Recoil Properties of Radionuclides Formed in Photospallation Reactions on Complex Nuclei at Intermediate Energies

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A short review is given on our studies of recoil properties of radionuclides formed in photospallation reactions induced by bremsstrahlung of end-point energies (E_0) from 600 to 1100 MeV, in which the thick-target thick-catcher method was employed. The measurements have been successful on 14, 24, 26, 31, 21 and 20 nuclides from ^{nat}V, ^{nat}Cu, ^{93}Nb, ^{nat}Ag, ^{nat}Ta, and ^{197}Au, respectively. Reflecting the resonance character in a photonuclear reaction, the mean ranges *FW* and *BW* in the forward and backward directions, respectively, are E_0-independent at the studied energies and classified into two groups accounting for the (γ,*x*n) ($x \geq 1$) and (γ,*x*n*y*p) (x, $y \geq 1$) processes. The forward-to-backward ratios (F/B) are independent of the mass difference (ΔA) between a product (A_p) and a target (A_t) and also of A_t. The kinematic properties of the product nuclei were analyzed by the two-step vector velocity model. The forward velocity v after the first step of photon-reaction is quite different from that of proton-reaction at proton energies of $E_p \leq 3$ GeV, though the difference disappears at higher energies. On the other hand, the mean kinetic energy T of the residual nucleus in the second step is almost equal to that of proton-reaction irrespective of E_p. A comparison with T values calculated by the PICA (Photon-Induced Intranuclear Cascade Analysis) code at E_0 = 400 MeV was also performed. It was found that although the code well reproduces the experimental results of ^{nat}V and ^{nat}Cu, the same calculation for heavier targets gives T values lower than the experimental results, indicating some nuclear-structure effect, such as a medium effect notably at $A_t \geq 100$. An average kinetic energy carried off by the emitted particles $\varepsilon_s = T/(\Delta A/A_t)$ of both photon- and proton-reactions seem to increase with an increase of A_t up to around A_t = 100, and become almost constant at larger A_t, implying some change in the nuclear structure effect in this heavy target region, as also found in our recent yield measurements of photospallation and photopion reactions. The ε_s values of photon-reaction appear to be slightly lower than those of proton-reactions for ^{nat}Ag, ^{nat}Ta, and ^{197}Au. This difference may indicate the lower excitation energy left after the first step in photon-reactions than in proton-reactions.

1. Introduction

The photonuclear reactions at low and intermediate energies are initiated by three types of resonance processes: giant resonance, quasi-deuteron resonance, and (3,3) resonance. These initial interactions of photons with nuclei are purely electromagnetic and are quite different from that of hadron-induced reactions, which are initiated by the strong interaction between the projectile and a nucleon in the target nucleus. It seems interesting to pursue whether there exist similarities or dissimilarities between the final steps of these two nuclear reactions.

In our group nuclear recoil experiments using the thick-target thick-catcher method were applied to photonuclear reactions in order to examine the effect due to a difference in the initial interactions between photon-induced reaction and hadron-induced one dynamically [1–3]. The possibility of this technique was first successfully examined with photospallation reactions on ^{nat}Cu at bremsstrahlung end-point energies (E_0) of 250–1000 MeV [1], because the reaction yields were previously well investigated at E_0 = 100–1000 MeV by Shibata *et al.* [4]. The observed recoil properties of the photospallation products from ^{nat}Cu were found to be E_0-independent at $E_0 \geq 600$ MeV and classified into two groups accounting for the (γ,*x*n) and (γ,*x*n*y*p) processes. Also, the PICA (Photon-induced Intranuclear Cascade Analysis) code [5, 6] at E_0 = 400 MeV was shown to reproduce well the kinetic energies (*T*) of the product nuclei, except for the (γ,*x*n) products. Furthermore an extended work of the recoil technique to the photospallation products from ^{nat}Ag, ^{nat}Ta, and ^{197}Au at the same energy region [2] showed the similar trends as found in ^{nat}Cu, though they were preliminary in terms of the replicated experiments and the detailed data analyses. Recently, the kinematic properties of ^{24}Na from the ^{27}Al(γ,2pn)^{24}Na reaction at E_0 = 60–1100 MeV were analyzed by the two-step vector model [7] and compared with those from the ^{27}Al(p,3pn) reactions [3]. The recoil velocity *v* after the first step of the photon-reaction was found to be quite different from those of the proton-induced reaction, reflecting the difference in the reaction mechanism at the initial step. On the other hand, the mean kinetic energies *T* of ^{24}Na in the second step at $E_0 \geq 600$ MeV appeared to be equal to those at 0.18–300 GeV-protons.

