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# Secondary neutron production from $^{56}Fe$ bombarded by $^{12}C$

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SUMMARY

In the present study, to test the validation of nuclear reaction model codes, the neutron yield from targets $^{27}Al$, NatTi and $^{56}Fe$ when bombarded by $^{12}C$ is calculated with EMPIRE 3.2 and PACE 4 nuclear reaction model codes, and compared with the available experimental data at beam energy of ≈ 10 MeV/A for different angles. More over in this work the contribution of pre-equilibrium emission is also discussed in detail. This excess amount of high energy neutrons is expected to induce secondary reactions in core and structural materials of reactor.

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## INTRODUCTION

The nuclear reactions, with projectile energy ≈ 10 MeV/A or above shows pre-equilibrium emission. This concept is very well established for light projectiles. In Heavy ion induced reaction regime, this concept is not well evaluated, there is an enhanced interest for pre-equilibrium emission, in the fields of nuclear reactors, accelerator shielding and dose requirements for radiation treatments. More over the neutron yield from thick target heavy ion interaction is of considerable interest to other applications in interdisciplinary fields. The state-of-the-art modern carbon ion therapy uses high energy $^{12}C$ beam for medical therapy and the design and operation of such accelerator facility require accurate knowledge on neutron shielding due to background neutrons produced by beam hitting on surfaces. The chosen reaction is important to understand the production of neutrons from thick targets as Fe is a prominent structural material for heavy ion accelerator and reactors.

Though neutron emission from proton and alpha induced reactions are generally well explored, data are scarce for production of neutrons by heavy ion reactions [1-4]. Few measurements of thick target neutron yield using heavy ion reaction have been performed at 10 MeV/A or lower energies to get insights into the reaction mechanisms [5-7]. The available data are still inadequate to generate a systematic and consistent description of the dynamics of pre-equilibrium reactions and its dependence on projectile energy. In the light of these findings from national and international researchers, we would like to study pre-equilibrium contribution in neutron emission in $^{12}C$ induced reaction on $^{56}Fe$ at high beam energies using nuclear reaction model codes.

## NUCLEAR REACTION MODEL CODES FOR THEORETICAL STUDY

There are several nuclear reaction model codes available to simulate compound nucleus reaction and decay process. The main reaction processes involved are direct (DIR), Pre-Equilibrium (PEQ) and compound nuclear processes. Direct reactions are modelled through coupled channel calculations, PEQ reactions are calculated based on two widely used models, exciton model and hybrid model. Compound nuclear reactions are calculated using Hauser-Feshbach theory. Some of the codes appropriate for estimation of neutron yield we use PACE 4 and EMPIRE 3.2. Among this the PACE 4 do not have the PEQ model included. Code EMPIRE 3.2 has provisions to invoke hybrid, exciton or other models such as Multi-Step Direct (MSD) and Multi-Step Compound(MSC) models.

## Empire 3.2

The EMPIRE 3.2 is a modular system of nuclear reaction codes and is used for calculating various physical observables related to nuclear reaction [8]. In EMPIRE we can use neutron, proton, any ion (including heavy-ions) or a photon as projectiles in energy range of Kev to several hundred MeV. The code provides the major nuclear reaction mechanisms, including direct, pre-equilibrium and compound nucleus ones.

1. Direct reactions are described by a generalized optical model (ECIS03) or by the simplified coupled-channels approach (CCFUS).
2. The pre-equilibrium mechanism can be treated by a deformation dependent multi-step direct (ORION + TRISTAN) model, or by pre-equilibrium exciton model with cluster emission (PCROSS).
3. The compound nucleus decay is described by the full featured Hauser-Feshbach model with γ-cascade and width-fluctuations.

To check the effect of pre-equilibrium contribution in the chosen reactions, we have done the calculations with PCROSS-1.5 in the input parameter. Also we used several optical model potential parameters suggested by Koning et al. and Morillon et al. to examine the sensitivity of different optical model potential parameters accessible in the RIPL-3 library [9,10].

The main purpose of the EMPIRE is to provide a powerful environment for modelling nuclear reactions that can be used in basic research as well as for the generation of evaluated nuclear data files [8].

## PACE 4

PACE 4, is based on Hauser-Feshbach formalism which follows the correct procedure of angular momentum coupling at each stage of de-excitation of an excited nucleus [11]. For light ions, optical model calculations are used whereas, for heavy projectiles bass model is used for fusion cross section and initial spin distribution [12]. The Gilbert-Cameron level density is used in the calculation, with level density parameter, a=A/10, where A is mass number of compound nucleus.

