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Evaluation of n+Mn-55 cross section data up to 150 MeV neutron energy

P. Pereslavtsev[a] and U. Fischer

Forschungszentrum Karlsruhe, Institut für Reaktorsicherheit, Postfach 3640, 76021 Karlsruhe, Germany

Abstract. A new evaluation was performed for the reaction system n + ^{55}Mn in the neutron energy range from 0.001 to 150 MeV. The evaluation is based on the use of the ECIS96 and GNASH codes. A good description of available experimental data was achieved. A very limited set of existing evaluated data from the available international nuclear data libraries was used for the evaluation. The final general purpose data file was prepared in standard ENDF-6 format and was verified with standard format checking utilities. The data file will undergo benchmark testing and will be finally integrated into the JEFF-3.2 data library.

1 Introduction

The European Fusion Technology Programme has assigned highest priority to the development of a high quality general-purpose neutron data library up to 150 MeV by adopting existing high-energy evaluations, up-grading and adapting them to the EFF/JEFF data and performing new evaluations as required [1]. According to the priority needs a general purpose neutron data file was elaborated for the reaction system n + ^{55}Mn up to 150 MeV neutron energy.

2 Evaluation procedure

The flowchart of the evaluation procedure is shown in figure 1. Optical model calculations represent the first and the most important step in the process of evaluating nuclear data. The ECIS96 code was employed for the optical model calculations [2]. It was used to generate transmission coefficients for subsequent nuclear model calculations, to calculate total, reaction and elastic scattering cross sections, to prepare cross sections for collective excitations, to calculate angular distributions for elastic and inelastic neutron scattering. For the nuclear model calculations there are also required nuclear level structure, mass table and some model parameters. This information was taken from the RIPL-2 international reference library [3]. Nuclear model calculations were performed with the GNASH code [4]. It was used for calculating individual reaction cross sections and secondary particle emission spectra. The evaluation procedure has been automated to a large extent to enable the prepararation of the final evaluated file in ENDF-6 data format.

3 Optical model calculations

The proper chosen optical model potentials (OMP) determine the quality of the final evaluated data. In the present

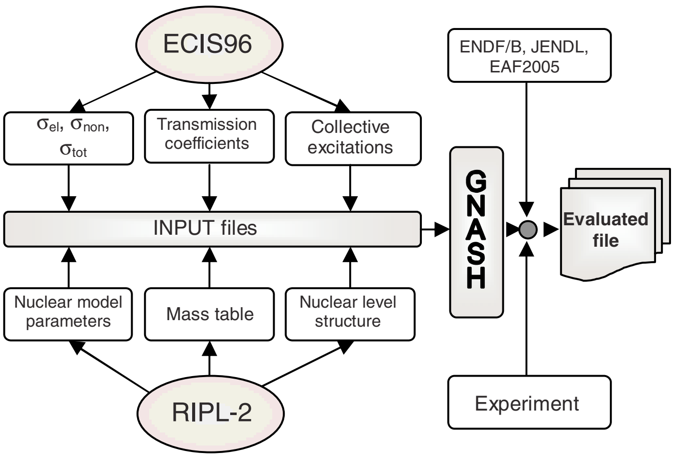

Fig. 1. Flowchart for the evaluation of ^{55}Mn neutron cross section data up to 150 MeV neutron energy.

evaluation, emissions of neutrons, protons, deuterons, tritons hellions (He-3) and alphas were considered. For incident neutrons and protons the OMPs of Koning and Delaroche [5] were used. These OMPs include local modifications for ^{55}Mn which were used for the present optical model calculations. For deuterons and alphas only the global OMPs of Nankai university, China [6] and by Avrigeanu [7] were applied. For tritons and helions new global OMPs were developed [8]. An automated procedure was elaborated to generate the transmission coefficients for the required energy mesh for all particles mentioned; the optical model potential used in this procedure can be easily changed.

The total cross section is the sum of cross sections for all possible reaction channels and thus indicates the consistency of the nuclear data evaluation. Total and elastic scattering cross sections are directly used in transport calculations. The results of ECIS96 optical model calculations for total cross section are shown in figure 2. The ECIS96 results obtained with the Koning and Delaroche OMPs fit very well the experimental data above 3 MeV. Although the calculated total cross section below 3 MeV looks quite reasonable, the evaluation for these energies is based on experimental data as shown in figure 2.