More recently we reported a result of an extensive recoil study of the photospallation reactions on ^{nat}V, ^{nat}Cu, ^{93}Nb, ^{nat}Ag, ^{nat}Ta, and ^{197}Au at $E_0 \geq 600$ MeV [8]. We have accumulated the additional data for ^{nat}Cu, ^{nat}Ag, ^{nat}Ta, and ^{197}Au, and added ^{nat}V and ^{93}Nb as new targets since the previous works [1–3]. The kinematic parameters such as *v* and *T* obtained from an analysis based on the two-step vector model [7] were then discussed systematically with respect to E_0 and A_t, by referring to the proton results as well as to the PICA calculations at E_0 = 400 MeV. The following is a short review of these studies.

2. Experimental

Irradiations by bremsstrahlung beams with end-point energies of E_0 = 600–1100 MeV were carried out using the 1.3-GeV electron synchrotron of the High Energy Accelerator Research Organization (KEK) at Tanashi. The targets consisted of a stack of 20–50 sets of a high-purity target metal foil of 25 x 25 mm^2 in size. The target thicknesses were 14 mg/cm^2 for ^{nat}V, 22 mg/cm^2 for ^{nat}Cu, 24 mg/cm^2 for ^{93}Nb, 32 mg/cm^2 for ^{nat}Ag, 32 mg/cm^2 for ^{nat}Ta, and 90 mg/cm^2 for ^{197}Au. Each metal foil was sandwiched by one pair of 3.5–7.0 mg/cm^2 thick Mylar foils of the same size, which collected the recoil nuclei in the forward or backward directions with respect to the beam. The photon intensities evaluated from the monitor reaction of ^{27}Al(γ,2pn)^{24}Na were 10^9–10^{10} equivalent quanta per second (eq.q./s). The typical irradiation times were 3 h for ^{nat}V, ^{nat}Cu, and ^{93}Nb, 4 h for ^{nat}Ag and ^{nat}Ta, and 5 h for ^{197}Au. After irradiation, some selected target foils and all of the forward and backward catcher foils from one target pile were collected separately, and assayed for radioactivities nondestructively with high-purity Ge detectors.

3. Results and Discussion

Radioactivities of 14, 24, 26, 31, 21 and 20 nuclides produced from ^{nat}V, ^{nat}Cu, ^{93}Nb, ^{nat}Ag, ^{nat}Ta, and ^{197}Au, respectively, have been identified both in the target and catcher foils [8]. From the fractions of each nuclide measured in the forward and backward catcher foils, expressed as $F = N_F/(N_F + N_B + N_{target})$ and $B = N_B/(N_F + N_B + N_{target})$, *N* being the number of atoms, respectively, the effective mean ranges, *FW* and *BW*, in the targets were obtained by multiplying the target thickness *W* in units of μg/cm^2. As found previously [1–3], the *FW* and *BW* values observed in the present work are independent of E_0 above 600 MeV. This E_0-independece of *FW* and *BW* is consistent with that of the slope parameter (*P*) in the CDMD formula [4, 9], and indicates that the photons responsible for the production of these nuclides are mostly of energies lower than 600 MeV, and that there is no appreciable change in the reaction mechanism at $E_0 \geq 600$ MeV. Therefore, the following discussion proceeds on the basis of the average quantities at $E_0 \geq 600$ MeV. The *FW* values are higher than the corresponding *BW*, and both increase in parallel with an increase of the mass difference (ΔA) between a product (A_p) and a target (A_t). This increasing trend of *FW* and *BW* with ΔA can be divided into two components: one is a steep increase for the (γ,*x*n) ($x \geq 1$) products mainly produced by the giant resonance absorption; the other is a gentle increase for the (γ,*x*n*y*p) (x, $y \geq 1$) products mainly produced by the quasi-deuteron mechanism and/or the (3,3) resonance absorption. It is interesting to note that the forward-to-backward ratios (*F*/*B*) at $E_0 \geq 600$ MeV are independent of ΔA and also A_t (*F*/*B* = 2–3).

