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Effect of Angular Momentum Transfer on Isomeric Cross-Section Ratio

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Abstract

The isomeric cross-section ratios are calculated for the reactions $^{113}In(a,n)^{116}Sb^{m,g}$, $^{115}In(\alpha,3n)^{116}Sb^{m,g}$, $^{116}Sn(p,n)^{116}Sb^{m,g}$, $^{116}Sn(d,2n)^{116}Sb^{m,g}$, $^{117}Sn(p,2n)^{116}Sb^{m,g}$, $^{115}In(\alpha,n)^{118}Sb^{m,g}$, $^{116}Sn(\alpha,pn)^{118}Sb^{m,g}$, $^{118}Sn(p,n)^{118}Sb^{m,g}$, $^{118}Sn(d,2n)^{118}Sb^{m,g}$, $^{119}Sn(p,2n)^{118}Sb^{m,g}$, $^{117}Sn(n,p)^{117}In^{m,g}$, $^{118}Sn(p,a)^{115}In^{m,g}$ over the energy ranges from threshold up to 40 MeV using the nuclear reaction code EMPIRE 3.1. It is found that isomeric cross-section ratio depends on the spins of ground and isomeric states of residual nucleus as well as the incident energy. The isomeric cross-section ratio increases slowly for the cases where larger angular momentum (ΔJ) is carried away by the emitted particle and increases sharply when ΔJ is smaller.

Key words: Nuclear reaction, isomeric cross-section ratio, angular momentum transfer, spin dependence, EMPIRE.

Introduction

In nuclear reaction, the relative population of isomeric state is generally expressed in terms of isomeric cross-section ratio (ICR) which is defined as the ratio of isomeric cross-section to the total cross-section ($\sigma_m/(\sigma_{m+}\ \sigma_g)$). The study of ICR gives important information about the nuclear reaction mechanism, particularly the energy and angular momentum transfer during the reaction process as well as the progress of the nuclear reactions. ICR is expected to depend on several factors, such as spin of the target nucleus, type and energy of the projectile used, type of the emitted particle, and, more importantly, on the spins of the isomeric states concerned[1-3]. Satheesh *et al*[4-5] reported that ICR found to depend on the magnitude of spins of the ground and isomeric states, energy difference between the levels, presence of intermediate states and some dependence on decay modes as well as on the onset of pre-equilibrium emission and also suggested that further study is needed to justify the exact dependence. In this background, we studied a set of nuclear reactions to investigate the dependence of ICR on various factors like relative spin of the isomeric and ground state, angular momentum carried away by the ejectiles, single particle or multiparticle emission. Statistical nuclear reaction code EMPIRE 3.1[6] is used for the analysis. The experimental data available from the literature[7-12] are used for verifying the validity of theoretical predictions.

Model Calculation: In the present study nuclear reaction code EMPIRE 3.1 which makes use of the Hauser-Feshbach and the Exciton model formalisms has been used. Hauser-Feshbach formalism helps in calculating the ground and isomeric cross-sections separately. The code accounts for the major nuclear reaction models, such as Spherical and deformed Optical Model including coupled-channels code ECIS06, Soft-rotator deformed Optical Model including coupled-channels code OPTMAN, Hauser-Feshbach statistical model including HRTW width fluctuation correction, and the optical model for fission with partial damping, Quantum-mechanical MSD TUL model (codes ORION and TRISTAN), and MSC NVWY model, Exciton model with Iwamoto-Harada cluster emission and Kalbach systematic angular distribution (code PCROSS), Hybrid Monte Carlo preequilibrium model (code DDHMS). A comprehensive library of input parameters based on the RIPL-3 covers nuclear masses, optical model parameters, ground state deformations, discrete levels and decay schemes, level densities, fission barriers and γ-ray strength functions. The experimental data is automatically retrieved from EXFOR/CSISRS library. The results can be converted into the ENDF-6 format using the accompanying EMPEND code. The package contains the full EXFOR library of experimental data in computational format C4 that are automatically retrieved during the calculations.

In the present calculation Optical model parameters due to A. J. Koning[13] have been used for both protons and neutrons that due to McFadden and Satchler[14] for alpha. Discrete levels were taken from the RIPL-3 level file based on the 2007 version of ENSDF, width fluctuations are calculated within HRTW up to 3.00 MeV, Exciton model calculations are done with code PCROSS, cluster emission in terms of the Iwamoto-Harada model. Mean free path parameter in PCROSS set to 1.5. These theoretical calculations are compared with the available experimental data.

