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Excitation Functions for ^{16}O-Induced Reaction on ^{115}In

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Excitation functions for 21 products of the reaction induced by ^{16}O on ^{115}In have been determined in an energy region between 51 and 97 MeV using nuclear chemistry techniques. The experimental results have been compared with those calculated using Alice code and Monte-Carlo simulation.

1. INTRODUCTION

Many years' study of heavy ion reactions has proved that the contribution of preequilibrium emission in heavy ion reactions is not significant at the incident energy ≤ 10 MeV/u, and that the reaction products with a mass number slightly smaller than that of the compound system come predominantly from complete fusion. The statistical model of evaporation of the compound nucleus has frequently been used to predict cross sections of evaporation residues from the compound nucleus. In the case of the synthesis of new nuclide far from the ß stability line via the evaporation reaction of the compound nucleus, this model has in fact become the main approach to the prediction of production cross sections of the new nuclides. However, the prediction is not always successful, especially for nuclides which are very far from the ß stability line because of the limitation of the statistical model applied to a finite nucleus system and the complexity of the nuclear reaction mechanisms involved. In recent years, for example, it has been found that there exists a massive transfer or incomplete fusion process in heavy ion induced reactions, even at incident energies as low

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TABLE 1. Nuclear Data Used in Cross Section Calculation

Nuclide	Half-life	Energy (keV)	Branching ratio (%)	Nuclide	Half-life	Energy (keV)	Branching ratio (%)
^{126}Ba	1.67 h	233.6	20.4	^{127g}Xe	36.41 d	172.1	25.5
		241.0	6.22			202.9	68.3
		388.6	42.3			375.0	17.2
		925.2	4.99	^{130g}I	1.35 h	560.4	73.0
^{127}Ba	12.7 min	180.8	12.4	^{121}I	2.12 h	212.2	85.0
^{128}Ba	2.43 d	273.4	14.5	^{123}I	13.2 h	159.0	83.3
		442.9	25.8	^{119g}Te	16.05h	644.0	84.5
^{125}Cs	45 min	526.0	24.0	^{119m}Te	4.69 d	153.6	66.7
^{127}Cs	6.25 h	411.9	58.4	^{121g}Te	16.8 d	573.1	80.3
		462.3	4.2	^{116m}Sb	60.3 min	542.9	52.0
		587.2	3.5			972.6	72.0
^{129}Cs	32.1 h	371.9	31.1	^{117}Sb	2.8 h	158.6	86.1
		411.5	22.7	^{118m}Sb	5.0 h	253.7	94.2
^{122}Xe	20.1 h	564.1	17.7			1050.7	96.5
^{123}Xe	2.08h	148.9	48.6			1229.6	100.0
		178.1	14.8	^{117m}Sn	13.61 d	158.6	86.4
^{129g}Xe	16.9 h	188.4	54.9	^{115m}In	4.49 h	336.2	45.8

as 5 MeV per nucleon. The cross sections for such processes are very large, particularly in the reactions induced by light heavy ions consisting of α clusters[1--4]. Thus how to reproduce production cross sections of the residues by using the existing theoretical models has become an interesting problem.

Misaelides had determined excitation functions for 19 products of the reaction ^{12}C on ^{93}Nb in an energy region between 4 and 9 MeV/u[5]. A comparison of the experimental results with the values calculated by Alice code indicated that a new set of parameters was necessary to get a good agreement. In this work, excitation functions for 21 reaction residues were determined using off-line γ-spectroscopy for the reaction of 57--97 MeV ^{16}O ions colliding with the natural indium target. The experimental data were compared with the values calculated both by Alice code and the Monte-Carlo simulation describing the decay of the compound nucleus in order to evaluate to what extent the models work, and to obtain some information on the reaction mechanisms.

