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Calculated Proton-Induced Thick-Target Neutron and Gamma Yield Spectra for $E_p \leq 100$ MeV

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Introduction

Medium-Energy activation and shielding requirements have led to the production of libraries of evaluated nuclear data describing the reactions of charged particles and neutrons with typical accelerator materials. These libraries build mainly upon results of calculations with the GNASH preequilibrium statistical nuclear model code, as it has evolved during the past few years. One library describes the production of activation products by reactions of neutrons with $E_n \leq 100$ MeV; these data have been used to extend and enhance the cross-section library of the REAC-2 neutron activation code developed by Fred Mann at the Hanford Engineering Development Laboratory. A second library describes the production of activation products in reactions of protons with $E_p \leq 100$ MeV; these data have been used with the proton stopping data of Anderson and Ziegler to obtain thick-target activation yields for protons incident on several materials.

A third library contains evaluated proton and neutron reaction data for several targets, giving the cross sections for the production of secondary photons, neutrons, protons, deuterons and alphas. Also given are the angle-integrated spectra of these particles, expressed as discrete particle energies and/or continuous energy distributions. The angular distribution of secondary particles is described with the functional angular distribution systematics of Kalbach and Mann, as further developed by Kalbach for higher-energy applications. The data describing reactions with hydrogen are unique, combining R-Matrix analyses by D. C. Dodder and G. M. Hale with phase shift calculations by E. R. Siciliano and using Legendre polynomial angular distribution expansions produced in these two models. This library is in ENDF/B-VI format, using the new file six secondary particle production representation. Cross-sections for all materials extend to 100 MeV or higher and consist of data evaluated from ENDF/B-V below 0.0 MeV, modeled data at all energies, and sparse measured data. These files have been processed with the NJOY cross-section processing system for different applications. Coupled neutron-photon radiation transport libraries have been produced for continuous-energy Monte-Carlo calculations and for multigroup Monte-Carlo and $S_n$ calculations. These applications are the subject of a companion paper.
Thick-Target Yield Spectra

The library has been used to produce proton-induced thick-target secondary particle spectra by first using NJOY to process the library, producing incident-secondary group-to-group differential cross sections. These have been used in thick-target calculations with the stopping data of Anderson and Ziegler, producing thick-target angle-integrated secondary particle spectra. Similar calculations for thick-target angle-dependent secondary particle spectra have been accomplished by first producing double-differential incident-secondary group-to-group angle-dependent cross sections, which are then used in the thick target calculations.

The thick-target spectra of greatest interest have been for neutral particles produced by accelerated protons reacting with target and accelerator materials; these neutrons and γ spectra have been used to describe the sources in a variety of subsequent radiation transport calculations, such as that described in Ref. 13 for 75-MeV p+Cu neutrons in concrete. Benchmarking of calculated thick-target neutron spectra has been accomplished in Ref. 13 for p+Cu at 75-MeV, using the 0° measured neutron spectrum of Shin, Ishii, Uwamino, Sakai and Numata. The measurements by Nakamura, Yoshida and Shin of neutron and γ spectra at 0°, 15°, 30°, 45° and 75° produced by 52-MeV protons on C, Fe, Cu and Pb provide an excellent collection of data against which calculations with this library may be compared. Fig. 1 compares the calculated angle-integrated thick-target neutron yield spectrum for 52-MeV p+Fe with those measured by Nakamura et al. at the five angles. The calculated spectrum includes low- and high-energy components not measured and compares well with the measured spectra. Angle-dependent calculated spectra not shown compare very well with the corresponding measured spectra, indicating a softening and decrease in magnitude with angle. Fig. 1 also compares the calculated thick-target γ spectrum for 52-MeV p+Fe with those measured by Nakamura et al. at the five angles. The calculated spectrum is isotropic because of the assumption in GNASH, and thus the data library, that photons are emitted isotropically. Again, the calculated spectrum includes low- and high-energy components not measured.

Conclusions

Considering that photons and neutrons emitted at back angles were not measured by Nakamura et al., the benchmark comparisons of calculated and measured spectra are very good. The use of evaluated data in the calculation of proton-induced neutron and γ sources and in the subsequent transport of these particles is offered as an alternative methodology to the use of intranuclear-cascade and evaporation model cross sections, which are limited in validity below 100 MeV.
References


Figure Captions

Fig. 1 52-MeV p on Fe measured and calculated n and γ spectra.
Angle-integrated thick-target $n$ yield spectrum and isotropic thick-target $\gamma$ yield spectrum calculated with proton stopping data of Anderson and Ziegler and group-to-group $p$-to-$n$ and $p$-to-$\gamma$ cross sections processed with NJOY from an ENDF/B-VI format library of data evaluated using GNASH results.


Fig. 1 52-MeV $p$ on Fe measured and calculated $n$ and $\gamma$ spectra.