Evaluation of Cross Sections of ^{56}Fe up to 3 GeV
and
Integral Benchmark Calculation for Thick Target Yield

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The neutron and proton cross sections of ^{56}Fe were evaluated up to 3 GeV. JENDL High Energy File of ^{56}Fe were developed for use in transport calculation. For neutrons, the high-energy data are merged with JENDL3.3-file. Integral benchmark calculations for thick target neutron yields (TTY) for 113 MeV and 256 MeV proton bombardment of Fe targets were performed using the evaluated libraries. Calculated TTY neutron spectra were compared with experimental data. For 113 MeV, calculated TTY at 7.5 degree underestimated in the emitted neutron energy range above 10 MeV. For 256 MeV, calculated TTY well agree with experimental data except below 10 MeV.

1. Introduction

High-energy evaluated nuclear data are needed for accelerator engineering and radiation protection of air crew and space astronauts. In LA150[1], neutron and proton cross sections up to 150 MeV are included. Above 150 MeV, nuclear data file are also needed. High-energy nuclear data evaluation for more than 40 elements has been started by JNDC High Energy Nuclear Data Evaluation Working Group. For some elements, evaluations were performed. Integral benchmark calculations has also been performed by the JNDC Intermediate and High Energy Nuclear Data Integral Test Working Group. In this study, nuclear data evaluation for ^{56}Fe and Integral benchmark calculations for proton induced thick target neutron yields were reported.

2. Evaluation of ^{56}Fe cross section

2.1 Evaluation code

Several kinds of computation codes were used in this evaluation as shown in **Fig.1**. ECISPLOT [2] and Quick-GNASH [3] code system were used for data evaluation up to 250 MeV. Total, elastic and non-elastic cross sections for neutron and proton in the energy range from 250 MeV to 3GeV were calculated by TOTELA [4] code. Particle production cross sections and angular distributions for non-elastic scattering were evaluated with JQMD code [5]. For neutrons, the high-energy data are merged with JENDL3.3-file [6].

2.2 Results of evaluation

Experimental data [7] are presented from **Fig.2** to **Fig.5** compared with evaluated data. **Figure 2** shows neutron induced total cross section of ^{56}Fe. Neutron elastic scattering cross sections were also presented in **Fig. 3**. As shown in those figures, evaluated cross sections well agree with experimental data. Proton induced reaction and elastic cross sections are shown in **Figures 4 and 5**, respectively. In the same manner for neutron, there are good agreement between evaluated data and experimental data.

In **Fig.6**, evaluated double differential cross sections of (p,xn) reactions are shown compared with experimental data[8,9,10,11]. PLDDX[12] were used to calculate DDX from evaluated nuclear data file. Above 597 MeV, evaluated data well agree with experimental data. At 113 MeV, there is some differences below neutron energy 10 MeV. There are also some differences above 80 MeV at 30 degree. and above 60 MeV at 60 degree.

3. Integral benchmark calculation

3.1 Experimental data

Experimental data of Thick target neutron yield (TTY) were used in this integral benchmark calculation. For Fe target, experimental data from LANL[11,13] were compared with calculation results. For, Cu target, JAERI data[14] were used. Experimental conditions are shown in **Table 1**.

Table 1 Experimental conditions of TTY data

Target	Proton energy (MeV)	Detected angle (degree)	Reference
^{nat}Fe	256	7.5, 30, 60, 150	[13]
	113	30, 60, 120, 150	[11]
^{nat}Cu	68	0, 15, 30, 45, 90, 120	[14]

3.2 Calculation method

TTY spectra were calculated by **Eq(1)** [15], using neutron production cross sections and non-elastic cross sections of evaluated nuclear data.

$$\frac{d^2n}{d\Omega dE_n} = \int_0^{E_p} N \frac{d^2\sigma}{d\Omega dE_n}\left|\frac{dE}{dx}\right|^{-1} \exp\left(-N\int_E^{E_p}\sigma_{non}(E')\left|\frac{dE'}{dx}\right|^{-1}dE'\right)dE \, , \tag{1}$$

where $d^2n/d\Omega dE_n$ is the TTY neutron spectra, N the atomic density of the target material, $d^2\sigma/d\Omega dE_n$ the double differential neutron production cross section, dE'/dx the stopping power and $\sigma_{non}(E')$ the non-elastic cross section for proton at the energy E'. PLDDX was used to calculate double differential neutron production cross sections from JENDL high-energy file.

3.3 Results of calculation

(1) Fe

For TTY calculation of ^{nat}Fe, evaluated reaction cross section and DDX of ^{56}Fe were used. **Figures 7 and 8** show comparisons of experimental[11,13] and calculated TTY for 256 MeV and 113 MeV proton incidence, respectively. There are some differences in these comparisons. For 256 MeV, neutron energy below 10 MeV, calculated results overestimated experimental data. This differences are attributed to multiple scattering of neutron in Fe target. In this TTY calculation, multiple scattering is ignored. Above 60 MeV, calculated results also show overestimation. Calculated 113 MeV TTY using LA150 are shown in **Fig.7**. Calculated TTY with present evaluated data overestimate below 10 MeV. There are no overestimation with LA150 in the same energy region. It is necessary to compare between present evaluation and LA150. Above 10MeV, there are no large differences between results from present data and LA150. For 7.5 degree, there are large differences between experimental data and calculation results.

One of the reason is assumed to thickness of experimental target is not enough long. Because, in this calculation, all primary proton is stopped in the target.