2. EXPERIMENT

The experiment was performed on the 1.7 m heavy ion cyclotron SFC at the Institute of Modern Physics. The maximum energy of the incident ^{16}O ions was 97 MeV. The target assembly consisted of 8 natural Indium (^{115}In isotope abundance of 95.7%) foils deposited on high pure aluminum foils by spraying in vacuum. The thickness was about 0.3 mg/cm^2 for each indium foil. The beam energies after passing through the In foils and Al catcher foils were calculated using the Range/Energy Table of Northcliffe and Schilling[6]. The beam intensity was recorded by means of a Faraday cup as a function of time. The typical beam intensity varied between 40 and 100 nA. The

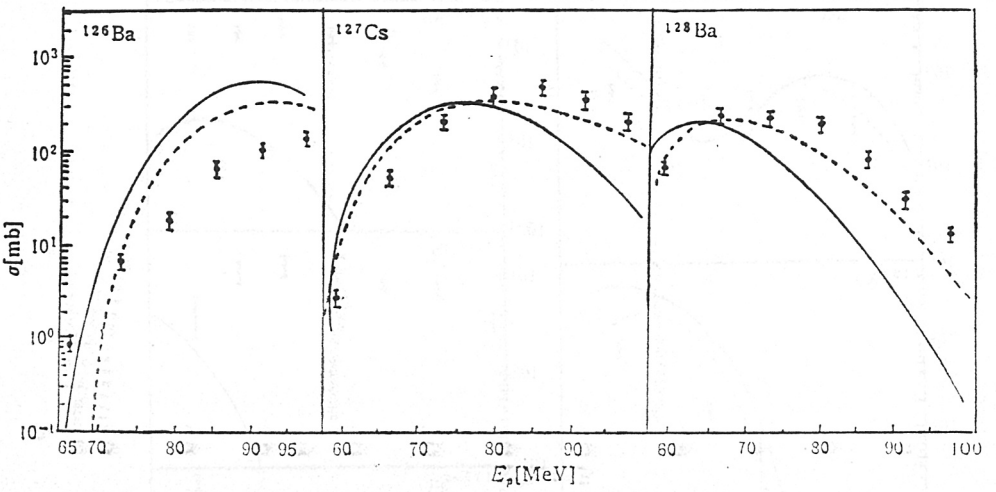

FIG. 1
Experimental cross sections for Ba and Cs isotopes from the traction of $^{16}O + ^{115}In$ in comparison with the statistical model calculations. The solid line represents the calculated excision functions by Alice code. The dashed line shows the calculated excitation function by Monte-Carlo simulation.

irradiations were 1.7 and 4.2 hrs. long for two experimental runs and the fluences were 260 and 1520 μC, respectively. 26 minutes after the irradiations, the Indium targets and Aluminum catcher foils began to be assayed by a γ-ray spectroscopy.

The γ-ray spectroscopic measurements were performed with a data acquisition system which consisted of 4 sets of Ge (Li) or HPGe detectors and a Plurimat-N multichannel analyzer. The resolution of the spectrometers was 2.5 KeV (FWHM) for the 1332 keV γ-ray of ^{60}Co. The absolute efficiency of the detector system was determined using a set of standard γ-ray sources from the Institute of Atomic Energy. The measurements lasted for a period of about two weeks in order to cover the nuclides with the half lives as long as possible, and over 100 γ-spectra were obtained in all. The γ-spectra were analyzed with GAMPU code. The radioactive decay curves were constructed by sorting the characteristic γ-ray of the nuclide under study. The decay curves were resolved on a graphic terminal Tektronix-4111 with the code TAU88, and the radioactive intensity at the end of bombardment was obtained. The production cross sections of the nuclides were calculated after various corrections. The details of the data analysis were reported elsewhere[7]. Nuclear data selected for the use of the cross section calculation were quoted from Ref.[8] (see Table 1). The data analysis and the theoretical calculation were performed on VAX-11/750 and VAX-8350 computers.