# RESULT AND DISCUSSION

There are few data regarding neutron production by $^{12}C$ on $^{56}Fe$. In this study, we present the neutron spectra of the $^{12}C$ on 56Fe reaction at incident beam energy ≈ 10 MeV/A and validate nuclear reaction model codes EMPIRE 3.2 and PACE 4. Since the experimental data from $^{12}C$ and $^{56}Fe$ is scarce, we chose the adjacent system $^{12}C$ on $^{27}Al$ at incident beam energy 115 MeV to evaluate the pre-equilibrium contribution and validate the data with nuclear reaction model codes EMPIRE 3.2 and PACE 4 as Aluminium is also an important structural material for particle accelerators. Figures 1-4 shows the available experimental data of $^{12}C$ on $^{27}Al$ from V. Suman et al., as well as the theoretical result from EMPIRE 3.2 and PACE 4 [13]. We investigated the effect of various level densities and optical potentials in this study, the calculations of the level densities were performed on the base of LEVDEN-0 option which is a default case for the level densities which is described as an Enhanced Generalized Superfluid Model (EGSM), LEVDEN-1, 2, and 3 which are described as Generalized Superfluid M odel ( GSM), Gilbert-Cameron level densities and RIPL-3 microscopic HFB level densities respectively. The following optical potentials proposed by Koning et al. and Morillon et al. were considered [9,10]. we are seeking for EMPIRE 3.2's pre-equilibrium contribution and whichever level density model and optical potential of EMPIRE 3.2 will produce the best theoretical result.

## $^{12}C$ on $^{27}Al$ at 0°

The neutron energy data of $^{12}C$ on $^{27}Al$ at 0° reported by V. Suman et al. is compared with EMPIRE 3.2 and PACE 4 at different available level density model is shown in Figure 1 [13]. The reported experimental data is found to be in good agreement with the theoretical result (shown in the orange colour by dotted line) made using ld model-3. Also the pre-equilibrium emission, is taken into account in theoretical calculations. It has been observed that the pre-equilibrium parameters of the code EMPIRE 3.2 satisfactorily reproduces the calculated data result, whereas PACE 4 predicts lower amount of high energy neutrons this is because PACE do not account pre-equilibrium emission. PACE 4 predictions are underestimated when compared to experimental data at the most forward angles and highest neutron energies.

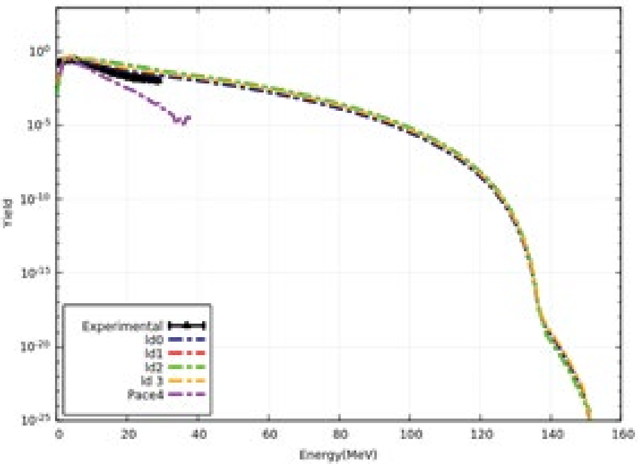


**Fig. 1.** The neutron energy spectrum of $^{12}C$ on $^{27}Al$ at 0° with experimental data reported by V. Suman et al. and theoret cal results from EMPIRE 3.2 and PACE 4 [13]

## $^{12}C$ on $^{27}Al$ at 30°

The neutron energy data of $^{12}C$ on $^{27}Al$ at 30° reported by V. Suman et al., is compared with EMPIRE 3.2 and PACE 4 at different available level density model is shown in Figure 2 [13]. The reported experimental data is found to be in good agreement with the theoretical result (shown in the yellow colour by dotted line) made using ld model-3. At this angle the PACE 4 calculation falls off faster than the EMPIRE 3.2 calculations, this is because the possibility of pre-equilibrium effects causing more neutron emission at higher energy.

