Pre-equilibrium neutron multiplicity from ^{12}C bombardment on thick targets

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Introduction

The study of nuclear reactions and emission of particles at incident energies beyond 20 MeV per nucleon is challenging in nuclear physics due to the coexistence of multiple particle emission phenomenon like evaporation, pre-equilibrium (PEQ) and direct reactions. In this work, a theoretical estimate of PEQ neutron multiplicity study is carried out using the in-house developed HION code [1-3]. Neutron multiplicities from ^{12}C induced reaction on different targets at energies of 10 to 50 MeV per nucleon are estimated. A comparison of the relative contribution of evaporation to PEQ neutrons and a simplified empirical relation for estimating total PEQ yield at higher energy are also presented. These estimates are important from the radiological protection purposes like design of shielding or estimation of equivalent doses for occupational workers at higher neutron energies.

Method of calculation

In this work, the PEQ neutron emissions from heavy ion reactions, at projectile energies in the energy range of a few tens of MeV per nucleon were estimated using pre-equilibrium (PEQ) model HION [1]. The modified version of HION is used, which determines the energy angle distribution of PEQ neutrons from two body scattering kinematics. The influence of nuclear mean field on the neutron emission was incorporated through the spatial density distribution of nucleons [2, 3] in the composite system. At incident energies above 25 MeV per nucleon, simultaneous and sequential multi-particle PEQ emissions are considered. The evaporation contribution is calculated from the PACE4 [4] code and compared with the PEQ yields.

Choice of targets

Choosing target materials for study in an accelerator facility is a bit difficult considering the variety of elements available in different shielding materials, beam line assembly and beam dump. Among these, the dump is the prominent source of radiation during operations. Mostly Ta and Cu are used for fabrication of the dump assembly. So yields from ^{63}Cu, ^{65}Cu and ^{181}Ta are chosen for the evaluation studies. ^{12}C and ^{56}Fe are chosen as C and Fe are the constituents of the components of beam line assembly. ^{197}Au is widely used in basic research as scattering or stopping target in experiments. Considering these aspects, a total of six targets were chosen for this study.

Results and Discussions

The PEQ neutron multiplicities were estimated using the multiple PEQ model HION3 [3] in the energy regions of 10-50 MeV per nucleon and corresponding evaporation estimates are shown in fig. 1 with 3 targets viz., ^{12}C, ^{63}Cu, ^{181}Ta. Left axis indicates evaporation multiplicity with a solid line and the right axis represents PEQ yields with dashed line. Fig. 1 shows that, both evaporation and PEQ multiplicity increases with increase in the beam energies, but the slope of the curves are different.

The fraction of evaporation to PEQ multiplicities vary between 3-40% depending upon energy, composite system and density of states available at the effective excitations. The reduction in the PEQ yield with increasing target mass is shown in fig.2. For heavy targets, the PEQ yield decreases to less than 10% of the evaporation yield, even at 50 MeV per nucleon.

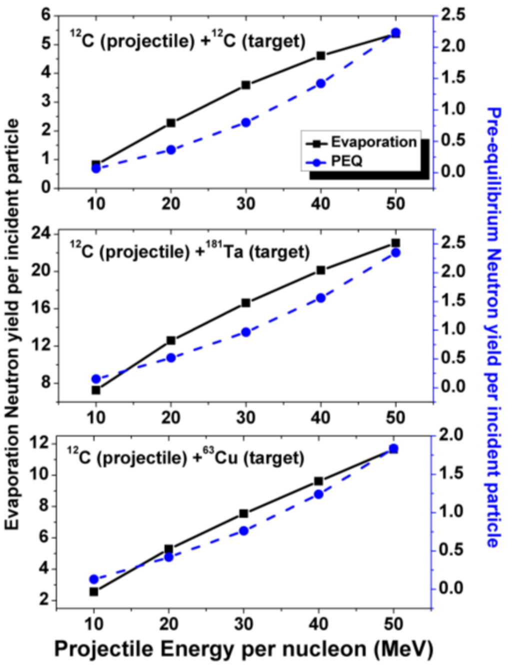

Fig. 1 Evaporation and PEQ neutron multiplicities with ^{12}C beam at different targets.

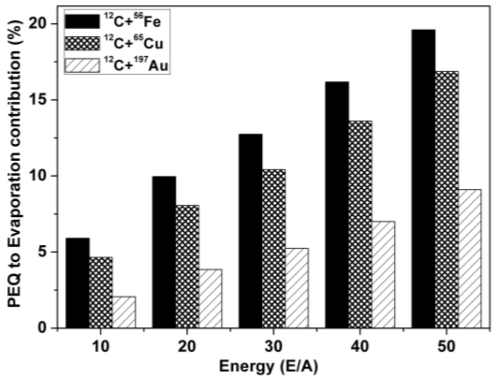

Fig. 2 Yield percentages from pre-equilibrium to Evaporation with ^{12}C beam at different targets.

In the present work, a simplified empirical relation is also proposed to calculate the integral yield of PEQ neutrons for these systems. The empirical relation is developed by fitting the PEQ yields obtained from HION code. For projectile energy of 10 MeV per nucleon, only single PEQ emission is considered whereas at higher energies, both simultaneous and sequential MPEQ are used [3]. This empirical relation calculates the total yield of neutrons per incident particle at a given projectile energy. The relation can be presented as;

$$Yield = \begin{cases} \dfrac{5\times10^3}{A_C^2}\left(\dfrac{E_p}{A_P}\right)^2\left[A_P^{1/3}+A_T^{1/3}\right]^2 N_P\left(N_T - Z_T\right) & N_T \rangle Z_T \\ \dfrac{5\times10^3}{A_C^2}\left(\dfrac{E_p}{A_P}\right)^2\left[A_P^{1/3}+A_T^{1/3}\right]^2 N_P & N_T = Z_T \end{cases}$$

Here the subscripts P, T and C denote the projectile, target and composite systems. E_p is the incident particle energy in MeV.

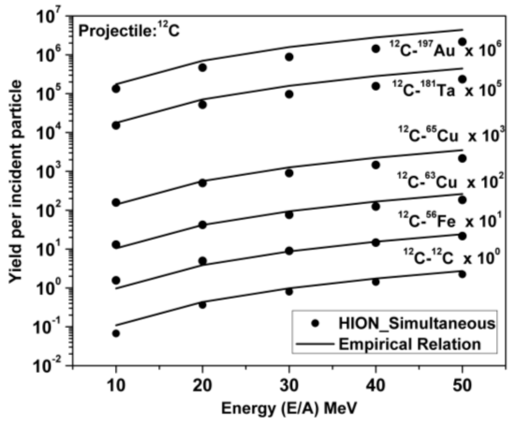

Fig. 3 Comparison of integral yield from HION with empirical relation for ^{12}C beam

The results obtained using this formalism is compared with the HION estimated total neutron multiplicities and are shown in fig. 3.

Conclusion

This work presents the relative contribution of PEQ emission to evaporation from ^{12}C projectiles on different target materials in the mass range of A=12-197. An empirical formalism for estimation of the total neutron yield is proposed and reproduced with the HION data. These empirical estimates can be highly beneficial for the estimation of the shielding calculations around heavy ion accelerator in this energy range.

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[4] O.B. Tarasov, D. Bazin, Nucl. Instrum. Meth. B 204, 174 (2003).