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7.2.2 Secondary Neutron Production Cross Section Measurements from Heavy-mass Targets at HIMAC

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The measurements of secondary neutron production cross sections from heavy-ion interactions play a key role in the development of transport model calculations that are used in a wide variety of applications. We briefly describe and highlight experiments conducted at HIMAC since the late 1990's that measured secondary neutron cross sections over a wide variety of beam species, beam energies, and heavy target materials.

Key Words: HIMAC (Heavy Ion Medical Accelerator in Chiba), secondary neutron cross sections, heavy-ion interactions

1. Introduction

Transport model codes such as PHITS,¹⁾ MCNP6,²⁾ FLUKA,³⁾ GEANT4,⁴⁾ to name a few, are indispensable tools for the calculation of radiation transport and effects for applications such as accelerator shielding, medical physics, isotope production, space radiation shielding, and electronics effects. Starting in the late 1980's, extensive effort has been put into the development of heavy-ion ($Z \geq 2$) interaction models employed by the codes to accurately predict the outcome of heavy-ion interactions ranging from a few MeV/nucleon to several TeV/nucleon. Given the importance that the production of secondary neutrons has regarding dose, material effects, induced radioactivity, and radiation protection, the ability of the codes to accurately predict neutron production was recognized early as a crucial element in the development of the

physics models in those codes.

Experiments conducted at HIMAC provided a substantial amount of data on both thick-target neutron yields and neutron production cross sections. The pioneering work done by Nakamura and Kurosawa on thick-target neutron yields from intermediate heavy-ion interactions (reviewed in another article in this issue) led to the development of a program of secondary neutron cross section measurements performed at HIMAC. In this paper, the results from heavy targets ($Z \geq 13$, $A \geq 27$) are highlighted. Results from lighter mass targets are discussed in another paper in this issue. Here, the choice of targets with mass equal to or greater than aluminum was based partly on their significance to event generators in transport model calculations, where models such as Fermi Breakup are used to describe the deexcitation and breakup of light-mass objects during the initial and pre-equilibrium

phases of the interaction. In addition to the elemental heavy target data sets, two hybrid targets—"marsbar" and "ISS wall"—are also included here. The marsbar is a target made of simulated Martian regolith (85%) and polyethylene binder (15%), and the ISS wall is a combination of aluminum, Nomex, Durette, and silicon rubber. Both targets were used in a study of neutron production behind candidate shielding materials to be used in space.

2. HIMAC experiments

Secondary neutron cross section measurements were run on either the PH2 or SB3 beam lines at HIMAC. Both beam lines provided ample space for neutron detector flight paths (between 3 and 5 meters), although the PH2 beamline had less room-scattered neutrons. Fig. 1 shows a schematic of the setup for several of the measurements which were conducted on the PH2 beam course. Beams from HIMAC were delivered on target and eventually stopped in a beam dump located 7–8 meters downstream from the target position. The placement of the liquid scintillator neutron detectors shown in Fig.

1 are typical; located at forward angles between 5° and 80° . Neutron energies were determined *via* time-of-flight techniques, and background neutrons were removed using the standard shadow bar method of periodically stopping neutrons coming directly from the target during the measurements.

Table 1 has information on the beam species, beam energy, target material, target density, measured angles, neutron energy thresholds, and location of the measurements performed at HIMAC. Information about target thicknesses, flight paths, and other experimental details may be found in [Nakamura 2006].⁵⁾ Elemental target masses ranged between Al and Pb, and beam masses ranged between He and Kr. In total, the measurements provided a comprehensive study on the systematics of neutron production on beam mass and target mass over a beam energy range between 200 and 600 MeV/nucleon.

Double differential cross sections, angular differential cross sections, and total cross sections were determined from the measurements and reported in various publications.^{6–8)} The data from the systems listed in Table 1 is available in [Nakamura 2006].⁵⁾

Fig. 1 Schematic layout of a typical time-of-flight experiment to measure secondary neutron cross sections on the PH2 beam line at HIMAC. Beam travels from left to right. Flight paths between the target and neutron detector varied between 3 to 5 meters. The He-filled tube was used with the Fe, Ar, and Kr beams (figure reprinted from [Heilbronn 2007]⁷⁾ by permission of author).

Table 1 Information on the beam, beam energy, targets, and measurement details for the heavy-target secondary neutron cross section measurements conducted at HIMAC

