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Study on the Nuclear Reactions of ^{93}Nb, ^{181}Ta, and ^{197}Au Induced by Secondary Neutrons in 40 MeV/nucleon ^{40}Ar Ion Collisions

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Nuclear reactions of ^{93}Nb, ^{181}Ta and ^{197}Au induced by secondary neutrons produced by irradiation of a thick stainless steel target with 40 MeV/nucleon ^{40}Ar ions were investigated by off-line γ-ray spectroscopy. Yields of the radioactive products have been determined relative to that of ^{24}Na produced by the ^{27}Al(n,α)^{24}Na reaction. The slopes of the mass distributions deduced from the experimental data are independent of the target species. Up to 7 nucleons were removed from the target nuclei, indicating significant presence of the neutrons with energies higher than 70 MeV.

Nuclear reactions induced by neutrons have been studied extensively, mainly in the energy range from thermal one to below about 20 MeV. However, few data are available on the reactions induced by higher-energy neutrons. It is well known that a large amount of neutrons with a wider energy range are emitted from the reactions induced by intermediate-energy heavy ions. Shikata et al.[1] and Nakajima et al.[2] have reported some measurements for the reactions induced by the secondary fast neutrons produced by the irradiation of an iron target with 135 MeV/nucleon ^{14}N ions. The main purpose of the measurements was to get information on the neutron spectrum for shielding calculations. The emphasis was placed only on the (n,xn) reactions, where x is 2 - 5.

It is interesting to carry out a full measurement for all of the reaction products in order to understand the secondary-neutron-induced reactions. This paper, as a first general survey, will give the experimental results from study of the nuclear reactions of ^{93}Nb, ^{181}Ta, and ^{197}Au targets with the secondary fast neutrons produced by irradiation of a thick stainless steel target with 40 MeV/nucleon ^{40}Ar ions.

The experiments were performed on the RIKEN Ring Cyclotron. 40 MeV/nucleon ^{40}Ar ions, traversing the primary targets, consisting mainly of 0.1 mm thick gold foil, were stopped in a stainless steel Faraday cup with a thickness of 1.2 cm. The thickness of the Faraday cup was large enough to stop not only the ^{40}Ar ions but also secondary charged-particle beams, with velocity close to that of the primary beam, which resulted from the projectile fragmentation in the ^{40}Ar ion collisions (the calculated ranges in iron are 0.04 cm and 0.294 cm for 40 MeV/nucleon ^{40}Ar ions and 40 MeV protons, respectively[3]). A secondary target assembly used for neutron irradiation was placed immediately behind the Faraday cup. The target assembly for neutrons consisted of ^{27}Al,

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^{93}Nb, ^{181}Ta and ^{197}Au foils, ≥ 99.9 % in purity, with thicknesses of 6.7 mg/cm^2, 85.7 mg/cm^2, 41.7 mg/cm^2, and 96.6 mg/cm^2, respectively. Each target (24 mm in diameter) was sandwiched between two additional Al foils.

The irradiation lasted for about 23 h (with several interruptions) with typical beam intensities of 10 enA. The total particle fluence was 1.15×10^{14} ^{40}Ar ions, assuming full ionization of the incident heavy ions. Following the irradiation, the secondary targets were analyzed by direct γ-ray spectroscopy. Counting of the target foils began about 1.5 h after the end of irradiation and continued for 4 - 5 weeks.

The γ-ray spectra were analyzed with the BOB code.[4] Decay curves were analyzed by use of a least-squares code. All the calculations were performed on a FACOM M1800 computer at RIKEN. Assignments of nuclides were made on the basis of energy, half-life and concordance with other γ-rays emitted by the presumed nuclides. The nuclear data used for the assignment and yield calculation of the radioactive products were quoted from Ref. 5.

In this work, a number of radioactive products have been identified for each target. Because of the unknown neutron fluence and energy spectrum, we first calculated the nominal cross sections for these radionuclides using the intensities of the heavy-ion beam. Then, the relative yields have been obtained by normalizing the nominal cross sections to that of the reference reaction, ^{27}Al(n,α)^{24}Na, which was 0.27 ± 0.01 mb. The relative yields for the products from the reactions of ^{93}Nb, ^{181}Ta, and ^{197}Au are listed in Table 1. While some of the yields represent independent ones (labeled I in the table), the majority are cumulative yields (labeled C+) including the yields of more neutron-deficient isobaric progenitors. There are very few neutron-rich nuclides (labeled C-) whose yields were determined in this work. The errors listed are the standard deviations.

Table 1. Relative yields determined in the reactions of ^{93}Nb, ^{181}Ta, and ^{197}Au with secondary neutrons produced from the irradiation of a thick stainless steel target with 40 MeV/nucleon ^{40}Ar ions. The yields are given relative to that of ^{24}Na produced by the ^{27}Al(n,α)^{24}Na reaction.

