

NEUTRON ENERGY SPECTRA AND DOSE EQUIVALENT RATES FROM HEAVY-ION REACTIONS BELOW 20 MEV/U USING THE PHITS CODE *

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Abstract

Neutron energy spectra from 6.25 MeV/u ¹²C ions incident on a copper target, 10 MeV/u ¹²C ions incident on carbon, copper, and lead targets, and ¹⁶O ions incident on a copper target have been calculated using the Quantum Molecular Dynamics model (QMD) [1] coupled to the Generalized Evaporation Model (GEM) [2] in the Particle and Heavy Ion Transport Code (PHITS) [3]. In particular, the influence of the “switching time”, defined as the time when the QMD calculation stops and the GEM calculation begins, was studied. The calculated neutron energy spectra obtained using a value of 100 fm/c agree well with the experimental data from reactions on Cu and Pb targets, but not so for the 10 MeV/u ¹²C+C reaction. We have also used PHITS to simulate an experimental study by Ohnesorge et al. [4], by calculating neutron dose equivalent rates from 3-16 MeV/u ¹²C, ¹⁶O and ²⁰Ne beams incident on Fe, Ni and Cu targets. The calculated neutron dose equivalent rates agree very well with the data.

INTRODUCTION

The Monte Carlo heavy-ion transport code PHITS has been typically used to predict radiation levels around high-energy (above 100 MeV/u) heavy-ion accelerator facilities. However, predictions of radiation levels around low-energy (around 10 MeV/u) heavy-ion facilities (e.g. [5]) are also desirable. In this energy region, the fusion reaction generates compound nuclei, from which neutrons are emitted [6]. However, the accuracy of PHITS predictions of neutron production at such low energies has not been investigated.

Neutron energy spectra are calculated by PHITS using the Quantum Molecular Dynamics model (QMD) [1], to describe the dynamical phase of nucleus-nucleus interactions, coupled to the Generalized Evaporation Model (GEM) [2] to describe statistical phases of reactions. The separation of the QMD and GEM calculations within PHITS can give the individual production cross sections of various residues before and after statistical decay calculations. This possibility gives information on the relation between the dynamical and the statistical processes as a function of projectile energy and impact parameter. On the contrary, this hybrid approach introduces an ambiguity because the switching time, t_{sw} , is an arbitrary parameter. In a study of this parameter using 1.5GeV (p,xn) reaction data [3] a value of 150 fm/c was

chosen. However, this does not necessary mean that this value is also appropriate to predict reliable neutron energy spectra for low-energy heavy-ion incident reactions. Therefore, we have investigated how neutron energy spectra vary for t_{sw} = 50, 100, and 150 fm/c, for comparisons against experimental data [7] from 6.25 MeV/u ¹²C ions incident on a copper target, 10 MeV/u ¹²C ions incident on carbon, copper, and lead targets, and ¹⁶O ions incident on a copper target. A value of 100 fm/c for t_{sw} was found to give very good agreement with experimental data, except for the 10 MeV/u ¹²C+C reaction. We then used PHITS to simulate an experimental study [4] of neutron dose rates by calculating neutron dose equivalent rates using this value of t_{sw} for reactions between 3-16 MeV/u ¹²C, ¹⁶O, ¹⁴N and ²⁰Ne ions and Cu, Fe and Ni targets.

NEUTRON ENERGY SPECTRA

Calculated thick target neutron energy spectra using switching times of 50, 100 and 150 fm/c are compared to experimental data [7] taken at 90° for 10 MeV/u ¹²C+Cu and ¹⁶O+Cu reactions as shown in Figs. 1 and 2.

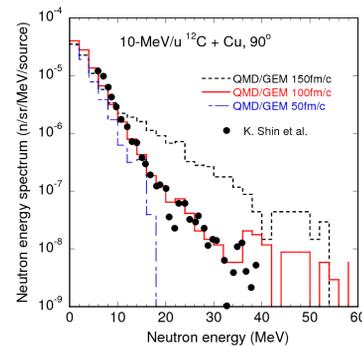


Figure 1: Neutron energy spectra using switching times 50, 100, and 150 fm/c for 10 MeV/u ¹²C+Cu reactions.

