Spin-dependent observables in surrogate reactions

Satoshi CHIBA,

Osamu IWAMOTO, and Yoshihiro ARITOMO

Japan Atomic Energy Agency, Tokai, Naka, Ibaraki 319-1195, Japan

(Dated: January 15, 2013)

Abstract

Observables emitted from various spin states in compound U nuclei are investigated to validate usefulness of the surrogate reaction method. It was found that energy spectrum of cascading γ-rays and their multiplicities, spectrum of evaporated neutrons, and mass-distribution of fission fragments show clear dependence on the spin of decaying nuclei. The present results indicate that they can be used to infer populated spin distributions which significantly affect the decay branching ratio of the compound system produced by the surrogate reactions.
I. INTRODUCTION

Surrogate reaction is a method to measure neutron cross sections of unstable or rare nuclei, for which preparation of enough amount of samples is extremely difficult or practically impossible. For example, neutron cross section of minor actinides, long-lived fission products or branch-point nuclei of the s-process nucleosynthesis may be measured without having them directly but instead by preparing samples consisting of nascent stable isotopes. Because of this nature, the surrogate method can be a unique tool to investigate neutron cross sections of nuclei for direct measurement using neutrons is difficult. See, e.g., Ref. [1] for recent results and references therein.

By the surrogate method, the same compound nuclei populated in desired neutron-induced reactions are generated by (multi) nucleon transfer reactions, and decay branching ratios from them are measured. From this information, we can determine desired neutron cross sections either 1) by directly multiplying total reaction cross section to the branching ratio (surrogate absolute method) or 2) as a ratio to a decay branching ratio of a compound system for which neutron-induced cross section leading to it is known (surrogate ratio method, SRM). Generally speaking, however, decay branching ratios are sensitive to the spin value of the decaying compound system. Therefore, a great care must be paid to the condition in which the surrogate method can yield the correct neutron cross sections[2, 3].

Recently, SC and OI have shown that SRM works if 1) spin distributions in 2 compound nuclei populated in the surrogate ratio method are equivalent, 2) spin values populated by the surrogate reaction is not much larger than 10 (in unit of $\hbar$), which is hardly populated in neutron-induced reactions, and 3) $J^\pi$ by $J^\pi$ convergence of branching ratio, called weak Weiskopf-Ewing condition, is achieved[4]. The condition 1) is expected to be satisfied by selecting a pair of nuclei having similar discrete level structure. The condition 3) can be verified by a statistical model calculation. Then, the condition 2) must be verified which is the subject of this work. These theoretical conditions, altogether, then should be considered to design experimental equipments and setups.

In this work, we have investigated 3 observables which are possibly sensitive to the spin values of decaying nuclei, namely, energy spectrum of evaporated neutrons, energy spectra and multiplicity of emitted $\gamma$-rays and fission fragment mass distributions (FFMDs). In the next section, computational methods are explained, which is followed by their results and
II. COMPUTATIONAL METHODS

The details of this calculation is given elsewhere[5, 6], so only a simple explanation is given here.

As explained in the introduction, it is enough to estimate spin values in the step of approximately $10\hbar$. We then took an example of compound nucleus of $^{238}\text{U}$ at excitation energy of 10 MeV, and calculated spectra of emitted neutrons and $\gamma$-rays at $J^\pi=0^+, 5^+, 10^+$ and $20^+$ by the Hauser-Feshbach theory[7]. Nonetheless to say, it corresponds to neutron-induced reactions on $^{237}\text{U}$, or surrogate reaction such as $^{236}\text{U}(^{18}\text{O},^{16}\text{O})^{238}\text{U}$. The calculation was carried out by CCONE code system[5]. Parameters used to generate JENDL actinide file 2008[8] were used.