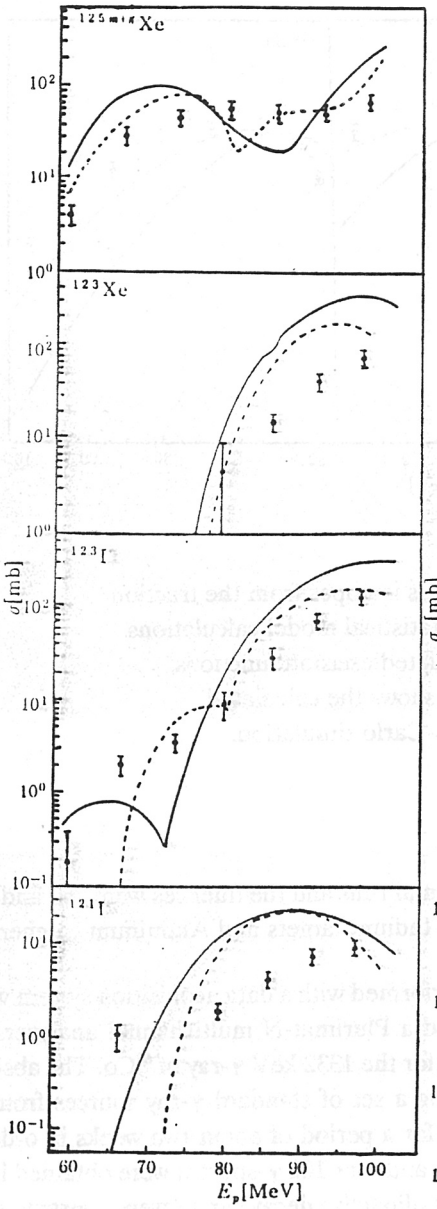

FIG. 2
As in Fig.1, for Xe and I isotopes.

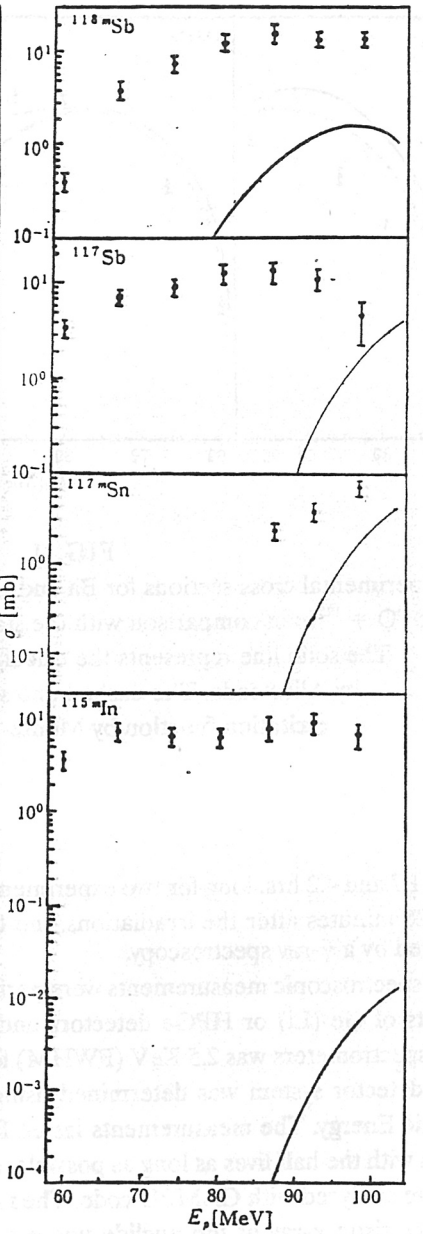

FIG. 3
As in Fig.1, for Sb, Sn and In isotopes.

3. RESULTS AND DISCUSSION

In this work 21 reaction products ranging in mass numbers from A = 115 (^{115m}In) to A = 129 (^{129}Cs) were identified and the excitation functions for these nuclides were obtained. The experimental errors include the uncertainties of the efficiency of the detectors, uncertainties in the measurements of the beam current and the target thickness, in the calculation of the photoelectric peak areas and in the fit of the decay curves, and finally in the counting statistical error. The statistical error of the production cross sections for most of the nuclides are about 15%, except a few nuclides for which larger errors are involved due to a very low counting rate.