The measured recoil data were used to derive some recoil parameters by means of the vector velocity model embodying the two-step mechanism commonly invoked in high-energy proton reactions. In the present series of work, the two-step vector model developed by Winsberg [7] was employed for this purpose. The analytical details were described in our previous papers [1, 3]. The forward velocity *v* is a good parameter to estimate the momentum transferred to an intermediate nucleus in the first cascade step, and is related to the deposited excitation energy. On the other hand, the average recoil energy *T* imparted to a residual recoiling nucleus is a convenient parameter to investigate the second evaporation step of the reaction.

As an example, the variations of *v* and *T* at $E_0 \geq 600$ MeV are shown as a function of ΔA by large open circles for ^{nat}Cu in Figs. 1a and 1b, respectively. The cascade velocity *v* in the photoreaction increases linearly with an increase of ΔA, indicating that the higher excitation energy is deposited on an intermediate nucleus to form a residual nucleus with a larger ΔA. The kinetic energy *T* also increases almost linearly with an increase of ΔA, as explained by a random-walk theory [10]. Proton results on ^{nat}Cu [11–16] are available at various proton energies (E_p), as indicated in the inset of Fig. 1b. The *v* values at $E_p \leq 3$ GeV (open symbols) are apparently higher than those of the photon-reactions and decrease with an increase of E_p up to 3 GeV. The values at $E_p > 3$ GeV, indicated by closed symbols, are almost the same as those of the photon-reactions. On the other hand, all of the *T* values of the proton-reactions are about the same as those of the photon-reactions, irrespective of E_p.

Based on a comparison with the available proton results for other targets of ^{27}Al, ^{nat}V, ^{93}Nb, ^{nat}Ag, ^{nat}Ta, and ^{197}Au [3, 8], it was found that for typical spallation the *v* values of proton-reactions at $E_p \leq 3$ GeV are higher than those of photon-reactions at $E_0 \geq 600$ MeV, and decrease steeply with an increase of E_p up to around $E_p = 3$ GeV, and become constant at $E_p \geq 3$ GeV. This distinct difference of the *v* values in the two types of nuclear reaction at the lower-energy region may be attributed to the lower momentum transferred in the initial electromagnetic resonance interaction in photon-reactions. The steep decrease of *v* in proton-reactions at $E_p \leq 3$ GeV is due to the increasing nuclear transparency to the incoming proton; the difference disappears at proton energies above 3 GeV, where the momentum transfer in proton-reactions is almost the same as that in photon-reactions. It seems interesting to note that the *v* values for photon-reactions at $E_0 \geq 600$ MeV are almost equal to those for proton-reactions in the limiting region above $E_p = 3$ GeV, though the initial interactions should be quite different from each other. On the other hand, *T* in proton-reactions seems to be independent of E_p in the energy region cited above, and agrees well with those of photon-reactions at $E_0 \geq 600$ MeV. This consistency of the *T* values suggests that the mechanism of the second deexcitation step is very similar in both photon- and proton-reactions, and the memory of the difference in the initial interaction seems not to remain in the second step.

The reproducibility of the kinetic energies *T* of residual nuclei of photospallation by the PICA code [5, 6] at $E_0 = 400$ MeV was examined. The calculated *T* values are indicated by crosses for the nuclides corresponding to the measured ones in Fig. 1b. The calculated *T* values increase with an increase of ΔA in a similar way as the experimental results. The *T* values of the (γ,*x*n) ($x \geq 1$) products are overestimated due to the absence of giant resonance in the PICA code. The PICA calculation reproduces the experimental results of the (γ,*xnyp*) products well for ^{nat}V and ^{nat}Cu, but the code underestimates the experiments for the heavier targets of ^{93}Nb, ^{nat}Ag, ^{nat}Ta, and ^{197}Au, especially at larger ΔA. This trend of the agreement and the disagreement is consistent with the findings from the systematic yield measurements of photospallation by Sarkar *et al.* [9, 17, 18]. The PICA code can reproduce the spallation yields of the medium-mass targets from ^{nat}V to ^{89}Y at E_0 = 400 MeV, but the code gives the yields higher than the observed ones, and results in asymmetric isotopic yield distributions for targets heavier than A_t = 100. The underestimation of the mean kinetic energies and the overestimation of the reaction yields by the PICA code in the heavy target region may imply that the separation energies of nucleons are higher than those assumed in the code.