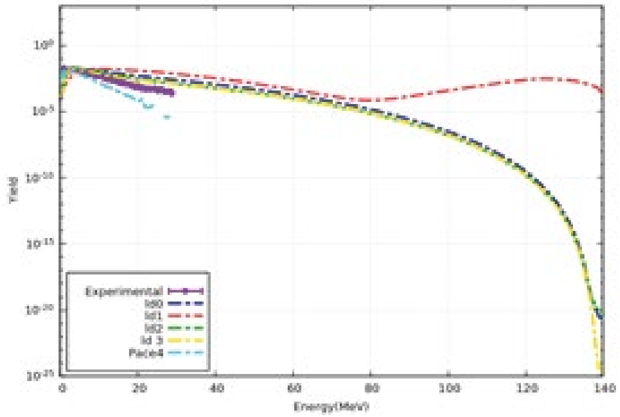


**Fig. 2.** The neutron energy spectrum of $^{12}C$ on $^{27}Al$ at 30° with experimental data reported by V. Suman et al. and theoretical results from EMPIRE 3.2 and PACE 4 [13]

## $^{12}C$ on $^{27}Al$ at 60°

The experimental data of $^{12}C$ on $^{27}Al$ at 60° reported by V. Suman et al., is compared with EMPIRE 3.2 and PACE 4 at different available level density model is shown in Figure 3 [13]. The reported experimental data is found to be in good agreement with the theoretical result made using ld model-3, theoretical data follows the trend with experimental data, but slightly higher than the experimental data in the energy range of about 0 MeV -15 MeV. At this intermediate angles EMPIRE 3.2 and PACE4 calculations are fairly close with each other but over predicted experimental data.

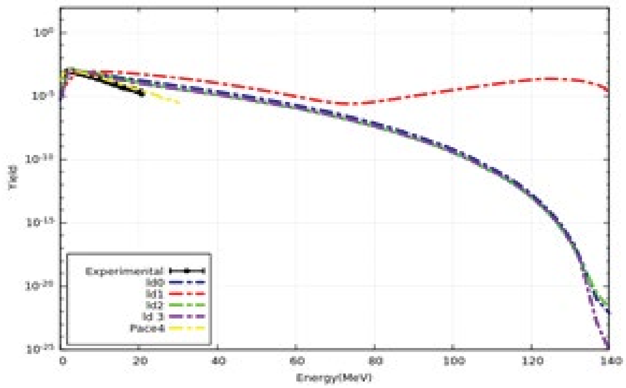


**Fig. 3.** The neutron energy spectrum of $^{12}C$ on $^{27}Al$ at 60° with experimental data reported by V. Suman et al. and theoretical results from EMPIRE 3.2 and PACE4 [13]

## $^{12}C$ on $^{27}Al$ at 90°

The experimental data of $^{12}C$ on $^{27}Al$ at 90° reported by V. Suman et al., is compared with EMPIRE 3.2 and PACE 4 at different available level density model is shown in Figure 4 [13]. The theoretical results made using ld model-3 are best in line with the present experimental data and follow the trend of experimental results of this reaction, experimental data and PACE 4 estimates are quite similar for backward angle 90°.

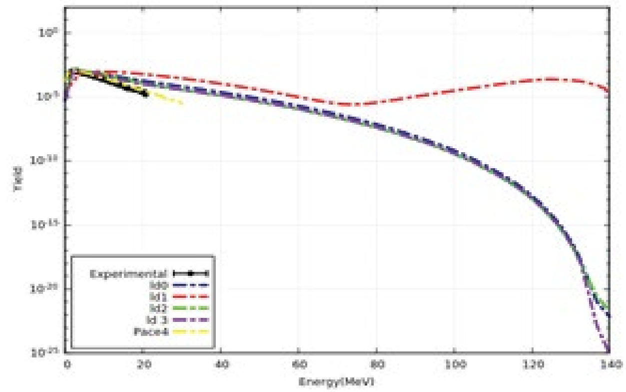


**Fig. 4.** The neutron energy spectrum of $^{12}C$ on $^{27}Al$ at 90° with experimental data reported by V. Suman et al. and theoretical results from EMPIRE 3.2 and PACE 4 [13]

From Figures 1-4 the neutron yield measured data reported by V. Suman et al. for the system $^{12}C$ on $^{27}Al$ is compared with EMPIRE 3.2 and PACE 4, here we found whichever parameters of EMPIRE 3.2 matches the experimental data well and summarises the contribution of pre-equilibrium. Using the same set of input parameters for level density, PCROSS and optical model potential of EMPIRE 3.2, we are producing the results for $^{12}C$ on NatTi system along with the available experimental data from Nandy et al., and data from EMPIRE 3.2 and PACE 4 for validation purpose [14]. It is clear from the Figure 5 that the trend of neutron yield obtained from the theoretical calculation EMPIRE 3.2 is consistent with the experimental data reported by Nandy et al. [14].