Systems under study: The isomeric pairs $^{115}In^{m,g}$, $^{117}In^{m,g}$, $^{116}Sb^{m,g}$ and $^{118}Sb^{m,g}$ are produced through the reactions $^{118}Sn(p,a)^{115}In^{m,g}$, $^{117}Sn(n,p)^{117}In^{m,g}$, $^{113}In(a,n)^{116}Sb^{m,g}$ and $^{118}Sn(p,n)^{118}Sb^{m,g}$ in the respective order. The nuclei $^{115}In^{m,g}$ and $^{117}In^{m,g}$ have isomeric state spin less than ground state spin while others two have isomeric spin greater than that of ground state spin. While studying the variation of isomeric cross-section ratio with incident energy, it is noticed that ICR also has some dependence on the angular momentum carried away by the emitted particles. Inorder to study this effect in detail the formation of isomeric pairs $^{116}Sb^{m,g}$ and $^{118}Sb^{m,g}$ through the reaction channels $^{113}In(a,n)^{116}Sb^{m,g}$, $^{115}In(\alpha,3n)^{116}Sb^{m,g}$, $^{116}Sn(p,n)^{116}Sb^{m,g}$, $^{116}Sn(d,2n)^{116}Sb^{m,g}$, $^{117}Sn(p,2n)^{116}Sb^{m,g}$, $^{115}In(\alpha,n)^{118}Sb^{m,g}$, $^{116}Sn(\alpha,pn)^{118}Sb^{m,g}$, $^{118}Sn(p,n)^{118}Sb^{m,g}$, $^{118}Sn(d,2n)^{118}Sb^{m,g}$ and $^{119}Sn(p,2n)^{118}Sb^{m,g}$ are considered.

Results and Discussion

In the present study many isotopes having isomeric pairs are formed in each case with various combinations of nuclear parameters like level spin, energy, life time, decay mode etc. The nuclei of interest in the present work are $^{115}In^{m,g}$, $^{117}In^{m,g}$, $^{116}Sb^{m,g}$ and $^{118}Sb^{m,g}$. The cross-sections for the formation of these isomeric pairs are calculated for the incident energy ranges from reaction threshold up to 40 MeV using EMPIRE 3.1 and the isomeric cross-section ratios are plotted against incident energy in figure-1 along with available experimental data. The prediction of the present calculations agree well with the literature data.

As can be seen that the isomeric cross-section ratio depends primarily on incident energy and relative spins of the isomeric pairs. In the case of $^{118}Sb^{m,g}$ and $^{116}Sb^{m,g}$ spin of isomeric state is greater than that of ground state while for $^{117}In^{m,g}$ and $^{115}In^{m,g}$ spin of isomeric state is less than that of ground state. The spin values of the ground and isomeric states of these nuclei are given in the table.1. From figure-1, it can be notice that ICR

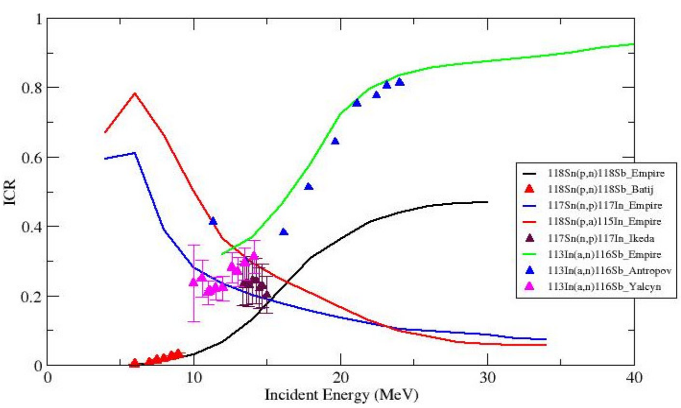

Figure-1
ICRs for the reactions $^{118}Sn(p,n)^{118}Sb$, $^{113}In(\alpha,n)^{116}Sb$, $^{17}Sn(n,p)^{117}In$ and $^{118}Sn(p,a)^{115}In$ for incident energy from threshold to 40 MeV

Table-1
Spins of ground and isomeric states

Nuclide	Spin	
	Ground state	Isomeric state
^{118}Sb	1+	8-
^{116}Sb	3+	8-
^{117}In	9/2+	1/2-
^{115}In	9/2+	1/2-

increases with incident energy for the case of ^{118}Sb and ^{116}Sb and latter it gets saturated whereas for ^{115}In and ^{117}In it decreases with incident energy and latter remains almost constant for further increase in energy. The EMPIRE calculation satisfactorily reproduces the available experimental data within the error limit for the reactions $^{118}Sn(p,n)^{118}Sb$, $^{113}In(\alpha,n)^{116}Sb$ and $^{17}Sn(n,p)^{117}In^{m,g}$ and taking this as reference ICR is calculated for $^{118}Sn(p,a)^{115}In^{m,g}$ for which no experimental data is obtained. As indicated by Satheesh *et al*[4-5], a nucleus with isomeric spin greater than the ground state spin, the isomeric cross-section ratio increases steadily upto certain energy and thereafter it gets saturated. This is due to the fact that as the energy of the incident particle increases, the state with lower spin gets populated initially and thereafter the higher spin state getting more and more populated and finally reaches an equilibration between the states. In the case of nuclei with isomeric spin less than that of ground state the isomeric cross-section ratio shows an initial increase with incident energy and thereafter it decreases up to certain energy and it remains almost constant on further increase of incident energy. Since at very low energy the ground state start populating irrespective of the spin state and after that sufficient energy is available for the population of the isomeric state the system prefer lower spin state first and then started populating the higher spin state accordingly and later get equilibrated as the previous case.

