Analysis of activation yields by INC/GEM

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Excitation functions of the nuclides produced from the reaction on nitrogen and oxygen target irradiated by nucleons are analyzed using INC/GEM. It is shown that INC/GEM reproduces most of the cross sections within a factor of two to three.

1 Introduction

It is very important issue to estimate activation yields in water and air for radiological safety in the shielding design of a high intensity proton accelerator facility. In order to investigate scenarios of drainage of activated cooling water and of ventilation of activated air, it is required to calculate precise activation cross sections of oxygen and nitrogen.

The combination of the Bertini intranuclear cascade model and the generalized evaporation model has been succeeded to predict the cross sections of light particle produced from proton induced on O to Nb target reactions [1]. In this study, we apply this calculation procedure to nucleon induced light target reactions, and investigate its prediction power of nuclide productions from the reactions on light targets. Excitation functions of nuclides produced from the reactions are calculated using the combination of the Bertini intranuclear cascade model (INC) implemented in LAHET [2] and the GEM code [3] which is based on the generalized evaporation model proposed by Furihata [1] (We call this calculation procedure "INC/GEM"). MASS A_i, charge Z_i, excitation energy E, recoil energy, and the direction of motion are extracted from the INC calculation done by LAHET. Then GEM simulates the rest of a nuclear reaction, i.e, de-excitation of an excited nucleus, which is mostly described by the Fermi break-up model in LAHET. The results are compared with those estimated by LAHET as well as experimental data.

2 Generalized Evaporation Model

The generalized evaporation model proposed by Furihata [1] is based on the Weisskopf-Ewing model [4]. According to the model, the total emission width Γ_j of a particle j from the nucleus i with excitation energy E is expressed as

$$\Gamma_j = \frac{g_j}{\rho_i(E)} \int_V^{E-Q} \epsilon \sigma_{inv}(\epsilon) \rho_d(E-Q-\epsilon) d\epsilon, \tag{1}$$

where Q is the Q-value, V is the Coulomb barrier, and $g_j = (2S_j+1)m_j/\pi^2\hbar^2$ with the spin S_j and the mass m_j of the emitted particle j. The Q-value is calculated by using the Audi-Wapstra mass table [5]. The cross section for an inverse reaction is expressed in the general form as $\sigma_{inv}(\epsilon) = \sigma_g \alpha(1+\beta/\epsilon)$, where σ_g is the geometric cross section, and $\beta = -V$ for charged particles. We use the parameters in σ_{inv} (i.e. α, β and parameters for V) determined by Dostrovsky *et al.* [6] for n, p, d, t, ^{3}He, and α emissions. For other ejectiles, the parameters determined by Matuse *et al* [7] are used. Based on the Fermi-gas model, the level density function ρ is expressed as [8]

$$\rho(E) = \begin{cases} \dfrac{\pi}{12} \dfrac{e^{2\sqrt{a(E-\delta)}}}{a^{1/4}(E-\delta)^{5/4}} & \text{for} \quad E \geq E_x \\ \\ \frac{1}{T} e^{(E-E_0)/T} & \text{for} \quad E < E_x \end{cases}, \tag{2}$$

where a is the level density parameter, δ is the pairing energy, and E_x is determined by Gilbert and Cameron [8] as $E_x = U_x + \delta$ where $U_x = 150/A_d + 2.5$ and A_d is the mass of a daughter nucleus. Nuclear temperature T is also given as $1/T = \sqrt{a/U_x} - 1.5/U_x$, and E_0 is defined as $E_0 = E_x - T(\log T - 0.25 \log a - 1.25 \log U_x + 2\sqrt{aU_x})$. In the GEM code, the Gilbert-Cameron-Cook-Ignatyuk (GCCI) level density parameter a [2], and the pairing energy δ tabulated by Cook [9], Gilbert and Cameron [8] are used.

By substituting Eq. (2) into Eq. (1), the following expression can be obtained.

$$\Gamma_j = \frac{\pi g_j \sigma_g \alpha}{12 \rho_i(E)} \times \begin{cases} \{I_1(t,t) + (\beta + V) I_0(t)\} & \text{for } E - Q - V < E_x, \\ \\ [I_1(t,t_x) + I_3(s,s_x)e^s + (\beta + V) & \{I_0(t_x) + I_2(s,s_x)e^s\}] \\ & \text{for } E - Q - V \geq E_x. \end{cases} \tag{3}$$