Winsberg [10] suggested that $\varepsilon_s = T/(\Delta A/A_t)$, which represents the average energy carried off by an evaporated nucleon, is a good parameter to systematize the second step, and found that ε_s is independent of $\Delta A/A_t$ for typical spallation reactions induced by protons. In the present work, the ε_s values were obtained for the (γ,*xnyp*) products in the limiting region at $E_0 \geq$ 600 MeV, and they were found to be independent of $\Delta A/A_t$, as in proton reactions. The average ε_s values for each target are plotted as a function of A_t by open circles in Fig. 2, together with those of the proton-reactions by closed squares based on our compilation [8]. The ε_s values of both the photon- and proton-reactions seem to increase slightly with an increase of A_t up to around A_t = 100 and become almost constant at heavier targets. This A_t-dependent feature of ε_s has not been reported previously as far as we are aware. The suppression of the increasing trend above A_t = 100 may reflect a decrease of the separation energy per nucleon with an increase of A_t from about 8.2 MeV for ^{nat}Ag to 7.0 MeV for ^{197}Au.

It was reported [4, 9] that there are linear relationships between the neutron-to-proton ratios of the most probable product, $(N/Z)_p$, and those of targets, $(N/Z)_t$, both in the photon- and proton- (and α-) spallation of ^{nat}V–^{197}Au. The slope for the photospallation is steeper than that for proton- (and α-) spallation, and the $(N/Z)_p$ of photospallation is shifted to the more neutron rich side for the targets of $(N/Z)_t > 1.2$ with respect to that of proton- (and α-) spallation. This suggests that the average excitation energy of cascade residues in photospallation is lower than in hadron-spallation. The ε_s values of the photon-reactions obtained in the present work are almost equal to those of the proton-reactions for ^{27}Al of $(N/Z)_t = 1.08$ and ^{nat}Cu of $(N/Z)_t = 1.19$, but systematically lower for the targets of $(N/Z)_t > 1.2$, such as ^{nat}Ag of $(N/Z)_t = 1.30$, ^{nat}Ta of $(N/Z)_t = 1.48$, and ^{197}Au of $(N/Z)_t = 1.49$. This variation of ε_s shown in Fig. 2 seems to be consistent with the above-mentioned findings of A_t-dependent features of T and also of the photospallation [9] and photopion reaction [19] yields, though fairly large errors are accompanied with the ε_s values.