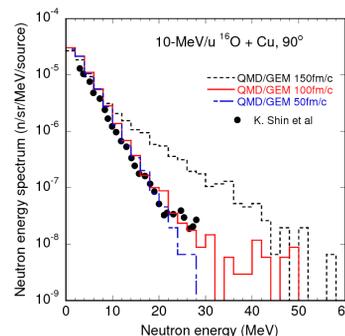


Figure 2: Same as Fig. 1 except for 10 MeV/u ¹⁶O+Cu reactions.

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The QMD calculation using 150 fm/c generates many more neutrons at higher energies than experimentally observed. The calculated temperatures of residual nuclei are too high as evident from the calculated slope being too low. On the other hand, for the switching time of 50 fm/c, the calculated nuclear temperature is evidently too low, as observed by the lower than observed cut-off of the calculated neutron energy spectra. Calculated neutron energy spectra with 100 fm/c switching time agree very well with experimental data as shown in Fig. 1 and 2. Similar calculations of neutron energy spectra at 0, 30, 60, and 120° were also made for beams of 6.25 MeV/u ^{12}C ions incident on a copper target, 10 MeV/u ^{12}C ions incident carbon, copper, and lead targets, and ^{16}O ions incident on a copper target. Except for the $^{12}\text{C}+\text{C}$ reaction at 10 MeV/u, the results also give good agreement with experimental data. We conclude that the switching time value of 100 fm/c is the best value of the three used to simulate neutron yields at these low incident heavy ion energies.

NEUTRON DOSE EQUIVALENT RATES

We have used PHITS with a switching time of 100 fm/c to simulate the experimental study of Ohnesorge et al. [4] by calculating neutron dose equivalent rates for low-energy heavy-ion incident reactions. In that study, neutron dose rates were measured at several facilities at Oak Ridge National Laboratory, at ORIC's heavy ion time-of-flight target station and, for 3 MeV/u ^{12}C -induced reactions only, at the ORNL EN Tandem Van de Graaff facility. We simulated reactions within only the ORIC facility. To take into account room-scattered neutrons, we considered the geometry of the concrete shielded room, and used an iron block to represent the magnetic spectrometer that was present at the time of the experiments. The geometry used in the PHITS simulation is shown in Fig. 3 and the list of beam conditions are given in Table 2. Beam ions were incident on the dump, a composite of the target and a graphite Faraday cup. Unfortunately, there was no available information on the specific target material and thickness used in each experiment. It was stated that "thick targets of iron, nickel or copper" were used [4]. Therefore, in our calculations we set the thickness of each target to 1.5 mm and calculated dose rates for all target materials.

Table 1: Beam ions and specific energies

Beam ion	Specific energy (MeV/u)
^{12}C	3.0, 7.0, 9.7, 15.9
^{14}N	10.5, 11.8, 13.3
^{16}O	5.5, 12.6
^{20}Ne	8.7

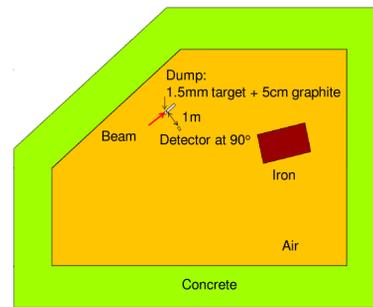


Figure 3: Geometry used in the neutron dose equivalent calculations. The beam line is 1.2 m above floor level. Targets were iron, nickel or copper.

In the experiments, a neutron detector was placed at 1 m from the target and at 90° from the beam direction. The ORNL Fast Neutron Survey Meter, Model Q-2047 [8], was used. The fluence-to-dose conversion factors, P , used by the instrument and the calculated neutron energy spectrum for the 9.7-MeV/u $^{12}\text{C} + \text{Cu}$ reaction are shown in Fig. 4. The neutron dose equivalent, H , is calculated from

$$H = \sum_{i=1}^{E_{\max}} \int_{E_{\min}}^{E_{\max}} dEP_i(E)\Phi_i(E) \quad (1)$$

where $\Phi_i(E)$ is the fluence of particles of type i with energy between E and dE and $P_i(E)$ is the dose equivalent per unit fluence in appropriate units. Fluence-to-dose conversion factors and neutron flux are largest in the energy region from 0.1 MeV to 10 MeV. Neutron flux in the low energy region is due to neutrons scattered from materials such as the floor and walls of the room. This contribution to equivalent dose is not strong because of low values of the conversion factors in the energy region below 10^{-2} MeV. From our work described in the previous section, PHITS can reliably simulate neutron energy spectra in the energy region above 1 MeV. Thus, neutron dose equivalents should also be reliable.