^{93}Nb target			^{181}Ta target			^{197}Au target		
Nuclide	Type	Relative yield	Nuclide	Type	Relative yield	Nuclide	Type	Relative yield
^{86}Yg	PC[a)]	0.019 ± 0.015	^{175}Ta	C+	0.36 ± 0.13	^{191}Pt	C+	0.26 ± 0.02
^{86}Zr	C+	0.0045 ± 0.0034	^{175}Hf	C+	0.28 ± 0.04	^{192}Au	C+	0.38 ± 0.07
^{87}Yg	PC	0.076 ± 0.009	^{176}Ta	C+	0.69 ± 0.05	^{193}Au	C+	1.66 ± 0.21
^{87}Ym	C+	0.136 ± 0.025	^{177}Ta	C+	2.34 ± 0.15	^{194}Au	I	4.61 ± 0.23
^{88}Y	PC	0.23 ± 0.06	^{178}Tam	I	1.41 ± 0.09	^{195}Au	C+	9.08 ± 0.58
^{88}Zr	C+	0.092 ± 0.018	^{180}Tag	I	12.7 ± 5.5	^{196}Aug	I	17.6 ± 0.9
^{89}Zr	C+	0.46 ± 0.06	^{181}Hf	C-	0.11 ± 0.07	^{196}Aum[b)]	I	1.20 ± 0.13
^{90}Ym	I	0.041 ± 0.009	^{182}Tag	C-	4.76 ± 0.35	^{198}Au	I	6.76 ± 0.33
^{90}Nb	C	1.18 ± 0.07						
^{92}Nbm	I	4.80 ± 0.25						

a) Partial cumulative yield. b) 9.7 h isomer.

Fast-neutron-induced reactions are dominated by evaporation of neutrons, i.e., (n,xn) reactions. For the lighter target nuclei ^{93}Nb, the possibility of emission of charged particles increases due to the lower Coulomb barrier. Sequential β^+ or E.C. decays are the predominant decay modes for neutron-deficient primary products produced from the reactions. Consequently, the cumulative yields of the nuclides determined in this work are good representations of the mass yields at the mass numbers. The mass yield distributions obtained from the experimental data are shown in Fig. 1 as a function of mass loss ΔA from the target for the reactions of ^{93}Nb, ^{181}Ta, and ^{197}Au.

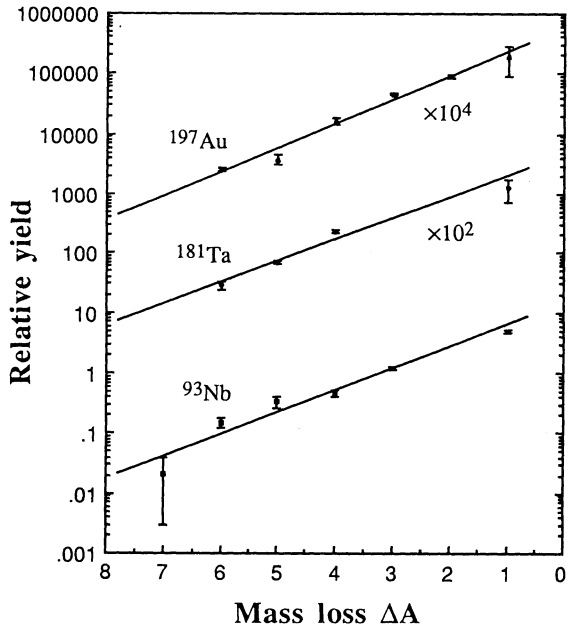

Fig. 1. The mass yield distributions as a function of mass loss ΔA from the target nuclei for the reactions of ^{93}Nb, ^{181}Ta, and ^{197}Au with the secondary neutrons produced from the irradiation of a thick stainless steel target with 40 MeV/nucleon ^{40}Ar ions. The solid lines are the calculations from the linear fitting to the data. The yields are given relative to that of ^{24}Na produced by the ^{27}Al(n,α)^{24}Na reaction.

The mass yield distributions show a form similar to those obtained from high-energy proton-induced reactions: the mass yields decrease rapidly and basically exponentially with increasing mass loss from the target.[6] On the other hand, the mass yield distributions vary exponentially only over a certain mass interval for the interactions with energetic heavy ions.[7] It is found, however, that the slope of this exponential region is a quantitative measure of the excitation energy deposited in the composite system for a variety of projectiles interacting with copper target.[8] The slope decreases with increasing total energy of the incident heavy ions before limiting fragmentation is achieved. In the present work, as seen from Fig.1, the mass yield distributions are approximately parallel with each other. The slopes were calculated to be 2.30 ± 0.27 u^{-1}, 2.29 ± 0.26 u^{-1}, and 2.48 ± 0.18 u^{-1} for the reactions of ^{93}Nb, ^{181}Ta, and ^{197}Au targets, respectively. These values are in good agreement within experimental errors, indicating that the slope of the mass yield distribution is independent of the target species for the secondary-neutron-induced reactions. It is expected that the slope of the mass yield distribution may be strongly dependent on the incident energy per nucleon of the heavy ions.

Shikata et al. and Nakajima et al. have carried out a series of measurements on the secondary neutrons produced by the reaction of a thick iron target with 135 MeV/nucleon ^{14}N ions.[1,2] Several γ–rays were observed, whose energies correspond to those from the reaction products of (n,2n), (n,3n), (n,4n), and (n,5n). They also indicated the significant presence of neutrons with energies higher than 40 MeV. In the present work, as seen from Table 1, the lightest products in the activated ^{93}Nb targets were found to be ^{86}Yg and ^{86}Zr, which resulted from removal of 8 nucleons from the composite systems. The separation energy of a neutron is about 8 MeV for the nuclides involved in this work. The kinetic energy of the neutrons emitted from the composite system is assumed to be about 2 MeV on average. Thus, we can draw the conclusion that a significant fraction of the secondary neutrons would have had the energy higher than 70 MeV, which is much higher than the incident energy per nucleon of the heavy ions. This estimation is supported by the neutron inclusive measurements by the time-of-flight method in ^{14}N + Ag reaction at 35 MeV/nucleon, where a significant fraction of neutrons were found to have the energy almost three times higher than the incident energy per nucleon at small outgoing angles.[9]

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