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Double Differential Neutron Emission Cross Sections on n+Fe-56 reaction for Reactor Shielding

Young-Ouk Lee and Jonghwa Chang

Korea Atomic Energy Research Institute
P.O. Box 105 Yusong, Taejon 305-600, Korea

Abstract

We have evaluated energy-angle correlated neutron emission spectra on the n+Fe-56 reaction for incident neutron energies from a few MeV to 20 MeV, based on available measurements and theoretical models. Optical-statistical approach was applied to take into account consistently the contribution of the direct, preequilibrium and statistical equilibrium processes into different reaction channels. Coupled-channel optical model calculation was performed to prepare neutron transmission coefficients and direct reaction contributions to inelastic scattering from low-lying discrete state. The Kalbach-Mann systematics was applied to generate the energy-angle correlated spectra of emitted neutrons into continuum state.

I. Backgroud

In many applications where there is a broad spectrum of neutrons and the neutron flux is not highly directionally oriented, the neutron multiplication, spectrum and orientation can be fairly accurately calculated without considering energy-angle correlation effects in the double differential cross sections. However, in a narrow spectrum of neutrons that are highly directionally oriented, these correlation effects should be considered. The uncorrelated data does not contain the correlation between energy spectra and cosine (angle) spectra of emitting neutrons, so that in a transport calculation all moments of the flux will have the same energy spectrum, and each will be effected by the average angular distribution. For lower energy applications, for example fission reactors, it is adequate to use the uncorrelated data - in this case the most important effect will be the overall neutron multiplication and spectrum. However, for directionally-oriented high energy applications, correlated data should be used.

Double differential cross sections of neutrons emitted from the n+Fe-56 reaction are important for highly directional and hardened neutron transport problems such as fast fission or fusion reactor shielding. While available high energy libraries provide energy-angle correlated double differential spectra of emitting particles for incident neutron energies above 20 MeV, most of conventional neutron libraries for energies below 20 MeV only provide uncorrelated emission spectra of neutrons using the combination of MF4 and MF5 sections.

In this work, we have evaluated energy-angle correlated neutron emission cross sections and spectra on the n+Fe-56 reaction for incident neutron energies from a few MeV to 20 MeV, based on available measurements and theoretical models. The resulting cross section data was compiled into MF6 file of ENDF6 format. An integral test is planned with an iron shielding benchmark problems using a modified ENDF6 library of n+Fe-56 reaction having the resulting MF6 file instead of the existing MF4 and MF5 files.

II. Evaluation Methods

1. Reference Measurements

For the reference data, the EXFOR [?] database was extensively surveyed and analyzed, especially on the emission cross sections and spectra of neutrons for energies above a few MeV up to 20 MeV. Direct reaction data such as total, reaction, elastic, and direct inelastic scattering data were also needed for the coupled-channel optical model calculations.

2. Direct Reaction Models

The optical model supplies particle transmission coefficients for Hauser-Feshbach statistical theory analysis used in nuclear data evaluations. Total, reaction, and elastic cross sections were theoretically calculated through the transmission coefficients adopted from Lee's recent optical model analysis for neutrons and protons of energies up to to 250 MeV [?]. Direct reaction contributions to elastic scattering and inelastic scattering from low-lying discrete states were provided by the coupled-channel optical model analysis with coupling built sing nuclear wave functions of the non-axial soft-rotator Hamiltonian model consistent with the nuclear structure of Fe-56 [?].

3. Emission Models

For the emission reaction, the latest version of the GNASH code [?] has been used to calculate nuclear reaction cross sections using the Hauser-Feshbach theory for equilibrium decay and the exciton model for preequilibrium decay. The Hauser-Feshbach theory with full angular momentum and parity conservation calculated the equilibrium emission. The exciton model was used to describe the processes of preequilibrium emission, and damping to equilibrium, during the evolution of the reaction. The energy-angle correlations for outgoing particles are based on the Kalbach systematics [?]. The file of discrete level information and ground-state masses, spin and parities were provided [?]. The mass values were based upon 1995 Audi compilation [?], and supplemented in the case of unmeasured masses with values from the Moeller and Nix calculations [?]. The Ignatyuk [?] nuclear level densities are used, which include the washing-out of shell effects with increasing excitation energy, and are matched continuously onto low-lying experimental discrete levels.