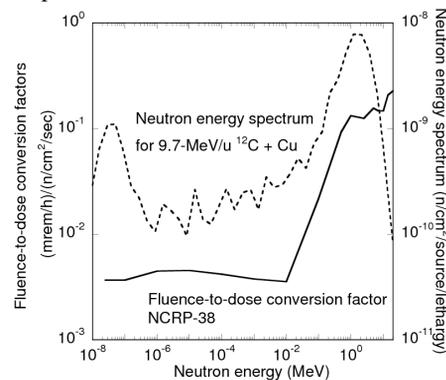


Figure 4: Fluence-to-dose conversion factors (solid line) and the calculated neutron energy spectrum (dash line) for 9.7 MeV/u $^{12}\text{C} + \text{Cu}$ reaction are shown.

Calculated neutron equivalent dose rates and comparisons to experimental data are shown in Fig. 5. The calculated results agree well with experimental data despite the lack of specific information on the targets. Generally, the calculated and measured data follow a general trend which appears to be insensitive to the heavy ion species. Neutron equivalent doses from the nickel target are smaller than those from iron and copper targets. This is because Q-values for neutron emission reactions using a nickel target are negative and smaller than for other targets. Therefore, the threshold energies for neutron emission for reactions using a nickel target are larger than for other targets.

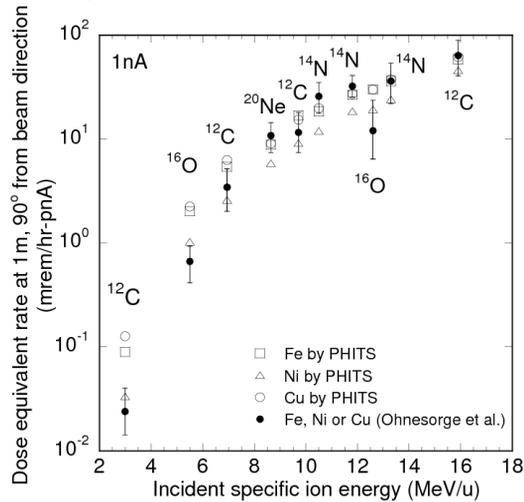


Figure 5: Neutron equivalent dose rates at 1m from thick targets of iron, nickel or copper, and at 90° from the incident heavy ion beam direction. The beam current is 1 particle nanoAmpere, equal to 6.25×10^9 particles/sec.

CONCLUSION

In order to validate the use of the Monte Carlo transport code PHITS in studies of radiation fields at low-energy (~10 MeV/u) heavy-ion accelerator facilities, neutron production using the QMD and the GEM models in PHITS was studied. It was found that 100 fm/c is the best of three values of the switching time studied, the switching time defined as the time when the QMD calculation is stopped and GEM model calculation commences. Using this value of 100 fm/c, neutron energy spectra for 6.25 MeV/u ^{12}C ions incident on a copper target, 10 MeV/u ^{12}C ions incident carbon, copper, and lead targets, and ^{16}O ions incident on a copper target were calculated and compared with the experimental data. Calculated results from PHITS give very good agreement

with experimental data except for the $^{12}\text{C}+\text{C}$ reaction at 10 MeV/u. Neutron equivalent dose rates were also calculated for 3-16 MeV/u ^{12}C , ^{16}O and ^{20}Ne beams incident on Fe, Ni and Cu targets. The calculated neutron dose equivalent rates also agree very well with experimental data. We conclude PHITS should be a useful and reliable code for the study of neutron fields at accelerator facilities using low-energy heavy-ion beams.

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