The theoretical calculation for the production cross sections of the residues was carried out on a VAX computer by using the statistical model evaporation code Alice[9] (a modified new version[10]). The calculation indicates that the shell correction has only a weak effect on our calculated results whereas the level density parameter is very sensitive. Just as Misaelides had done in the study of the excitation functions for ^{12}C + ^{93}Nb reaction, we used the level density parameter of $a = A/15.0$ instead of $a = A/8.0$ which is commonly used. In the calculation with Monte Carlo simulation[11], the nuclear masses were taken from Refs.[12,13]. At each incident energy the relevant sequential evaporation processes were simulated for 10,000 times. Because the cross sections of all the productions determined in the experiment are cumulative yields except ^{118m}Sb, the theoretical calculations were compared with the experimental values after summing the independent yields of the relevant products in the mass chain.

According to the degree of the agreement between the theoretical and experimental excitation functions, the products can be classified into the following three groups:

(1) ^{129}Cs, ^{128}Ba, ^{127}Ba, ^{127}Cs, ^{127}Xe, and ^{126}Ba:

For these nuclides with the mass numbers close to that of the compound nucleus, the excitation functions have the typical shape of neutron evaporation from a compound nucleus. The maximum values of the excitation functions for adjacent nuclides differ by approximately 10--15 MeV as expected for the emission of an additional neutron. It can be seen that these nuclides are formed mainly through a process of neutron evaporation from the compound nucleus followed by the sequential β^+ decay. However, there also exist some contributions of the direct evaporation of pxn or α from the compound nucleus. The representative excitation functions for ^{128}Ba, ^{127}Cs and ^{126}Ba are plotted in Fig.1. The statistical model evaporation code Alice can basically reproduce the shape of the experimental excitation functions. Except for ^{126}Ba, the peak values of the experimental excitation functions for all the isobars with A = 127 and ^{128}Ba are close to the theoretical values. However, the calculated peak positions are about 10 MeV lower than the experimental ones. If one introduces the concept of effective excitation energy or makes a correction for Coulomb barrier of the incident system, the calculate excitation functions would be shifted towards the high energy side. As a result, the agreement between the calculated and experimental values is expected to be improved. It is very interesting to note that the calculated values by Monte-Carlo simulation well agree with the experimental results for ^{127}Cs, and ^{128}Ba. Even in the worst case of ^{126}Ba, the discrepancy between the experimental and calculated values is only a factor of 3--4.

(2) ^{125}Cs, $^{125g+m}$Xe, ^{123}Xe, ^{123}I, ^{122}Xe, ^{121}I, ^{121g}Te, ^{120g}I and ^{119m,g}Te:

The mass numbers of these nuclides are in the transition region from the compound ucleus to the target nucleus. In the energy region to be investigated, the cross sections of these nuclides increase with increasing incident energies. Fig.2 shows 4 representative excitation functions for $^{125m+g}$Xe, ^{123}Xe, ^{123}I and ^{121}I. In most cases both Alice code and Monte-Carlo calculation give fair