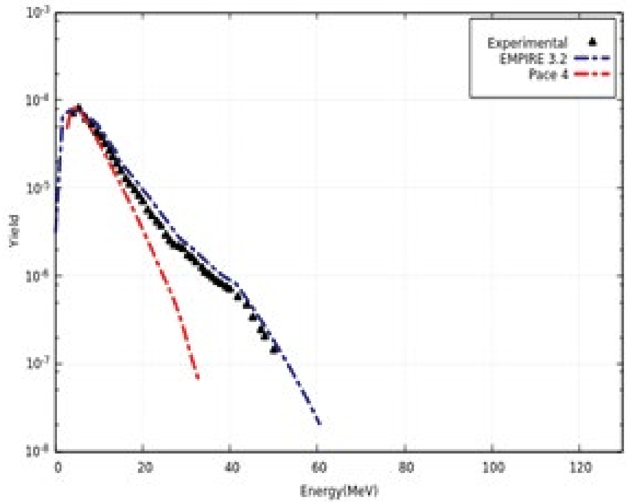


**Fig. 5.** Comparison of measured neutron yield with those obtained from model calculations EMPIRE 3.2 and PACE 4 for $^{12}C$ on Ti reaction at 144 MeV

Based on the above two studies with the systems $^{12}C$ on $^{27}Al$ and $^{12}C$ on NatTi, a comparison of neutron yield from the system $^{12}C$ on $^{56}Fe$ with nuclear reaction model codes EMPIRE 3.2 and PACE 4 is considered, as for this study we use the same parameters to optimize the result for the system $^{12}C$ on $^{56}Fe$, which is shown in Figure 6. Since there is no available experimental data for $^{12}C$ on $^{56}Fe$ in the incident energy of 12MeV/Nucleon we consider the available calculated data of $^{12}C$ on $^{56}Fe$ reported by H.W. Bertini et al. [15].

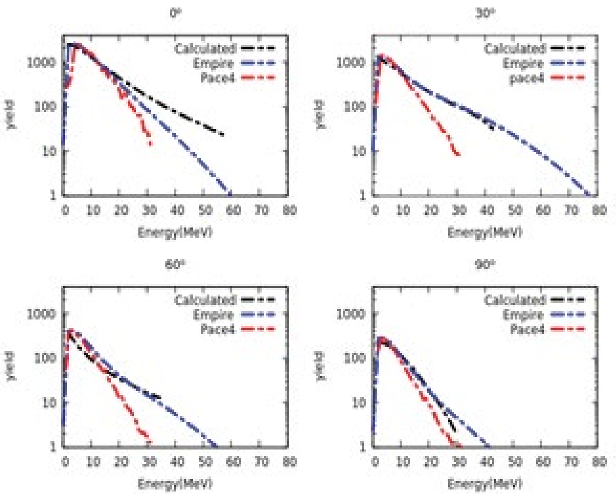


**Fig. 6.** Comparison of Calculated neutron yield data reported by H.W. Bertini et al. with those obtained from model calculations EMPIRE 3.2 and PACE 4 for 12C on 56Fe reaction at 192 MeV [15]

# CONCLUSION

It is interesting to examine that in all the cases; it is observed that there is a fall in the PACE 4 calculations at high energies (above 5 MeV). At forward angles less than 50° there is a significant discrepancy between PACE 4 and EMPIRE 3.2.

In this region, the PACE 4 calculation drastically underestimates the experimental result. This is to be expected because of pre-equilibrium emission. At backward angles higher than 50°C, PACE 4 calculation falls off faster than the EMPIRE 3.2 calculation, but the experimental and calculated data are in good agreement with EMPIRE 3.2 prediction. It is also observed that pre-equilibrium contributions increase with increase in incident energy of the neutron. Thus it is concluded that at high beam energies significant amount of high energy neutrons are produced this neutron in turn induces secondary reactions with core and structural materials. This will affect the criticality of the reactor. Such neutrons may be produced other structural materials like Nb, Ni, Cr etc.

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