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Mass yield distributions of target fragments from the reactions of iron with 135 MeV/nucleon ^{12}C and 80 MeV/nucleon ^{16}O ions

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Abstract. Cross sections for the production of target fragments in the reactions of iron with 135 MeV/nucleon ^{12}C and 80 MeV/nucleon ^{16}O ions have been measured by off-line γ-ray spectroscopy. Through these data, the mass yield distributions have been obtained. The result of the experiment for the reaction with 135 MeV/nucleon ^{12}C ions is compared with theoretical calculations using the fusion-fragmentation model and the GEMINI code for sequential binary decay, following a calculation with the fireball model.

PACS. 25.70-z Heavy-ion-induced reactions

1 Introduction

A great number of radiochemical measurements have been devoted to the study of the mass yield distributions of the target fragments from the interactions induced by intermediate energy heavy ions. One of the motivations for such measurements is to test theoretical models, describing the nuclear processes occurring in collisions with heavy ions. By using the fusion-fragmentation model, we have reproduced successfully the mass yield distributions for the reactions of copper and niobium with about 40 MeV/nucleon ^{12}C ions [1,2]. In the meanwhile, the code GEMINI, based on statistical binary decay has also been used to explain mass yield distributions measured by nuclear chemistry technique. A good agreement between the theoretical calculations and the experimental results has been reached for the reactions of indium and copper with approximately 40 MeV/nucleon ^{12}C ions [3,4]. In all of these reactions, however, the incident energies per nucleon were on the low energy side of the intermediate energy domain, with total projectile energy less than 1 GeV. Recently we have completed a radiochemical measurement of the target fragments in the reactions of iron with 135 MeV/nucleon ^{12}C and 80 MeV/nucleon ^{16}O ions. An improved antisymmetrized molecular dynamics model successfully reproduced the mass yield distribution of the fragments in the reaction of iron with 135 MeV/nucleon ^{12}C ions [5]. In the present work, we have reported the results of the experiments for the reactions of iron with 135 MeV/nucleon ^{12}C ions and 80 MeV/nucleon ^{16}O ions. The emphasis is put on a comparison of the experimental mass yield distribution of the fragments from the reaction induced by 135 MeV/nucleon ^{12}C ions with the fusion-fragmentation model and the sequential binary decay model.

2 Experimental method

The experiments were performed at the Institute of Physical and Chemical Research (RIKEN), Japan. 135 MeV/nucleon ^{12}C beam and 80 MeV/nucleon ^{16}O beam, with an intensity of ≈200 enA, were delivered from the RIKEN Ring Cyclotron. The beam intensity was measured by means of Faraday cup and recorded with a current integrator. The beam was impinging a target assembly, which consisted of three pieces of 15.7 mg/cm^2 iron foils, 99.99% in purity. In the experiment with ^{12}C ions, a 6.2 min irradiation was performed in order to obtain information for the short-lived target fragments. An additional irradiation of longer duration, 48.8 min, was performed for the longer-lived fragments. In the experiment with ^{16}O beam, a single irradiation, 60 min in duration, was conducted.

Immediately after irradiation, the target stack was transferred to a counting room in the Nuclear Chemistry Laboratory of RIKEN by the Falling Ball Irradiation System. Only the medial iron foil was assayed with a calibrated HPGe γ-ray spectrometer. The sample from the short irradiation was measured for 8 h, starting a few min after the end of bombardment. Those from the longer irradiation were measured for approximately 4 weeks.

The γ- ray spectra were analyzed with BOB code [6]. Decay curves were analyzed by an iterative least-square fit code. Assignments of radioactive nuclides were made on the basis of energy, half-life, and concordance with otherγ-rays, if any, emitted by the presumed nuclide. Cross sections for the production of radioactive products were calculated, assuming full ionization of the incident ^{12}C and ^{16}O ions. The nuclear data used for nuclide assignment and cross section calculation were quoted from [7]. The analysis of the γ-ray spectra and calculation of the production cross sections were conducted on FACOM 1800 computer at RIKEN. Further analysis of the experimental data was performed on VAX-8350 computer at Institute of Modern Physics.