[a] Presenting author, e-mail: pavel.pereslavtsev@irs.fzk.de

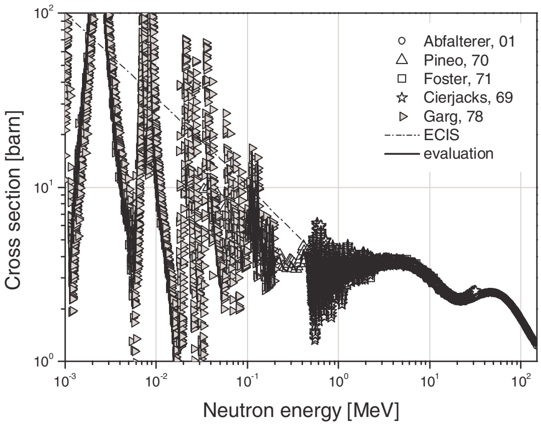

Fig. 2. Total cross section for n+^{55}Mn.

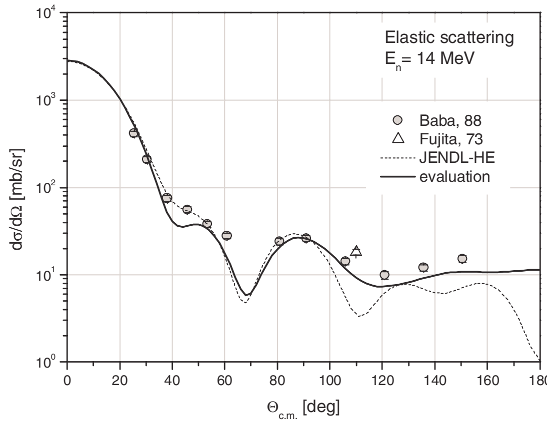

Fig. 3. Elastic scattering angular distribution for 14 MeV incident neutron energy.

Below 3 MeV, an underestimation of the elastic scattering cross section was revealed. Such an underestimation was also found for the elastic scattering angular distributions at low energies.

Direct contributions to the inelastic scattering were calculated with ECIS96 for several excited states. For other nuclear levels only equilibrium inelastic scattering was accounted for. The deformation parameters were chosen to fit the high energy tails of the secondary neutron emission spectra. The equilibrium parts of the cross sections leading to excited states of the nucleus were calculated with GNASH.

The angular distributions for elastically scattered neutron were compared with JENDL-HE results over the entire energy range up to 150 MeV. Experimental data cover neutron energies only up to 14 MeV. As already mentioned the elastic scattering cross section has serious deficiencies below 3 MeV. This problem was solved by adding the elastic scattering cross section from equilibrium step of nuclear reaction. This effect is especially important at low energies and rapidly washes out with energy increase. At energies above 5 MeV this effect is small and results obtained with OMP show good agreement with experimental data, figure 3. The angular distributions for inelastic neutron scattering were obtained as a sum of equilibrium and direct parts (whenever ECIS96 results are available).

4 Nuclear model calculations with GNASH

Nuclear reaction cross sections and particle emission spectra were calculated with the GNASH code. GNASH utilizes the Hauser-Feshbach model for multiple particle emissions through statistical processes, the exciton model of Kalbach [9] for single particle and the model of Chadwick [10] for multiple particle pre-equilibrium reactions. For compound nuclear reactions we used the Ignatyuk form of the Fermi-gas model with energy-dependent level density parameters [11]. Gamma-ray transmission coefficients were calculated using the Kopecky and Uhl model [12].

In the pre-equilibrium model used in GNASH, the excitation of the collective states with different multi-polarities is not considered. It was previously reported that for inelastically scattered particles, these collective states are responsible for the well known humps in the high energy tails of the energy emission spectra. To account for this effect we applied the model developed by Kalbach [13]. We considered the excitation of the giant resonances with four different multipolarities: low energy octupole (LEOR) with 3− collective state, 2+ giant quadrupole (GQR), 0+ giant monopole (GMR) and 3− high energy octupole (HEOR) resonances. The position of the maximum, the width and the deformation parameter of the resonances are calculated within this model. The cross section for each resonance was calculated with ECIS96 at all neutron incidence energies and then it was broadened in energy assuming a Gaussian distribution. This procedure was automated and the data generated for all collective excitations in the desired incidence energy mesh can be read in GNASH.

