross sections of Ir isotopes obtained in the experiment are listed in Table 1, along with the decay data ^[16] used in the calculations of the cross sections. The cross sections of ^{194m}Ir, ^{195g}Ir and ^{196g}Ir could not be obtained in the experiment. In the heavy ion induced reactions, the ratio of the cross section of the isomer with the higher spin to that of the ground state for the same isotope is usually higher.^[17] It has been found in the irradiation of ¹⁹⁷Au with 20 MeV/nucleon ¹²C ions that the isomeric cross section ratio of ¹⁹⁵Hg (σ_{m}/σ_{g}) is 9.24.^[17] Therefore, the cross sections of ^{195m}Ir or ^{196m}Ir can approximately be considered as total cross section ($\sigma_{m+}\sigma_{g}$) of ¹⁹⁵ Ir or ¹⁹⁶ Ir, respectively. The yields of Ir and part of Pt isotopes in the experiment are given in Table 1.

Isotopes	Half-life	Principal γ ray (keV)	Abundance (%)	Measured yield (mb)	Independent yield (mb)
¹⁸⁴ Ir	3.02 h	264.0	67.5	21.0±0.6	8.7±0.7
¹⁸⁵ Ir	14.0 h	254.3	13.0	17.1±0.6	12.1±1.0
¹⁸⁶ Ir(A)	1.75 h	743.0	24.4	2.57±1.6	
¹⁸⁶ Ir(B)	15.8 h	296.8	62.2	10.4±0.4	10.4±0.4
¹⁸⁷ Ir	10.5 h	427.1	4.4	47.6±2.2	13.0±2.5
¹⁸⁹ Ir	13.2 d	244.9	6.0	49.8±6.5	17.5±3.1
^{190g} Ir	12.1 d	186.7	48.2	12.7±0.8	14.1±0.8
^{190m2} Ir	3.1 h	616.1	98.5	1.4±0.1	
^{192g} Ir	73.83 d	468.1	48.1	10.2±2.2	10.2±2.2
^{194g} Ir	19.15 h	328.4	13.0	2.0±0.6	2.0±0.6
^{195m} Ir	3.8 h	432.9	9.4	1.68±0.27	1.68±0.27
^{196m} Ir	1.40 h	393.5	97.0	0.34±0.08	0.34±0.08
¹⁸⁴ Pt	17.3 min	191.9	94.0	17.2±1.4	
^{185g} Pt	70.9 min	255.1	51.0	6.81±0.55	
^{185m} Pt	33.0 min	135.3	80.0	4.82±0.39	
¹⁸⁶ Pt	2.0 h	689.2	70.0	38.0±3.4	
¹⁸⁷ Pt	2.35 h	106.4	8.3	43.5±3.9	
¹⁸⁹ Pt	10.89 h	721.4	5.8	50.5±2.8	

Table 1The yields of Ir and Pt isotopes in the interaction of 197 Au with 47 MeV/nucleon 12 C and the decay properties of the isotopes

We paid attention to the recoiling loss of Ir and Pd isotopes from the targets. However, the loss is very small in the case of intermediate energy, because the thick targets were used in the experiment. We also tested the possible effect of the charged-particle- induced secondary reactions on the production cross sections of Ir and Pt isotopes. It was found that, within the statistics, there is no significant contribution from the secondary reactions.

The isotope distribution of iridium in the present experiment is shown in Fig.1. The distribution has an FWHM of 10.0 mass units, with the peak position being at the vicinity of ¹⁸⁹Ir. Fig.1 shows that the yields of ^{187,189,190,192,195}Ir isotopes in the present work are higher than those (circles) in the bombardment of ²⁷Al with 1 GeV/nucleon ¹⁹⁷Au.^[5] Because the cross section of ^{194g}Ir was only obtained in our experiment, it is reasonable that the point of ^{194g}Ir is obviously lower in Fig.1. To more distinctly understand the formation mechanisms, the curves of Ir isotope distribution (solid and dashed lines) calculated with statistical model are also given in Fig.1. The exciting energies of the initial target-like residues in our experiment should be lower than those in 1 GeV/nucleon ¹⁹⁷Au + ²⁷Al reaction.^[5] Therefore, the values of cross sections of ^{187,189,190,192,195}Ir isotopes in our experiment are close to the solid curve, whereas the values in Reference [17] fit well with the dashed curve.



Fig.1 The isotope distribution of iridium in the present experiment and in Reference [14] compared with that calculated by the statistic chafing chipping modelPresent experiment

 \circ 1 GeV/nucleon ¹⁹⁷Au + ²⁷Al reaction

 Statistic chafing chipping model (excitation energies of 13 MeV/nucleon)

------ Statistic chafing chipping model (excitation energies of 26 MeV/nucleon)

The isotope distribution in the experiment is

broader than that obtained by Kudo et al.^[17] The lower exciting energies are, the fewer neutrons evaporating from the initial target-like residues are. The production cross section of a neutron-rich isotope can be obtained through extrapolating the isotopic distribution curve based on the Qgg systematics. In the experiment the cross section of 197 Ir (target nuclei -2p+2n) was obtained to be about 0.1 mb. In our previous studies, we have synthesized a few heavy neutron-rich isotopes,^{[11-13] 186}Hf, ²³⁸Th and ²⁰⁸Hg, by the target nuclei -2p+2n reactions. It can be concluded from the above results that the unknown heavy neutron-rich target-like nuclides can be synthesized by the multi-nucleon transfer if the more neutron-rich heavy target nuclei are bombarded using the heavy neutron-rich ions at intermediate energy.

Acknowledgement

The authors thank staff of the Heavy Ion Research Facility at Lanzhou for their assistance and support.

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