agreements with the measured results, withte-Carlo calculations yielding greater accuracy than the Alice code. It means that the formation of the compound nucleus followed by the evaporations of αxn, $2pxn$, $2\alpha xn$ (and the sequential β^+ decay) is the main mechanism responsible for the production of these nuclides. However large deviation of the experimental excitation functions from the calculated results can be found for a number of lighter nuclides such as ^{121}Te, ^{121}I and ^{120g}I. Misaelides also observed similar phenomena in his work[5] and attributed those discrepancies to the existence of an incomplete fusion process. We think that the large deviation is not the result of a contribution from incomplete fusion. Although the occurrence of the incomplete fusion leads to the decrease of the cross section of complete fusion, it does not necessarily decrease the cross sections of those nuclides involved in the evaporation of more neutrons. On the contrary, the cross sections will probably increase because such a reaction takes place at the peripheral region. As shown in this work the suggestion is supported by the fact that the cross sections for ^{123}Xe and ^{121}I are conversely close to or even higher than the values calculated by the theory at the lowest incident energy. Moreover, from Fig.1 and Fig.2 it can be seen that the agreement between the experimental and calculated excitation functions for the nuclides far from the ß stability line, such as ^{126}Ba, ^{132}Xe, ^{121}I, is not as good as those for their heavier isotopes ^{128}Ba, $^{125g+m}$Xe and ^{123}I. The calculated values are 5--6 times larger than the experimental results, which indicates that the statistical model overestimates the cross sections for the lighter isotopes. One of the possible reasons is that the statistical γ emission has not been taken into account in the theoretical calculations. It is helpful to take this into account when estimating the production cross sections of the new nuclides far from the ß stability line.

(3) ^{118m}Sb, ^{117}Sb, ^{117m}Sb, ^{116m}Sb and ^{115m}In:

The nuclides with the mass numbers close to that of the target are formed by a direct reaction rather than the evaporation of the compound nucleus. Accordingly, neither Alice code nor Monte-Carlo calculation can reproduce the experimental results for these nuclides (see Fig.3). The conclusion is supported by our previous work in which the angular distributions peaked at 40° for the residues ^{117}Sb and ^{118m}Sb[4].

4. CONCLUSION

The excitation functions for 21 residues from the reaction of ^{16}O ions with ^{115}In have been determined in an energy region between 51 and 97 MeV using nuclear chemistry techniques. The Monte-Carlo simulation, based on the statistical decay of the compound nucleus, agrees with the experimental measurement better than does the statistical evaporation Alice code. With the exception of residues with mass numbers close to that of the target, the reaction products are formed mainly by the evaporation mechanism of the compound nucleus. For neutron-deficient isotopes far from the ß stability line the deviations between the theoretical and experimental values are remarkably larger than those for the heavier isotopes close to the ß stability line. The residues with the mass numbers close to that of the target are produced with the cross sections much higher than that calculated by the theory, indicating that the direct reaction is the main source responsible for the production of the residues.

The determination of the excitation functions is one component in studying the reaction mechanisms. However, further investigations, including kinematic measurement, are required to get an insight into the mechanism responsible for the production of all the residues.

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REFERENCES

[1] R. Bimbot et al., *Nuclear Physics*, **A189**(1972)193.
[2] D. J. Parker, J. Asher, T. W. Conlon and I. Nagib, *Phys. Rev.* **C30**(1984)143.
[3] D. J. Parker, J. J. Hogan and J. Asher, *Phys. Rev.* **C35**(1985)161.
[4] Shun Tongyu et al., *High Energy Phys. and Nucl. Phys.* (in Chinese) **11**(1987)660.
[5] *P. Misaelides Radiochimica Acta.* **28**(1981)1.
[6] L. C. Northcliffe and R. F. Schilling, *Nucl. Data Tables*, 7A(1970).
[7] Li Wenxin et al., *Atomic Energy Science and Technology* (in Chinese), (to be publish).
[8] U. Reus, W. Westmeier and I. Warnecke, *At. Data Nucl. Data Tables* **29**(1983)1.
[9] M. Blann and J. Bisplinghoff, Report COO-3494-27 (1975), University of Rochester, N. Y.
[10] Xu Shuwei et al. *Annual of Institute of Modern Physics* , (1987)169.
[11] Wang Sufang et al. *Annual of Institute of Modern Physics* , (1987)71.
[12] A. H. Wapstra, K. Bos, *Atomic Data and Nuclear Data Tables* , **19**(1977)185.
[13] P. Möller and J. R. Nix, "Nuclear Masses from a Unified Macroscopic-Microscopic Model", (1986, no publish).