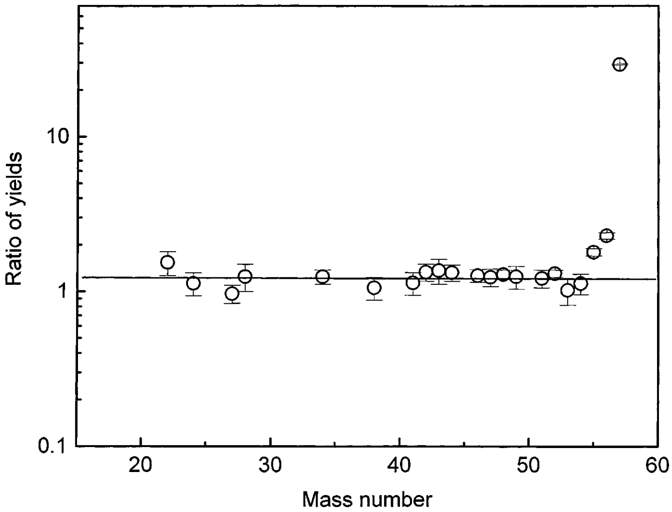

Fig. 1. Mass dependence of the cross section ratios for the reactions of iron with 80 MeV/nucleon ^{16}O and 135 MeV/nucleon ^{12}C ions

3 Results

The production cross sections were determined for 37 and 27 target fragments from the reactions of iron with 135 MeV/nucleon ^{12}C and 80 MeV/nucleon ^{16}O ions respectively. The experimental values are listed in Table 1. The uncertainties in these values are standard deviations, including errors in analysis of the γ-ray spectra, in the resolution of the decay curves by the least-squares method, and a 5% error in detector efficiencies. While the uncertainty in the thickness of the target was negligible, the uncertainty in beam current measurement was not taken into account. Some of the cross sections represent independent yields (labeled I in Table 1). The majority is cumulative. The latter are identified as either C^+ or C^-, depending on whether they represent the integrated isobaric cross section of more neutron-deficient or neutron-excessive precursors, respectively. Figure 1 shows a variation with fragment mass of the cross section ratios measured for a given fragment between the reactions induced by 80 MeV/nucleon ^{16}O ions and by 135 MeV/nucleon ^{12}C ions. These ratios are quite constant (average value of 1.23), with the exception of those for the trans-target (in Z) nuclides, i.e., the cobalt isotopes.

The tabulated data represent only a fraction of the total isobaric yields. In order to obtain the mass yield distribution, it is necessary to estimate the cross sections of the unmeasured nuclides by means of the isobaric yield distribution. Accordingly, one assumes that isobaric yield distribution can be expressed by a Gaussian distribution function:

$$\sigma(Z, A) = \sigma(A) \frac{1}{\sqrt{2\pi C_Z^2(A)}} \exp\left[-\frac{[Z - Z_p(A)]^2}{2C_Z^2(A)}\right] \quad (1)$$

where σ(A) is the total isobaric yield, $C_z(A)$ and $Z_p(A)$ are the Gaussian width parameter and the most probable Z value for that isobar, and σ(Z, A) is the independent yield for a given nuclide of the isobar. One can see from Table 1 that the cross sections have been determined for three nuclides, ^{48}Sc, ^{48}V, and ^{48}Cr, i.e., the A = 48 isobar in each reaction under study. The independent yield of ^{48}V was obtained by correcting for β-decay feeding from its precursor ^{48}Cr. Using an iterative calculation method, the independent yield of ^{48}Cr can be calculated. Thus the Gaussian isobaric yield distribution can be defined for this mass chain. The width parameters $C_z(A)$ calculated from the Gaussian isobaric distribution function are 0.538 and 0.531 for the reactions of iron with 135 MeV/nucleon ^{12}C and 80 MeV/nucleon ^{16}O ions, respectively. To define the isobaric yield distributions at the other mass chains, where the cross sections are determined for only one or two nuclides, further assumptions were made assuming that the width parameters $C_z(A)$ was a constant for the entire mass region in each reaction and that $Z_p(A)$ values are a linear function of mass number A. Thus the fractional independent yields resulting from correction for β-decay feeding from the precursors were used to fit the Gaussian isobaric distributions of (1) by adjusting the $Z_p(A)$ values. Resulting Gaussian isobaric yield distribution functions were defined by an iterative code. The mass yield distributions obtained by integrating the isobaric yield distributions are displayed in Fig. 2 for the reactions of iron with 135 MeV/nucleon ^{12}C and 80 MeV/nucleon ^{16}O ions. The details, by which the mass yield distribution was constructed have been described in our previous work [3].