Another calculation was also carried out. The FFMD from $^{240}\text{U}$ was calculated by a 3-dimensional Langevin method on a potential energy surface calculated by the two-center shell model[6, 9–11]. The total potential energy consists of a macroscopic rotating liquid-drop model which gives the bulk potential energy for arbitrary spin states and a microscopic shell- and pairing-correction part:

$$V(q, J, T) = V_{LD}(q) + \frac{\hbar^2}{2\mathcal{I}(q)} J(J + 1) + V_{SH}(q, T)$$

where $V(q, J, T)$ denotes the total potential energy for deformation $q$, spin $J$ and temperature $T$, $V_{LD}(q)$ potential energy of the finite-range liquid-drop model. The symbol $\mathcal{I}(q)$ denotes the moment of inertia of a rigid body at deformation $q$, while $V_{SH}$ designates the shell- and pairing-correction energy at temperature $T$. The temperature is related to the excitation energy $E^*$ as

$$T = \sqrt{\frac{E^*}{a}}$$

where $a$ denotes the level density parameter. The shell effect has a temperature dependence expressed by a dumping factor

$$\phi = e^{-\frac{E^*}{E_d}}.$$  

The shell dumping energy $E_d$ was chosen as 20 MeV[12], which was used in our previous calculations[6]. The deformation $q$ represents a set of parameters such as elongation, mass
asymmetry and fragment deformation used to express complicated shapes which appear during the fission process. The \( J(J + 1) \) dependence in the above formula changes the liquid-drop energy, which changes the smooth landscape of the potential energy surface on which collective variables \( q \) are driven as a function of time. On the contrary, the shell correction does not depend on \( J \) in our calculation. The nucleus \(^{240}\text{U}\) was selected since we have a preliminary experimental FFMD data, which was used to verify the general accuracy of our calculation.

III. RESULTS AND DISCUSSION

The calculated energy spectra of evaporated neutrons and cascading \( \gamma \)-rays are shown in Figs. 1 and 2, respectively. They do not include contributions from fission events, which can be eliminated by applying veto in actual experiments.

In Fig. 1 we notice that neutrons are emitted up to energy of about 4 MeV for low spin values. The highest energy neutrons show some irregular energy distributions reflecting the discrete level structure of \(^{237}\text{U}\). When the spin is increased to 10, the maximum energy is decreased to slightly less than 3.8 MeV, and the spectra becomes smoother. For \( J=20 \), the maximum neutron energy is further reduced to 3 MeV. The decrease of the maximum neutron energy comes from the fact that the level densities having large spins are rather low below excitation energy around 4 MeV. Therefore, if the surrogate reactions produces only the compound states having spin more than 10, it will be signaled by energy spectra of evaporated neutrons softer than those of normal neutron-induced reactions (or corresponding statistical model calculation).

The same trend is observed for the energy spectra of cascading \( \gamma \)-rays. In Fig. 2 both the \( \gamma \)-rays leading to ground-states of \(^{238}\text{U}\) and \(^{237}\text{U}\) are shown separately as \((n,\gamma)\) and \((n,n'\gamma)\) spectra. Difference of the \( \gamma \)-ray energy spectra for both reactions at \( J=0 \) and 10 are visible. The spin-dependence clearly affects the total \( \gamma \)-ray multiplicities, which is shown in Fig. 3. \( J=0 \) gives multiplicity of about 2, while it increases to 5 for \( J=10 \), and more than 10 for \( J=20 \). This is due to the fact that higher-energy \( \gamma \) transition leading to low-lying levels is hindered when \( J \) is large due to the fact that high \( J \) states are rare at low excitation energy.

The FFMD from \(^{240}\text{U}\) is shown in Fig. 4. In this mass region, FFMD show typical asymmetric distribution for low \( J \) values, which is well reproduced by our calculation. Then,
we put \( J = 10 \) and 20, and generated many Langevin trajectories and compared them with the \( J = 0 \) results. We can notice that the peak of the asymmetric mass division does not change, but the symmetric components are slightly enhanced when \( J \) becomes 10 and 20. It can be interpreted that when \( J \) becomes larger, the liquid-drop energy, which gives minimum at the symmetric division, increases, and the overall effect is to enhance the symmetric fission. If this is really the case, the FFMD data, which can be obtained in our forthcoming experiments, can be used to estimate the spin distributions populated in surrogate reactions. However, the spin-dependence of the FFMD pointed out here is not a phenomena confirmed yet. Therefore we must place a special care on this result, although it may give a new insight into the understanding of the fission mechanism.