III. Results

In Fig. 1, the total cross sections obtained from our theoretical calculations are compared with three measured data sets. The calculated cross sections agree very well with Dietrich's data which have the smallest errors. Figure 2 shows calculated elastic scattering cross sections for five incident neutron energies compared with measurement sets, showing quite a good agreements for all energies. Compound reaction contributions, which are not included in the figure, are negligible for energies above a few MeV. Direct reaction contributions to inelastic scattering from first 2+ level (0.847 MeV) were plotted in Fig. 3 for 7 incident neutron energies with available measurements. Angular distributions of the inelastically scattered neutrons are in acceptable agreements with all measured data.

As an example of emission model calculation results, neutron production cross sections are presented in Fig. 4, showing an excellent agreement with the measurement of Simakov [?]. Neutron production cross section is an integral of emitted neutrons in all energies and directions, and is an inclusive channel consisting of all neutron emitting reactions such as (n,n), (n,n'), (2,2n), ... etc from the direct reaction and emission models. Since we produced fairly good

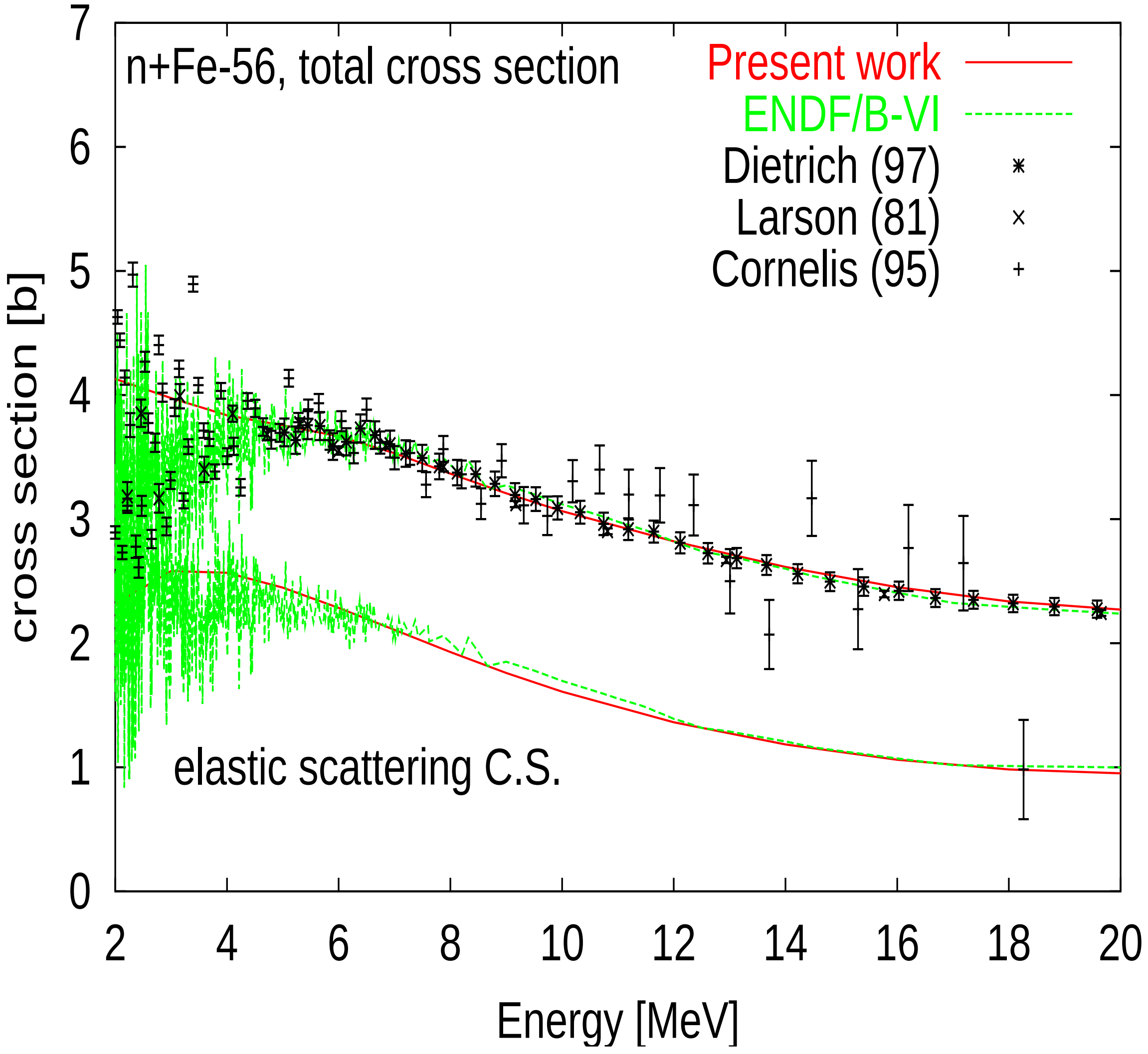

Figure 1: Neutron total cross sections

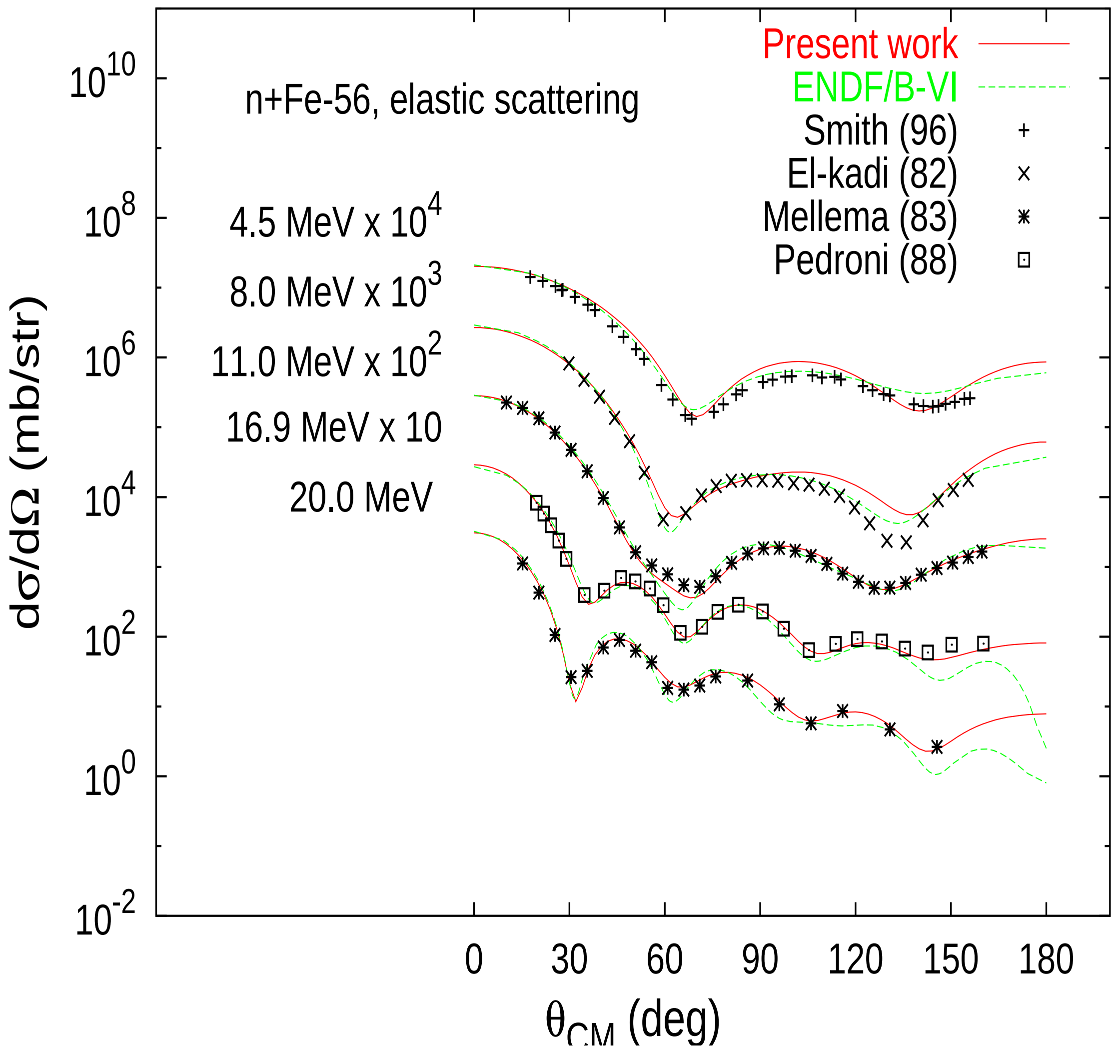

Figure 2: Elastic anglar distributions for five incident neutron energies

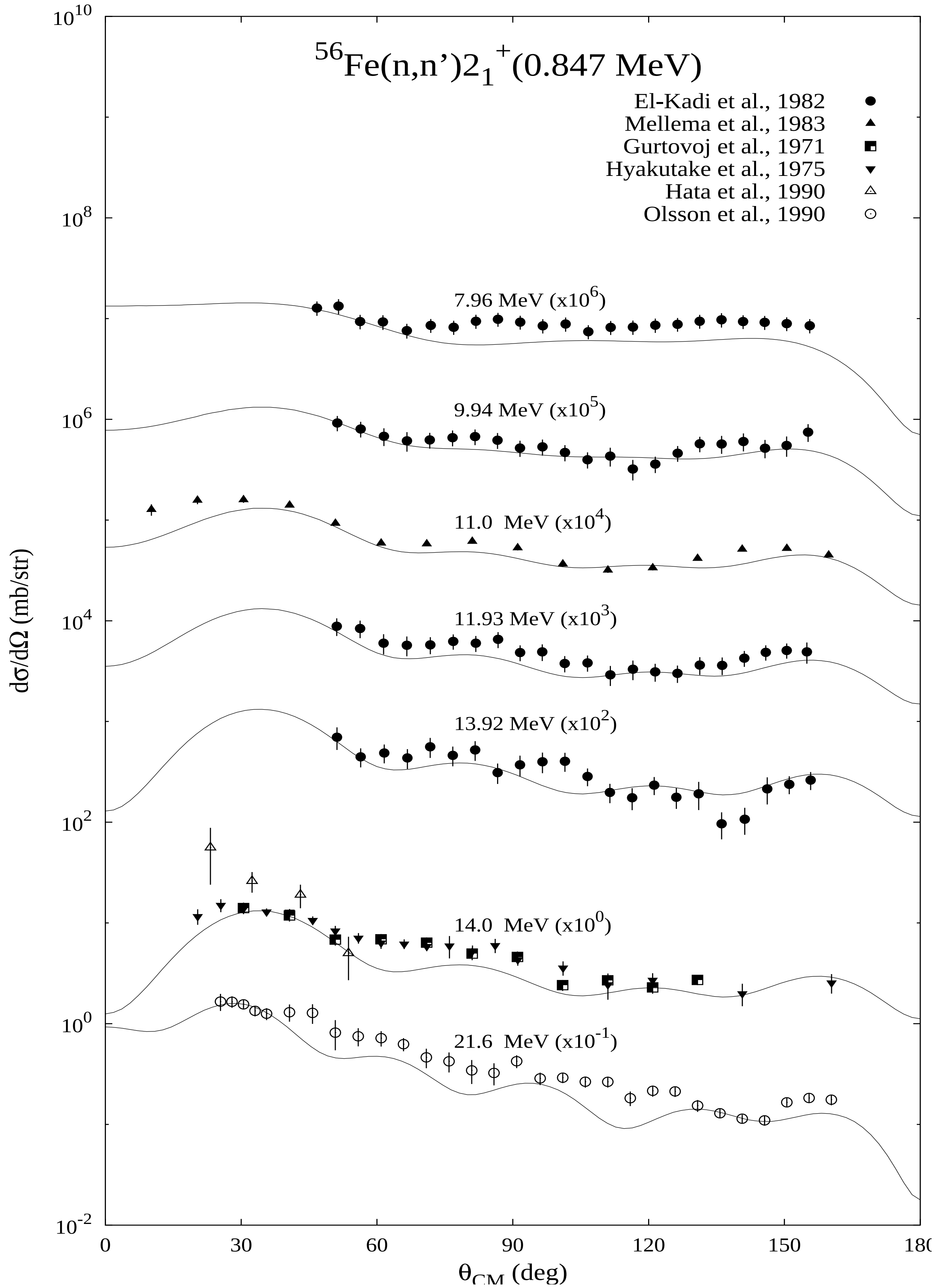

Figure 3: Direct reaction contributions to inelastic scattering from first 2+ level (0.847 MeV)