4 Discussion

Having a typical shape of the distribution for the reaction induced by intermediate energy heavy ions, the mass yield distributions obtained in this work are similar to each other. In order to characterize the mass yield distribution, the average mass loss from the target $\langle \Delta A \rangle$ and slope of the exponential region ($38 < A < 51$) of the distribution have been evaluated. The values of $\langle \Delta A \rangle$ extracted from the distributions are 46.3 and 46.7, about 9.5 units

Table 1. Cross sections (in mb) for the fragments from the reactions of iron with 135 MeV/nucleon ^{12}C and 80 MeV/nucleon ^{16}O ions

Nuclide	Type	Cross section (mb) ^{12}C + Fe	^{16}O + Fe	Nuclide	Type	Cross section (mb) ^{12}C + Fe	^{16}O + Fe
^{22}Na	C+	5.78 ± 0.92	8.90 ± 1.90	^{47}Ca	C-	0.09 ± 0.07	
^{24}Na	C-	7.36 ± 0.80	8.35 ± 1.50	^{48}Sc	I	0.80 ± 0.09	0.94 ± 0.10
^{24}Ne	C-	0.27 ± 0.18		^{48}V	C+	37.6 ± 2.2	48.5 ± 3.1
^{27}Mg	C-	3.04 ± 0.28	2.96 ± 0.26	^{48}Cr	C+	1.48 ± 0.12	1.62 ± 0.19
^{28}Mg	C-	0.65 ± 0.04	0.86 ± 0.06	^{49}Cr	C+	11.3 ± 0.9	14.1 ± 2.8
^{28}Al	C-	13.7 ± 1.8		^{51}Cr	C+	81.2 ± 9.3	98.9 ± 10.7
^{29}Al	C-	5.38 ± 0.75		^{51}Ti	C-	0.29 ± 0.17	
^{34m}Cl	C+	2.44 ± 0.19	3.07 ± 0.33	^{52}Mn	I	24.1 ± 1.1	31.6 ± 1.5
^{38}S	I	0.07 ± 0.02		^{52m}Mn	C+	0.10 ± 0.02	
^{38}Cl	C-	3.76 ± 0.53	3.98 ± 0.46	^{52}Fe	C+	1.2 ± 0.13	1.33 ± 0.15
^{39}Cl	C-	1.04 ± 0.09		^{53}Fe	C+	9.97 ± 1.41	10.2 ± 1.4
^{41}Ar	C-	1.24 ± 0.14	1.41 ± 0.21	^{53m}Fe	C+	0.66 ± 0.31	
^{42}K	I	7.20 ± 0.87	9.65 ± 1.20	^{54}Mn	I	72.5 ± 8.3	82.0 ± 10.2
^{43}K	C-	2.50 ± 0.16	2.79 ± 0.19	^{55}Co	C+	1.34 ± 0.10	2.41 ± 0.15
^{43}Sc	C+	9.41 ± 1.55	12.9 ± 2.4	^{56}Co	C+	2.67 ± 0.18	6.13 ± 0.54
^{44}Sc	I	30.1 ± 2.2	39.5 ± 3.7	^{56}Mn	C-	3.68 ± 0.29	4.50 ± 0.56
^{44m}Sc	I	18.1 ± 1.10	24.5 ± 1.5	^{56}Ni	C+	0.21 ± 0.04	
^{46}Sc	I	16.0 ± 1.40	20.3 ± 1.6	^{57}Co	C+	0.91 ± 0.16	26.6 ± 4.0
^{47}Sc	C-	5.59 ± 0.63	6.93 ± 0.75				

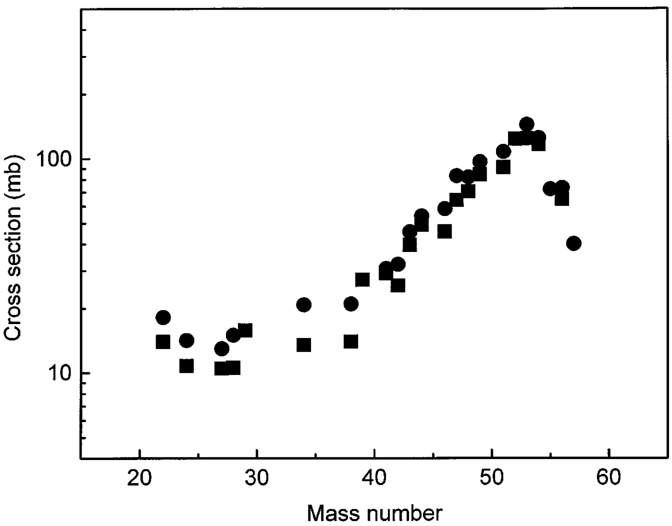

Fig. 2. Mass yield distributions for the reactions of iron with 135 MeV/nucleon ^{12}C and 80 MeV/nucleon ^{16}O ions. ■— ^{12}C + Fe, •%—^{16}O + Fe