$I_0(t)$, $I_1(t,t_x)$, $I_2(s,s_x)$, and $I_3(s,s_x)$ are expressed as:

$$\begin{aligned} I_0(t) &= e^{-E_0/T}(e^t - 1), \\ I_1(t,t_x) &= e^{-E_0/T} T\{(t - t_x + 1)e^{t_x} - t - 1)\}, \\ I_2(s,s_x) &= 2\sqrt{2}\left\{s^{-3/2} + 1.5s^{-5/2} + 3.75s^{-7/2} - (s_x^{-3/2} + 1.5s_x^{-5/2} + 3.75s_x^{-7/2})e^{s_x - s}\right\}, \\ I_3(s,s_x) &= (\sqrt{2}a)^{-1}\Big[2s^{-1/2} + 4s^{-3/2} + 13.5s^{-5/2} + 60.0s^{-7/2} + 325.125s^{-9/2} \\ -\{\,(s^2 - &\;\; s_x^2\;)s_x^{-3/2} + (1.5s^2 + 0.5s_x^2)s_x^{-5/2} + (3.75s^2 + 0.25s_x^2)s_x^{-7/2} + (12.875s^2 \\ + 0.625 &\;\; s_x^2\;)s_x^{-9/2} + (59.0625s^2 + 0.9375s_x^2)s_x^{-11/2} + (324.8s^2 + 3.28s_x^2)s_x^{-13/2}\Big\}\, e^{s_x - s}\Big], \end{aligned}$$

where $t = (E - Q - V)/T$, $t_x = E_x/T$, $s = 2\sqrt{a(E - Q - V - \delta)}$, and $s_x = 2\sqrt{a(E_x - \delta)}$.

Beside nucleons and helium nuclei, the nuclides up to ^{28}Mg, not only in their ground states but also in their excited states, are taken into account in GEM. The excited state is assumed to survive if its lifetime $T_{1/2}$ [sec] is longer than a decay time, i.e., $T_{1/2}/\ln 2 > \hbar/\Gamma_j^*$, where Γ_j^* is the emission width of the resonance calculated in the same manner as for ground state particle emission. The total emission width of an ejectile j is summed over its ground state and all its excited states which satisfy the above condition.

In the GEM code, ejectile j is selected according to the probability distribution calculated as $p_j = \Gamma_j / \sum_j \Gamma_j$, where Γ_j is given by Eqs. (3). The total kinetic energy ϵ of the emitted particle j and the daughter nucleus is chosen according to the probability distribution given by Eq. (1). The angular distribution of the motion is randomly selected from an isotropic distribution in the center-of-mass system.

3 Results

We calculated the excitation functions of nuclides produced from bombardment of nitrogen and oxygen irradiated by nucleons. The excitation functions are shown in Fig. 1 ~ Fig. 6. All the experimental data in the figures are extracted from and refs. [10, 11] and the EXFOR database maintained by National Nuclear Data Center [12]. Both the results of INC/GEM and LAHET agree with most of experimental data within a factor of 2 to 3.

Figure 1 shows the excitation functions of tritium productions from the reactions on N and O target irradiated by protons. The experimental data and the INC/GEM results are in good agreement above 1 GeV, while the LAHET results agree with the measurements better than INC/GEM below 1GeV.

The excitation functions of ^{14}N(p,X)^{11}C and ^{16}O(p,X)^{13}N reactions are shown in Fig. 2. The threshold reactions of these nuclide production are (p,α) reaction. The threshold energies estimated by INC/GEM are slightly higher than those by LAHET. Neither INC/GEM nor LAHET reproduces the complicated shape of resonances shown by the experimental data below a few tens of MeV.

Figure 3 shows the cross sections of beryllium productions. INC/GEM reproduces these excitation functions successfully, except for the threshold energy of ^{16}O(p,X)^{7}Be reaction. As shown in Fig. 2, INC/GEM overestimates threshold energy of α particle emissions The overestimate is also observed in the threshold energy of ^{16}O(p, 2α)^{7}Be reaction.

Figure 4 shows the excitation functions of (n,2n) reactions. The estimates calculated using INC/GEM are larger than those using LAHET, particularly at low incident energy.

Figure 5 shows the excitation functions of (p,np) reactions. Both INC/GEM and LAHET produce almost the same results for O target, whereas for N target, the results of INC/GEM is larger than those of LAHET by a factor of two.

The excitation function of (p,n) and (n,p) reactions are shown in Fig. 6. Above 10 MeV, INC/GEM produces more cross sections of (p,n) than LAHET. while LAHET produces more for (n,p) reactions than INC/GEM.