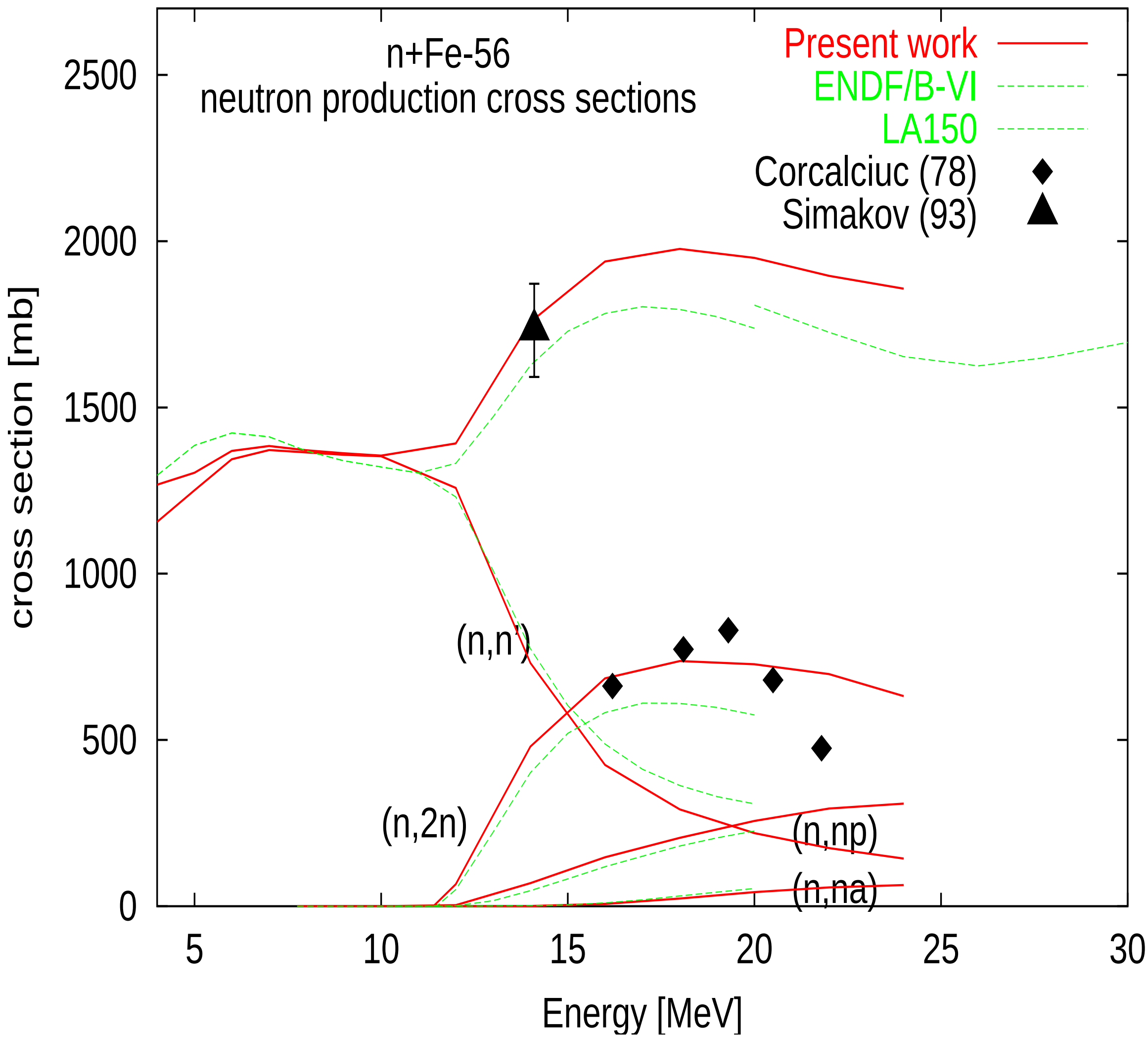

Figure 4: Neutron production cross sections

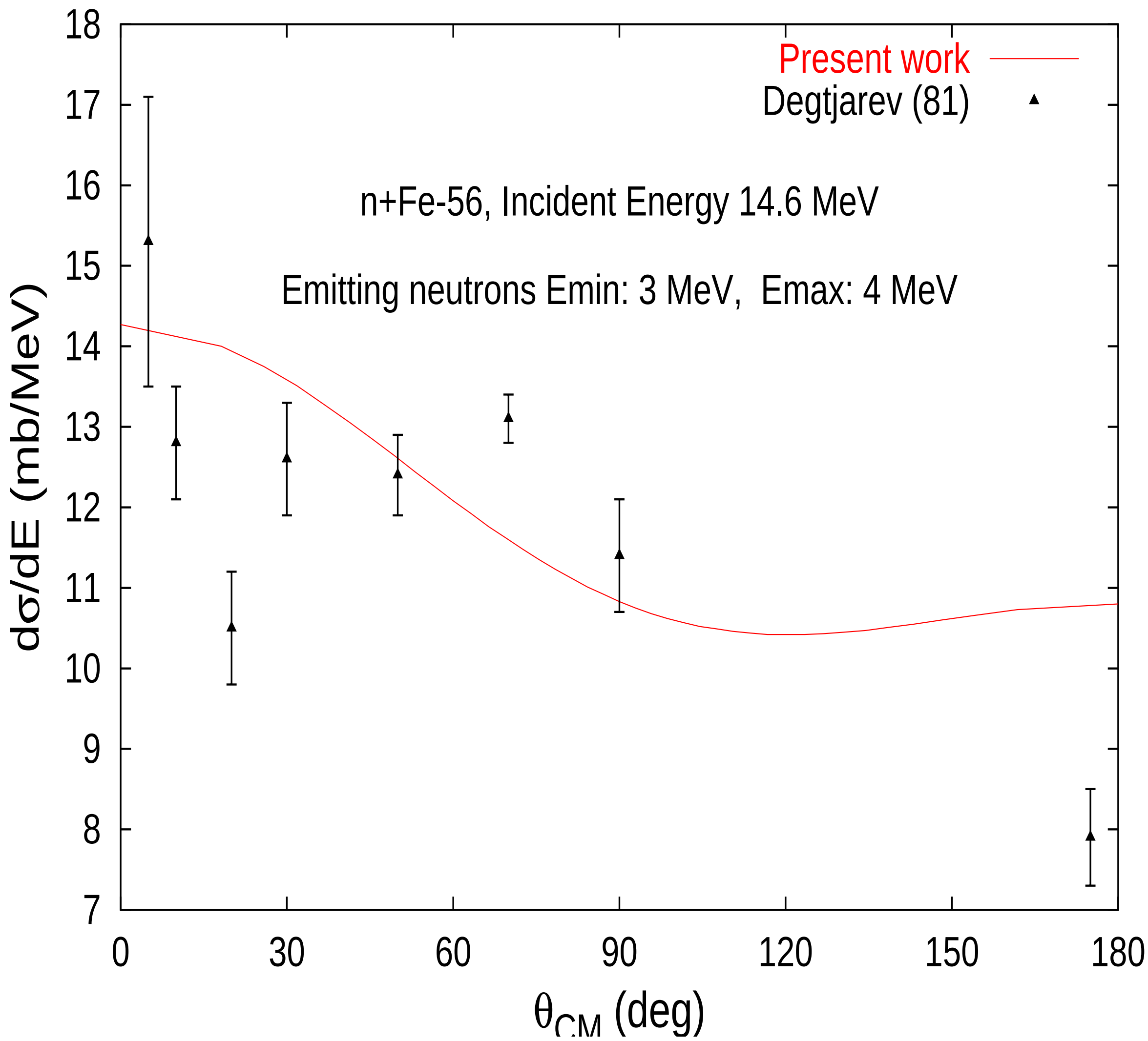

Figure 5: Angular distribution of emistting neutrons with energies between 3 and 4 MeV from 14.6 MeV incident neutron on Fe-56

calculated neutron-emitting exclusive channels from the direct reaction models as shown in Figs. 1-3 as well as the inclusive neutron production cross section as in Fig. 4, it is assumed that the emission models give us, at least, consistent integral quantity of neutron emitting channels.

Another good example of neutron emitting inclusive channels is presented in Fig. 5, which represents an angular distribution of emitting neutrons with energies between 3 and 4 MeV of incident 14.6 MeV of (n,xn) reactions compared with the measured data of Degtjarev [?]. As shown in the figure, the calculated results agree with the data within acceptable ranges except for the very backward angle (175 degree).

Acknowledgements

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