less than the target mass, and the slopes are 0.124 and 0.127 (A^{-1}) for the reactions of iron with 80 MeV/nucleon ^{16}O and 135 MeV/nucleon ^{12}C ions. Calculated results indicate that there is no significant difference in the mass yield distribution in this energy domain. By integrating the mass yield distributions in Fig. 2 over the mass region of $A = 26 - 57$, the total reaction cross sections are found to be 1680 mb and 1380 mb. The ratio of total reaction cross sections is 1.22, which is in good agreement with the average value of 1.23 for the ratios of the cross sections for single fragment mentioned above.

Factorization demands that the cross section from the reaction with ^{16}O ions be larger than that from ^{12}C ions by the ratio of the total reaction cross section σ_R. Using the parametrization proposed by Kox et al. [8], the σ_R was calculated to be 1860 mb and 1700 mb for the reactions induced by ^{16}O and ^{12}C ions, respectively. The calculated values are 17%, on average, higher than the experimental values. This discrepancy, which has been pointed out previously [4], suggests that the radiochemistry technique may miss some of the cross section. However, the ratio of the total cross section calculated is 1.09, which modestly agrees with the corresponding value of 1.22 measured experimentally in this work.

To test whether theoretical calculations can reproduce the experimental mass yield distributions or not, two statistical models, the fusion-fragmentation model and the sequential binary decay model, have been used. The calculation was performed only for the reaction induced by 135 MeV/nucleon ^{12}C ions. In the calculation with the fusion-fragmentation model, the nuclear radius parameter, characterizing the volume of hot nucleus at the freeze-out state r_h and fractional factor of effective excitation energy C_f were chosen to be 2.0 fm and 0.38, respectively. The impact parameters were obtained by sampling with equal geometric probability. Corresponding values of N_p, E_k, Q, and E^* at various impact parameters are given in Table 2, where N_p is the number of nucleons in that part of projectile located in the overlap region between the target and the projectile, E_k is the energy in the center of mass, Q is the reaction energy, and E^* is the excitation energy of hot nuclei before breakup. The details of the calculation

Table 2. Parameters used in the calculation using the fusion-fragmentation model

b (fm)	6.18	5.59	4.93	4.17	3.23
Hot nuclie	^{57}Fe	^{58}Co	^{60}Ni	^{62}Cu	^{65}Zn
N_p	1	2	4	6	9
	(1,0)[a]	(1,1)	(2,2)	(3,3)	(5,4)
E_k (MeV)	132.63	260.69	504.00	731.61	1046.77
Q (MeV)	7.65	12.38	6.30	16.28	16.66
E^* (MeV)[b]	53.31	103.77	193.90	284.20	404.10

[a] Digits in parentheses are the numbers of neutrons and protons, respectively.
[b] Take $C_f = 0.38$.

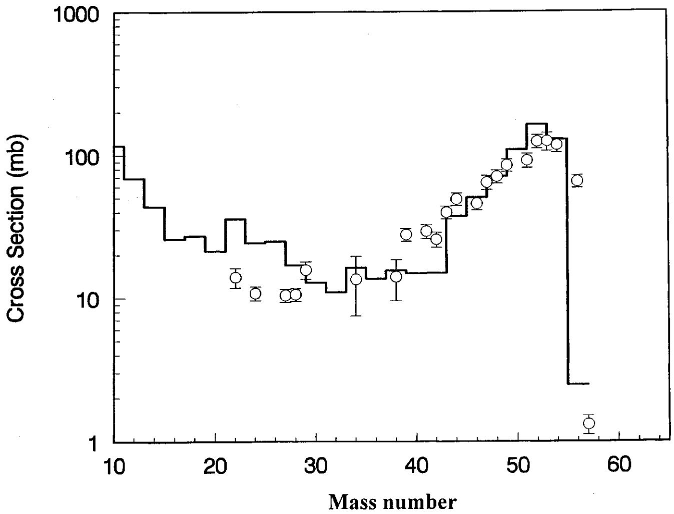

Fig. 3. Comparison of the experimental mass yield distribution for the reactions of iron with 135 MeV/nucleon ^{12}C with the calculations using the fusion-fragmentation model

have been described in our previous work [2]. By means of Monte Carlo simulations and a corresponding Metropolis simulation, calculated results are shown, as histograms, in Fig. 3.