4 Conclusion

We analyze the activation yields from the reactions on light targets by INC/GEM. The combination of INC and GEM reproduces most of the excitation functions within a factor of 2 to 3, as well as LAHET. It has been said that the implementation of the Fermi break-up model is necessary to accurately describe de-excitation process of a light excited nucleus. The results show that the generalized evaporation model has comparable prediction power to the Fermi break-up model.

INC/GEM overestimates the threshold energy of α emission reactions, however. It also underestimates proton emissions as shown in the figure of (n,p) reaction. The reevaluation of the parameters of the Coulomb potential V and the cross sections for inverse reaction (i.e., α and β) used in GEM might improve the suppression of charged particle emission.

Acknowledgements

The authors would appreciate to Dr. R. E. Prael for the LAHET code.

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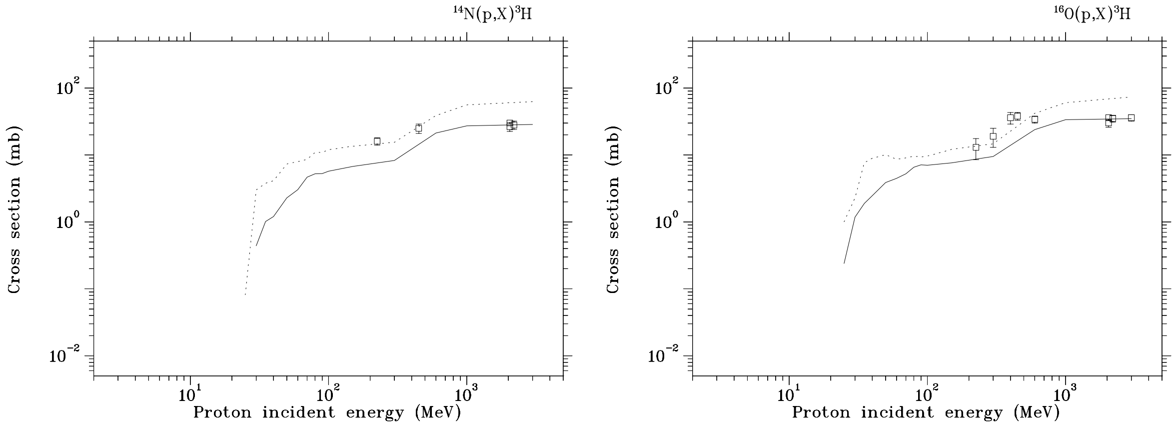

Figure 1: The excitation functions of tritium productions. Left figure shows the reaction on N target, and right figure shows the one on O target. The solid lines show the estimates calculated using INC/GEM, the dotted lines represent the LAHET results, and open squares show experimental data.

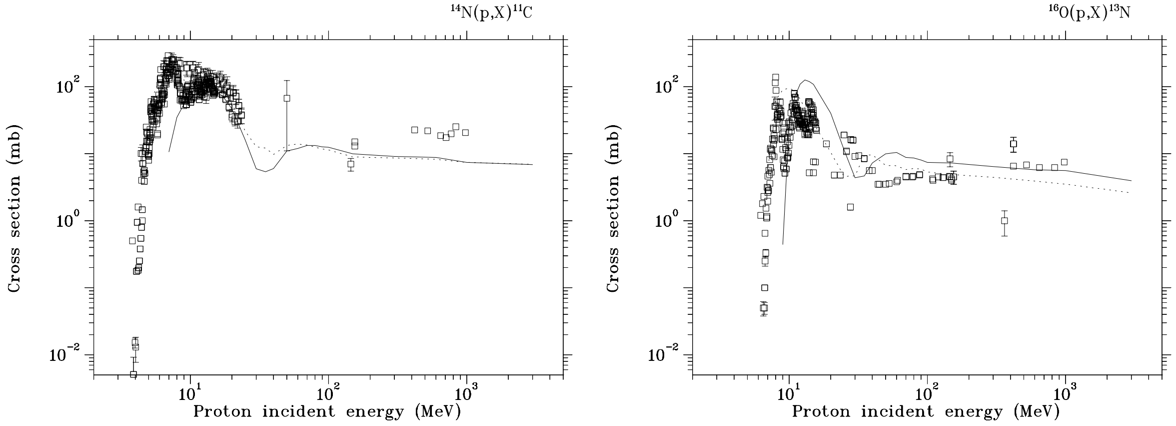

Figure 2: The excitation functions of ^{14}N(p,X)^{11}C (left) and ^{16}O(p,X)^{13}N reaction (right). The threshold reactions of these nuclide production are (p,α) reaction. The notations are the same as in Fig. 1.