Since the evaluation covers incident neutron energies up to 150 MeV, we accounted for in the calculations as many as possible reaction paths. The number of residual nuclides considered was limited by a maximum charge difference of $\Delta Z = 7$ and a maximum mass difference of $\Delta A = 20$ with respect to the target nucleus ^{55}Mn.

4.1 Exclusive nuclear reactions

Exclusive nuclear reactions are those with explicit specifications of the types and number of outgoing particles. In the evaluation we considered (n,n′), (n,2n), (n,p), (n,d), (n,t), (n,^{3}He), (n, α), (n,np), (n,nα) and (n,γ) reactions. Data for these reactions were included in the low energy part of the evaluated file. Above 20 MeV these cross sections were assigned zero on the file since they are included in the lumped MT = 5 reaction type. Since the secondary recoil emission spectra are included in the evaluation, these cross sections can be retrieved for energies up to 150 MeV.

The total inelastic scattering cross section for n+^{55}Mn is not well measured, figure 4. There are experimental data below 1 MeV and only one measurement at 14 MeV. At low energies the new evaluation fits experimental data and is close to JENDL-HE results. But at higher energies (especially at maximum) the difference is significant. The new results reproduce the experimental data point at 14 MeV while the

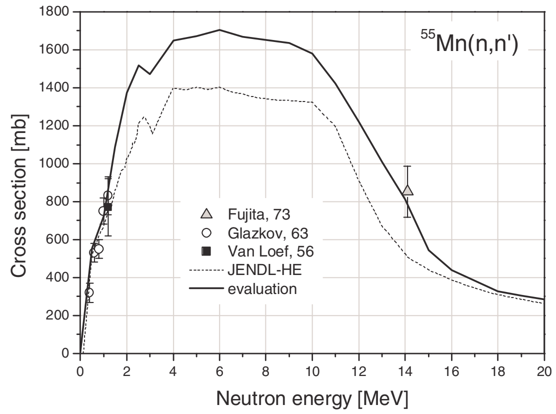

Fig. 4. Total inelastic scattering cross section.

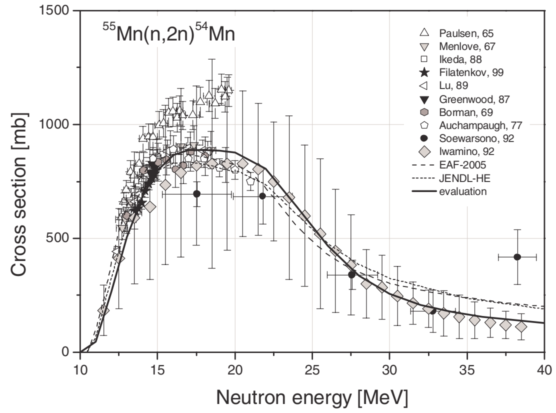

Fig. 5. ^{55}Mn(n,2n)^{54}Mn cross section.

JENDL-HE data are well below. This difference comes from lower neutron emission spectra at 14 MeV (see later).

The (n,2n) cross section is the second dominant channel at energies above 12 MeV, figure 5. For this cross section the GNASH results were used without any modifications. Although all evaluations (present, EAF-2005, JENDL-HE) are close together and fit well the majority of experimental data, the present results account for the latest measurements around 14 MeV and the high energy data above 20 MeV.

For the (n,p) reaction we used slightly normalised GNASH data. The EAF-2005 data do not fit the experimental results below 14 MeV. The (n,α) cross section calculated with GNASH reproduces the recent data around 14 MeV. Nevertheless EAF-2005 data were adopted for the evaluation because the agreement with experimental data is better for this channel.

The JENDL-HE evaluation for the (n,t) reaction (= EAF-2005) is declared to be (n,p) cross section shifted to the (n,t) threshold and normalized to experimental data. The evaluation for the (n,t) channel was performed fully with GNASH results without additional corrections. The very weak (n,^{3}He) channel has many problems. There are several measurements around 14 MeV but no evaluation reproduces them. There exists no explanation to this fact so far. GNASH results were used for the evaluation. JENDL-HE data were taken for the (n,γ) cross section. GNASH results were also used for the (n,np), (n,d) and (n,nα) channels.