The Monte Carlo code, GEMINI, based on the sequential binary decay model, has been used to reproduce successfully the mass yield distribution from the interaction of indium with 42 MeV/nucleon ^{12}C ions for the first time [3]. However, in that work, the fractions of the total reaction cross section for complete fusion and each of incomplete fusion were regarded as an adjustable parameter. In our latest work a fireball model was utilized to estimate the mass transfer, the momentum transfer, and the excitation energy for each fusion process [4]. When coupled with the GEMINI code which simulates the decay processes of compound-like nuclei, a good agreement between experimental mass yield distributions and theoretical calculations was obtained for the interactions of copper with intermediate energy ^{12}C ions at several bombarding energies [4]. In the present work the similar procedures were used for the interaction of iron with 135 MeV/nucleon ^{12}C ions. The parameters and formalisms used for the calculation were stated in [9]. The details of the calculation have been described elsewhere [10].

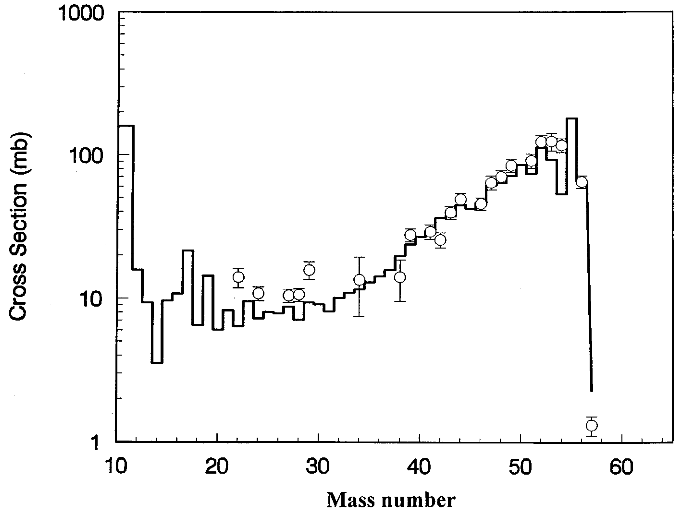

Fig. 4. Comparison of the experimental mass yield distribution for the reactions of iron with 135 MeV/nucleon ^{12}C with the calculations using the sequential binary decay model

However, it is worth stresing that the excitation energies extracted from the fireball model are too high to reproduce the mass yield distribution. After reducing the maximum value of the nuclear temperature of the composite system to 6.0 MeV, the theoretical calculations with the GEMINI code give a good fit to the experimental one (see Fig. 4). A similar trend has been observed in the calculation with the fusion-fragmentation model. To reproduce the mass yield distributions at different incident ^{12}C energies, the C_f values have been reduced from 0.73 for 44 MeV/nucleon [1] to 0.38 for 135 MeV/nucleon in this work. This behavior may be related to the limitation of excitation energy bearable by the hot nucleus created from the central collisions with intermediate energy heavy ions.

As seen from Fig. 3 and Fig. 4, the experimental mass yield distribution can be reproduced successfully by both fusion-fragmentation model and sequential binary decay model, especially for the position of the peak and the slope of the distribution. However when comparing carefully the experimental data with the calculations, we find that the fusion-fragmentation model overestimates the yields of the intermediate mass ($20 < A < 30$) fragments, whereas the sequential binary decay model underestimates the yields of these fragments. The latter situation has also been observed when studing the mass yield distribution from the interaction of copper with intermediate energy ^{12}C ions [4]. It is well known that the intermediate mass fragments originate from a disassembly of the highly excited hot nuclei arising from central collisions with heavy ions. With increasing projectile energy, in the intermediate energy domain, the contribution of the multi-fragmentation to total cross section is increasing. Therefore such deviations from the experimental mass yield distribution observed in this work can probably be attributed, in part, to the fact that the excitation energy of the composite system for more central collisions used in the fusion-fragmentation model is higher than that used in the sequential binary decay model. The physics behind this phenomena is an open question and deserves further study.

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