Beam species and energy (MeV/nucleon)	Targets	Angles measured	Minimum neutron energy	Beam line
^4He (230)	Al, Cu, Pb	5, 10, 20, 30, 40, 60, 80	5, 5, 5, 4, 3.5, 3.5, 3	PH2
^{12}C (290)	Cu, Pb, marsbar	5, 10, 20, 30, 40, 60, 80	10, 3, 3, 7, 4, 3, 3	SB3
^{12}C (400)	Cu, Pb, marsbar	5, 10, 20, 30, 40, 60, 80	8.5, 5, 3.5, 3, 3, 3, 3	PH2 and SB3
^{14}N (400)	Cu	5, 10, 20, 30, 40, 60, 80	6, 6, 5, 5.5, 5.5, 5, 3	PH2
^{20}Ne (400)	Cu, Pb, ISS wall	5, 10, 20, 30, 40, 60, 80	9, 6, 3.5, 3.5, 3, 3, 3	SB3
^{20}Ne (600)	Al, Cu, Pb, marsbar	5, 10, 20, 30, 40, 60, 80	6, 5.5, 4, 3.5, 3, 3, 3	PH2 and SB3
^{28}Si (600)	Al, Cu, Pb	5, 10, 20, 30, 40, 60, 80	7, 5.5, 4, 3.5, 3.5, 3, 3	PH2
^{40}Ar (400)	Cu, Pb	5, 10, 20, 30, 40, 60, 80	9, 6, 3.5, 3.5, 3, 3, 3	PH2 and SB3
^{40}Ar (560)	Cu, Pb, marsbar	5, 10, 20, 30, 40, 60, 80	10, 7, 3.5, 3.5, 3, 3, 3	PH2
^{56}Fe (500)	Al	5, 10, 20, 30, 40, 60, 80	12, 11, 7, 4, 3.5, 3, 3, 3	PH2
^{84}Kr (400)	Al, Cu, Pb	5, 10, 20, 30, 40, 60, 80	20 (all angles)	PH2
^{84}Xe (400)	Al, Cu, Pb	5, 10, 20, 30, 40, 60, 80	10, 6, 5, 3.5, 3.5, 3.5, 3	PH2 and SB3

3. Significance and impact of the HIMAC experiments

The cross-section data acquired through these experiments have been used extensively in the development and improvement of the physics models used in transport model calculations. Cross sections provide the most direct connection to event generators due to the absence of production of neutrons from interactions of secondary fragments in the target, leaving a clean description of the primary interaction between beam and target. Different transport codes use different physics models to describe the interaction, such as the quantum molecular dynamics model QMD, the Boltzmann master equation model BME, various versions of the cascade model such as the intra-nuclear cascade Liege model INCL, the quark-

gluon string model QGSM, the coalescence model, and various evaporation models such as the general evaporation model GEM. Because of the wide variety of models available to use, transport code predictions of the same phenomenon, such as neutron cross sections, can vary significantly from code to code. Comparison of code predictions to experimental data provides information on which physics models perform the best, and where those models can be improved if there are significant discrepancies between code and data. Fig. 2 shows a typical example of double differential neutron cross sections from the HIMAC experiments; in this case, the cross sections from 400 MeV/nucleon Kr+Pb.

The neutron spectra measured at HIMAC are unique in that (1) there is no dependence on the emission of neutrons from coulomb barriers, and (2) they

Fig. 2 Double differential secondary neutron cross sections from 400 MeV/nucleon Kr+Pb at the indicated angles. The spectra are offset by the successive factors of 10 for clarity. The lines are fits from a moving-source model. (reprinted from [Heilbronn 2007]⁷⁾ by permission of author).

are sensitive to all phases of the interaction as they are handled in transport code calculations (the initial phase, pre-equilibrium phase, equilibrium phase and final state interactions). At forward angles, such as 5°, high energy neutrons near the beam energy per nucleon are a result of projectile fragmentation (modeled by INCL, QMD, BME, QGSM) and evaporation from the projectile remnant (modeled by GEM). The low-energy neutron spectra below 20 MeV are almost exclusively from target remnant evaporation (GEM). The neutrons at intermediate energies are a result of several mechanisms including the initial stage, pre-equilibrium (i.e., coalescence) stage and equilibrium stage.

The HIMAC data have been used in several benchmark comparisons to transport code predictions.^{8,9)} Fig. 3 shows comparisons of double differential neutron cross sections from 400 MeV/nucleon Kr on ^{nat}Cu and ^{nat}Pb targets at 5, 10, 20, 30, 40, 60 and 80 degrees with FLUKA, MCNP6, and PHITS code predictions. The PHITS calculations were performed using two different

versions of their QMD model (JQMD and JQMD-2.0). In the past, the codes have had significant discrepancies between their predictions and data at high neutron energies, especially for heavy-mass targets.

Looking at the high-energy neutron data between 5 and 40 degrees for Cu and Pb targets in Fig. 3, there is a noticeable improvement in PHITS predictions using JQMD-2.0, a model whose improvements were guided in part by comparisons of JQMD with secondary neutron cross sections measured at HIMAC. To this day, improvements are continually being made to the physics models used in transport codes, and the data from HIMAC experiments highlighted here are an important component of the benchmarking process that leads to those improvements.

4. Summary

Secondary neutron cross section measurements performed at HIMAC have provided critical data needed for the improvement of transport codes calculations. The measurements conducted with

Fig. 3 Double differential neutron cross sections from 400 MeV/nucleon Kr projectiles on ^{nat}Cu and ^{nat}Pb targets (from [Tsai 2017]⁸⁾ by permission of the author) (Color online).

heavy targets (masses at or above aluminum) have led to improvements in many of the physics models employed by those codes that are used in all phases of intermediate heavy-ion interactions. In turn, improvements made in those physics models have led to more reliable predictions of neutron production across many applications, including isotope production, rare-ion beam production, accelerator shielding, space radiation protection, and medical physics.

Additional measurements are needed. One area of special need is the production of neutrons from He-induced interactions at higher beam energies than

have been measured to this point, which is particularly important for space radiation protection. Because He beams are being considered for pediatric radiotherapy, measurements at additional He energies between 50 and 300 MeV/nucleon that have not been measured thus far will be needed to provide an accurate prediction of the dose to healthy tissue from neutrons created by helium ions in tissue and beam line components.

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