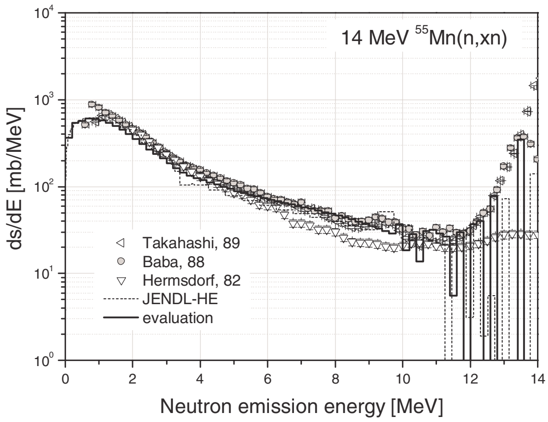

Fig. 6. Neutron emission spectrum for 14 MeV neutron incident energy.

4.2 Particle emission spectra

We applied different representation schemes for particle emission spectra below and above 20 MeV. Below 20 MeV particle emission spectra are given on the data file for all exclusive reactions in separate sections. Exclusive neutron emission spectra are not produced in GNASH. Therefore we elaborated an interface for the GNASH code to enable the calculation of exclusive spectra based on the approach developed in [14].

All measurements of neutron emission spectra for n+^{55}Mn were made at 14 MeV incident neutron energy. Figure 6 shows the evaluated neutron emission spectrum compared to experimental data. The newly evaluated neutron spectrum is closer to the experimental data than the JENDL-HE results. The evaluation of photon production data is based entirely on GNASH results. Below 20 MeV the evaluation contains photon production spectra for all exclusive reactions. The angular distributions of the secondary photons are assumed to be isotropic.

The angular distributions calculated for neutrons and charged particles are based on the Kalbach systematics [15]. In combination with the energy emission spectra this approach provides double differential particle emission spectra, figure 7.

The high energy part of the file contains the total, elastic scattering and lumped MT = 5 cross sections as well as secondary particle emission spectra and recoil nuclei spectra. For all emitted particles and recoil nuclei the energy dependent yields are given. For neutrons and charged particles the emission spectra are stored in the centre-of-mass frame and the pre-equilibrium fractions are given to enable the restoring of double-differential spectra. Total photon emission energy spectra are given in the laboratory frame with an isotropic angular distribution.

The inclusion of recoil spectra on the evaluated data file is required for radiation damage and nuclear heating calculations. The model we used for recoil spectra calculations is described in detail in [16]. The calculated recoil spectra are tabulated as angle-integrated energy distributions in the laboratory frame assuming the angular distributions to be isotropic.

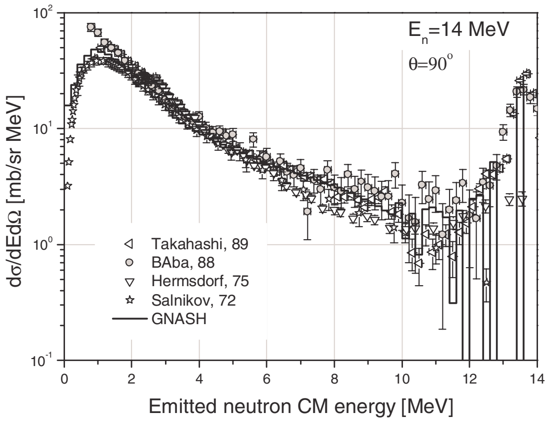

Fig. 7. Double-differential neutron emission spectrum for 14 MeV neutrons.

5 ENDF-6 formatted general purpose data file

The evaluated data were processed into a complete general purpose data file according to the ENDF-6 format rules. Below 20 MeV the data file is organized in the traditional way except the presence of the lumped MT = 5 section. The evaluated total and elastic scattering cross sections are given up to 150 MeV. Below 20 MeV the cross section of the MT = 5 reaction is set to zero. The energy-angle distributions for secondary particles below 20 MeV are stored on MF = 6 file for the individual MT = 103–107 reactions (rather than including them in the MT = 5 reaction section). For storing the photon production the MF = 12–15 file sections were used. The elastic scattering angular distributions are presented in tabular form for all incidence energies.

The high energy part of the evaluated data file contains the following file sections: MF = 3 with cross sections for the MT = 1,2,5 reactions (total, elastic scattering, and lumped particle emission), MF = 4 with angular distributions for MT = 2, and MF = 6 with energy-angle distributions for MT = 5. All other cross sections are set to zero above 20 MeV neutron incidence energy. The combination of MF = 3 (MT = 5) and MF = 6 (MT = 5) data enables the recovering of the double-differential spectra for the secondary particles and recoil nuclei.

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