In order to see the effect of angular momentum transfer in the reactions, the ICRs for $^{116}Sb^{m,g}$ and $^{118}Sb^{m,g}$ are calculated for various channels and are plotted in figure-2(a) and figure-2(b) respectively. It can be seen from figure-2(a) that ICR for the (α,n) and $(\alpha,3n)$ reactions increases sharply with the incident energy while that for other reactions increases slowly. In the case of reactions $^{113}In(\alpha,n)^{116}Sb$ and $^{115}In(\alpha,3n)^{116}Sb$ the angular

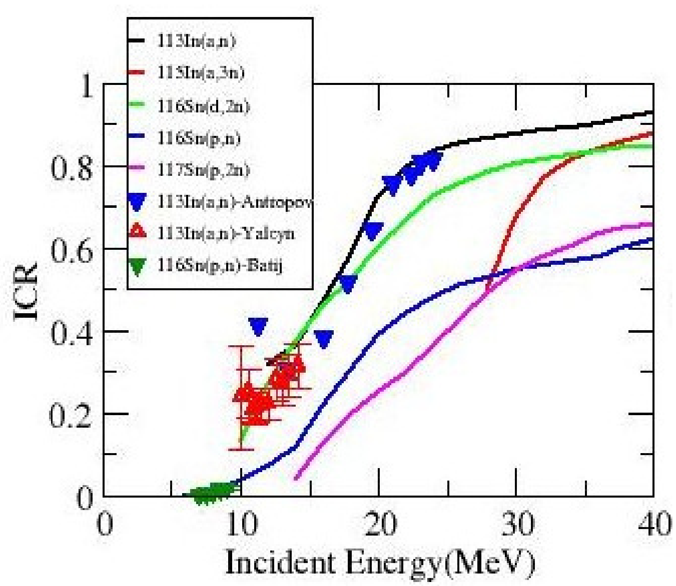

Figure-2(a)
ICR for the production of ^{116}Sb

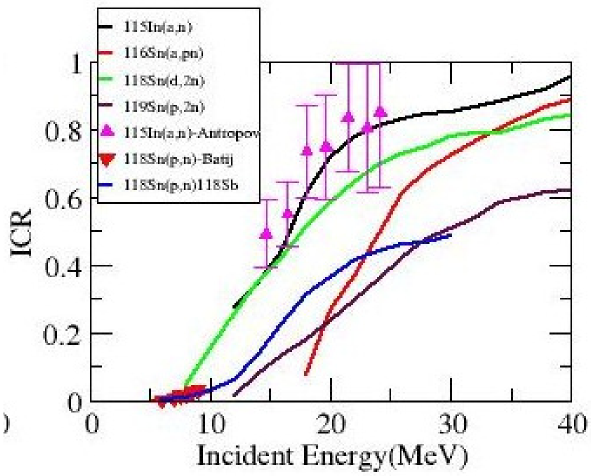

Figure-2(b)
ICR for the production of ^{118}Sb

Table-2
Possible values of angular momentum transferred by the emitted particles

Reaction	Possible ΔJ
^{116}Sn(p,n)^{116}Sb	7,8
^{117}Sn(p,2n)^{116}Sb	6,7,8,9
^{113}In(a,n)^{116}Sb	3,4
^{115}In(a,3n)^{116}Sb	2,3,4,5
^{116}Sn(d,2n)^{116}Sb	6,7,8,9
^{118}Sn(p,n)^{118}Sb	7,8
^{119}Sn(p,2n)^{118}Sb	6,7,8,9
^{115}In(a,n)^{118}Sb	3,4
^{116}Sn(a,pn)^{118}Sb	7,8,9
^{118}Sn(d,2n)^{118}Sb	6,7,8,9

Momentum ΔJ, transfered by the emitted particle is smaller than that for other reactions. Similarly, in Figure- 2(b), the ICR for ^{115}In(α,n)^{118}Sb reaction increases sharply but for other reactions it shows slow increase. Here ΔJ is smaller for ^{115}In(α,n)^{118}Sb than that for other reactions. From this it can be say that for the cases where ΔJ is small, ICR increases sharply and vice versa. This indicates that when the emitted particle carries larger angular momentum, the higher spin isomer is slowly populated.

Conclusion

It is found that the isomeric cross-section ratio critically depends on the spins of ground state and isomeric state as well as the incident energy. At extremely low energy, the ground state is preferentially populated irrespective of the spin state. As the energy increases, the higher spin state gets more populated. The ICR increases slowly for the cases in which angular momentum carried away by the emitted particle (ΔJ) is large and it increases sharply when ΔJ is smaller.

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