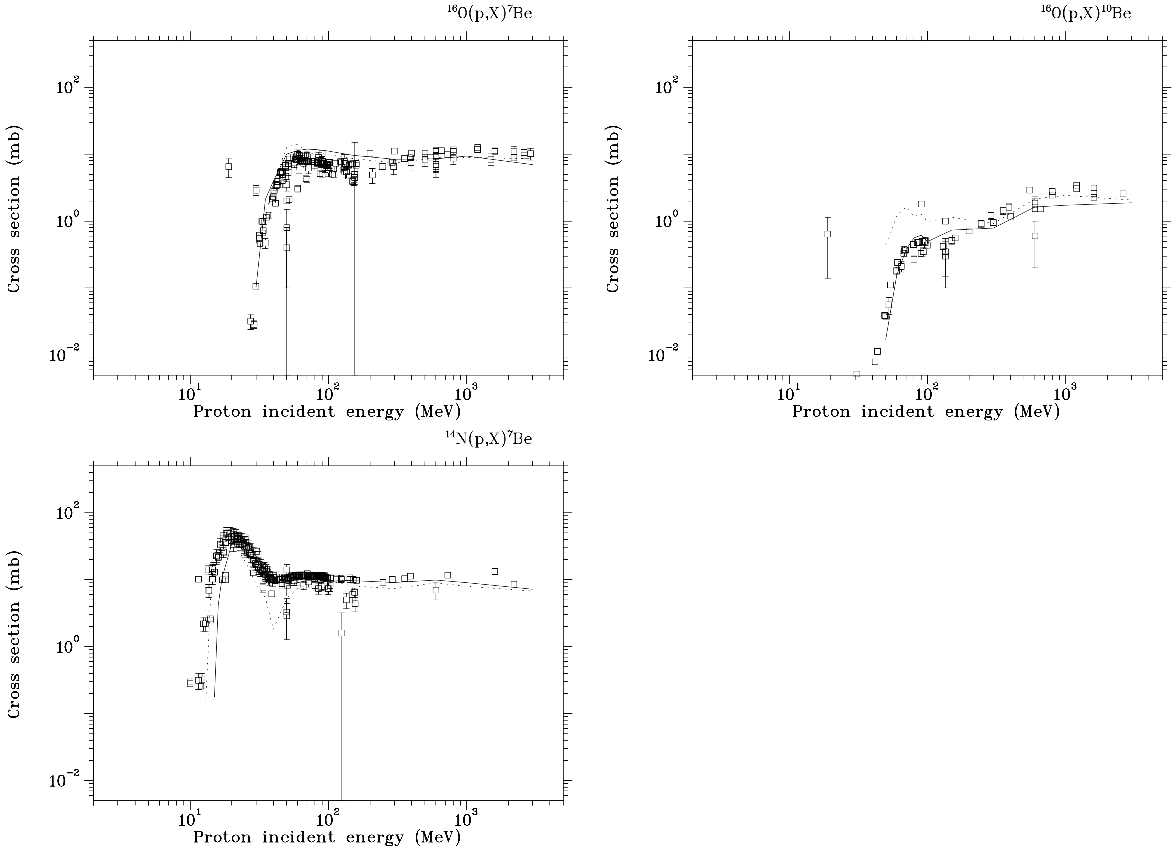

Figure 3: The excitation functions of beryllium productions. Upper left figure shows ^{7}Be produced from O target, upper right one shows ^{10}Be productions, and lower left one shows ^{7}Be productions from N target. The notations are the same as in Fig. 1.