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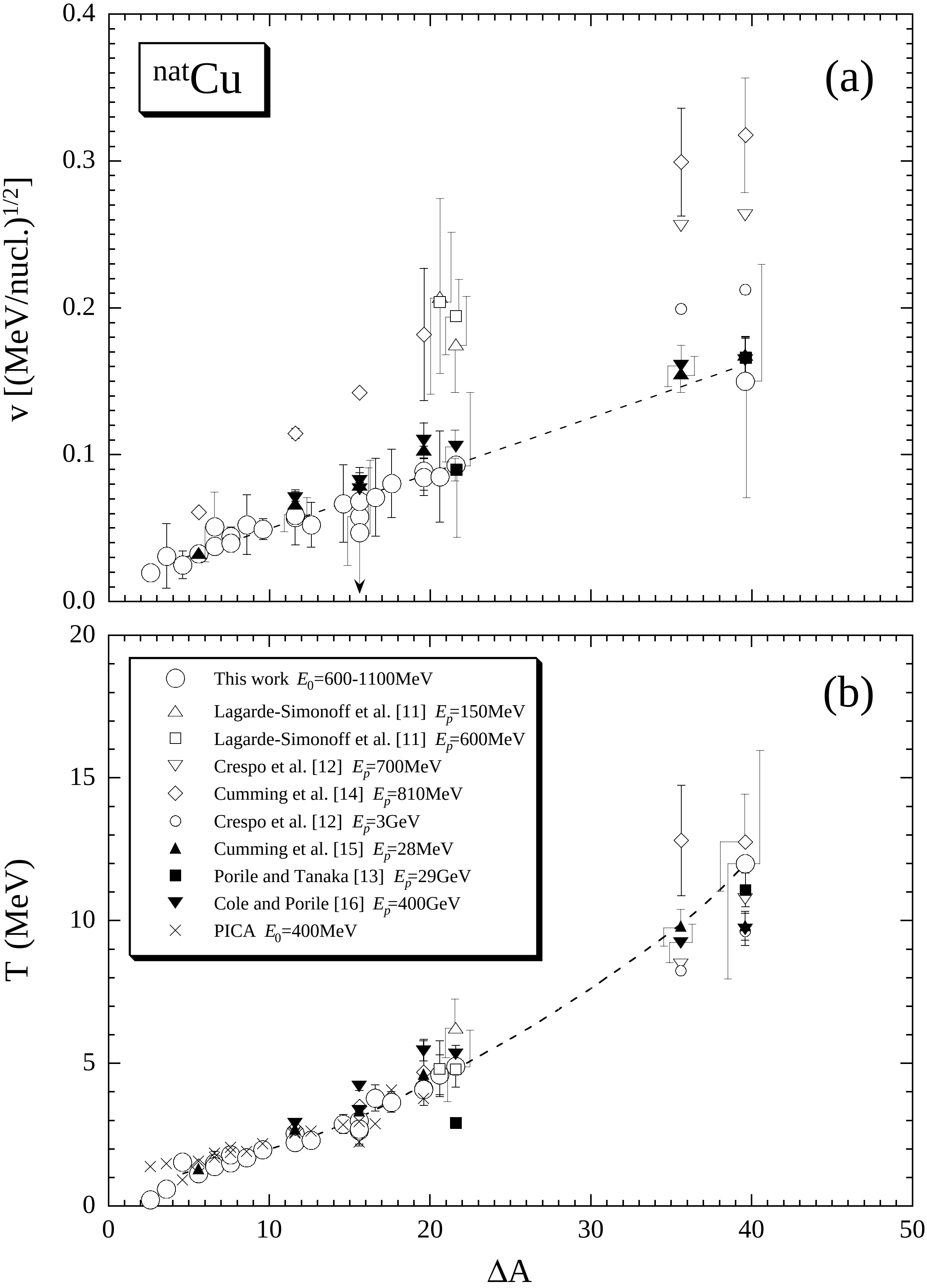

Fig. 1. (a) Forward velocity, *v*, in the first step and (b) kinetic energy, *T*, in the second step as a function of ΔA for ^{nat}Cu.

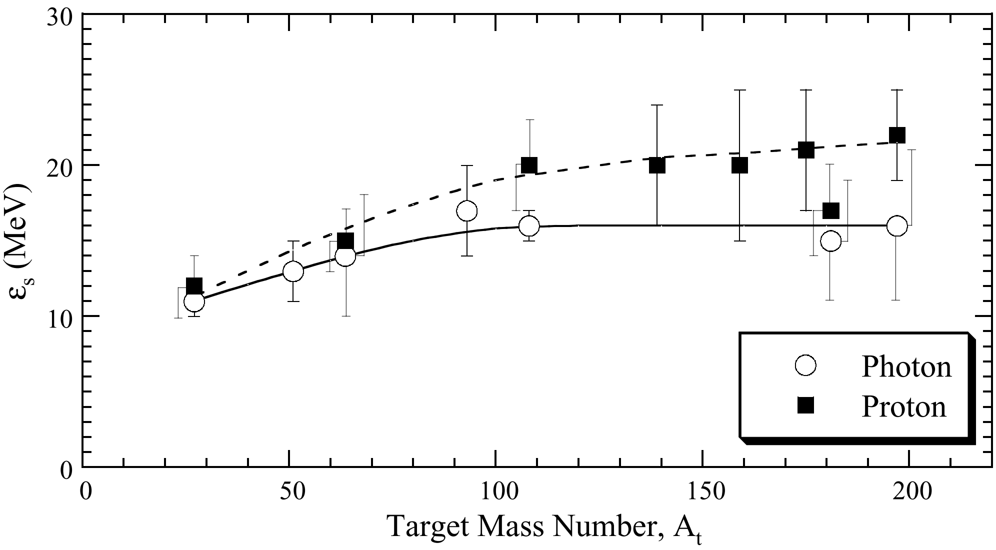

Fig. 2. Parameter ε_s as a function of target mass A_t for photon-reaction (open circles connected by a solid line) and proton-reaction (closed squares connected by a dashed line).