IV. CONCLUDING REMARKS

We have investigated possible observables which can signal the spin (distribution) of compound nuclei populated in surrogate reactions. The energy spectra of evaporation neutrons and cascading \( \gamma \)-rays clearly show difference for spin states of \( J = 0 \) and 10 or above. Generally, the high-spin states produces softer neutron and \( \gamma \)-ray spectra. This is due to the spin-dependence of level density. The \( \gamma \)-ray multiplicity increases as the spin of decaying compound nucleus increases since high-energy transitions leading to low-spin states near the ground state are hindered. We also found that fission fragment mass distribution may have spin dependence. This last point may become an interesting issue from the viewpoint of fission physics. We understand that it may not be easy to measure evaporation neutrons and cascading \( \gamma \)-rays in the presence of fission events. If so, we can use lighter, non-fissioning target to measure these quantities. These results, altogether, are used to design the forthcoming experiments and understanding the surrogate reaction and its relation to desired neutron-induced reaction will be enhanced.

Acknowledgments

The authors are grateful to Dr. K. Nishio for helpful discussions. Present study is the result of “Development of a Novel Technique for Measurement of Nuclear Data Influencing the Design of Advanced Fast Reactors” entrusted to Japan Atomic Energy Agency (JAEA)
by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT).

[1] G. Kessedjian et al., Phys. Lett. B 692, 297-301(2010).
[2] N.D. Scielzo et al., Phys. Rev. C 81, 034608-1-12(2010).
[3] B.L. Goldblum, S.G. Prussin, L.A. Bernstein, W. Younes, M. Guttormsen, and H.T. Nyhus,
Phys. Rev. C 81 054606-1-7(2010).
[4] S. Chiba and O. Iwamoto, Phys. Rev. C, 81, 04604-1-6 (2010).
[5] O. Iwamoto, J. Nucl. Sci. Technol., 44, 678(2007).
[6] Y. Aritomo, S. Chiba and K. Nishio, arXiv:1009.5924v1 (2010) [nucl-th].
[7] W. Hauser and H. Feshbach, Phys. Rev. 87, 366-373(1952).
[8] O. Iwamoto, T. Nakagawa, N. Otsuka, S. Chiba, K. Okumura, G. Chiba, T. Ohsawa and
K. Furutaka, J. Nucl. Sci. Technol., 46, 510(2008).
[9] J. Maruhn and W. Greiner, Z. Phys. A 251, 431 (1972).
[10] K. Sato, A. Iwamoto, K. Harada, S. Yamaji, and S. Yoshida, Z. Phys. A 288, 383 (1978).
[11] Y. Aritomo, Phys. Rev. C 80 (2009) 064604.
[12] A.N. Ignatyuk, G.N. Smirenkin, and A.S. Tishin, Sov. J. Nucl. Phys. 21, 255 (1975).
FIG. 1: (Color online) Energy spectra of evaporated neutrons from various spin states of $^{238}$U at excitation energy of 10 MeV.
FIG. 2: (Color online) Energy spectra of cascading $\gamma$-rays from various spin states of $^{238}\text{U}$ at excitation energy of 10 MeV.
FIG. 3: Multiplicities of $\gamma$-rays emitted from various spin states of $^{238}$U at excitation energy of 10 MeV.
FIG. 4: (Color online) Fission fragment mass distribution (FFMD) emitted from $J=0$, 10 and 20 states of $^{240}\text{U}$ at excitation energy of 10 MeV.