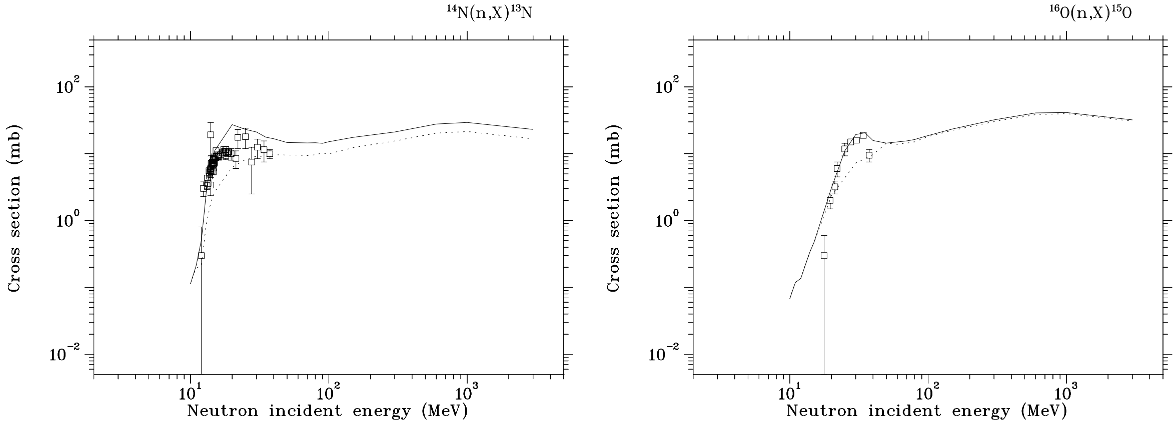

Figure 4: The excitation functions of (n,2n) reaction. Left figure shows the reaction on N target, and right figure shows the one on O target. The notations are the same as in Fig. 1.

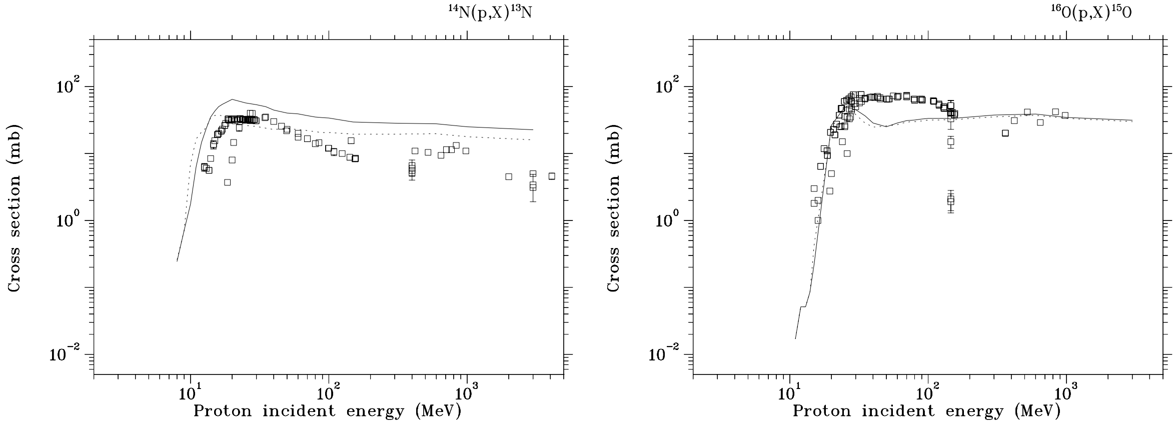

Figure 5: The excitation functions of (p,np) reaction. Left figure shows the reaction on N target, and right figure shows the one on O target. The notations are the same as in Fig. 1.

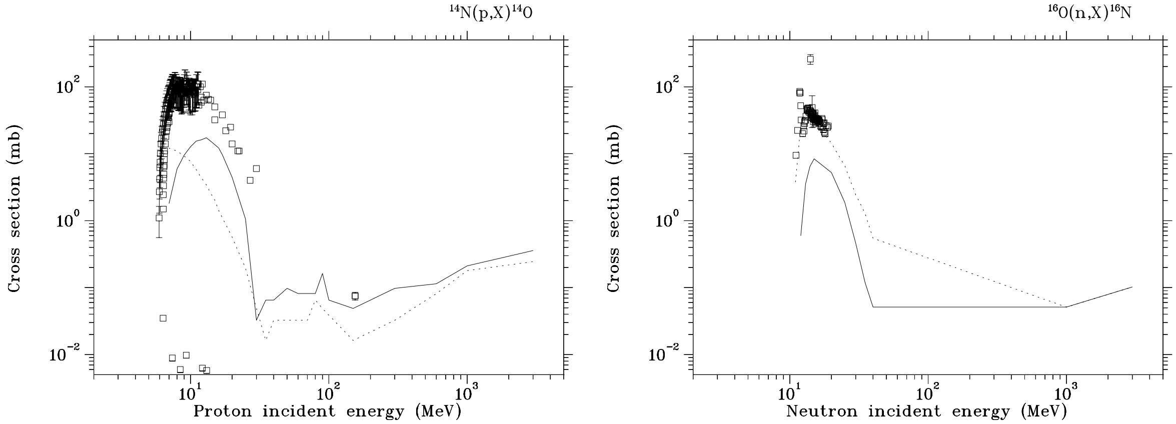

Figure 6: The excitation functions of (p,n) and (n,p) reaction. Left figure shows (p,n) reaction, and right one shows (n,p) reaction. The notations are the same as in Fig. 1.