To check the reason of the above mentioned differences, bench mark calculation using transport code (ex. MCNPX[16]) is needed. Unfortunately, the latest distributed version of MCNPX, transport calculation with proton nuclear data library can not be performed.

(2) Cu

For TTY calculation of ^{nat}Cu, evaluated reaction cross section and DDX of ^{63}Cu were used. **Figure 9** shows comparisons of experimental and calculated TTY. From 0 to 45 degree. calculated results well agree with experimental data. From 60 to 120 degree., above 15 MeV, calculated results overestimated experimental data.

4. Conclusion

The neutron and proton cross sections of iron (^{56}Fe) were evaluated up to 3 GeV and JENDL High Energy File of iron were developed. Integral benchmark calculations for thick target neutron yields (TTY) for Fe and Cu targets. Several differences were found between experimental data and calculation results. Bench mark calculation using transport code is needed to investigate these differences. The evaluated data are very useful for accelerator engineering related to radiation.

References

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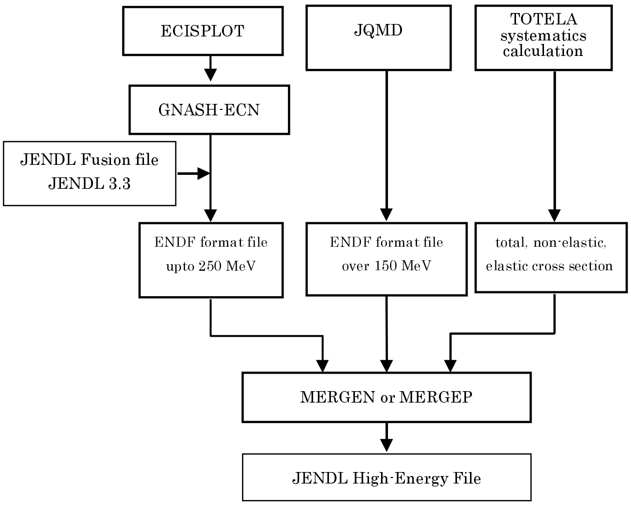


Fig 1 Flow chart of high-energy nuclear data evaluation and file development

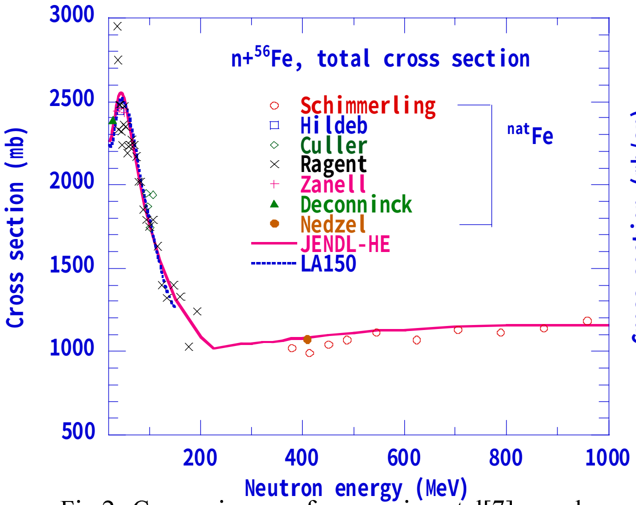


Fig.2 Comparison of experimental[7] and evaluated total cross sections of n + ^{56}Fe

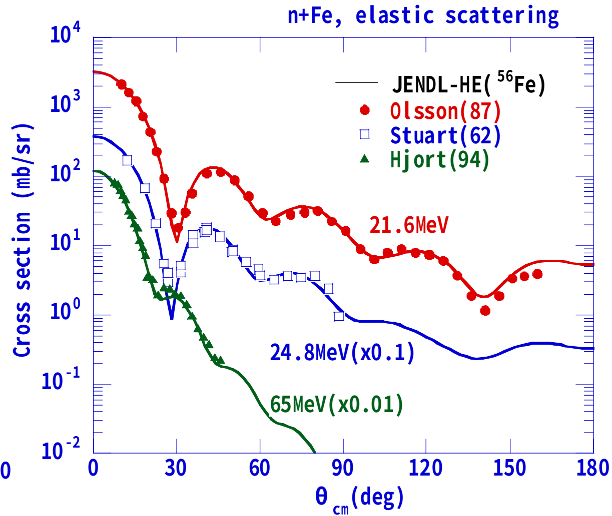


Fig.3 Comparison of experimental[7] and evaluated elastic cross sections of n + ^{56}Fe

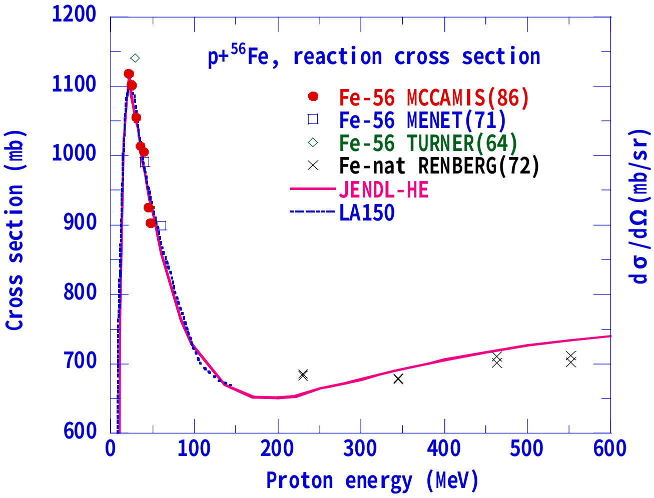


Fig.4 Comparison of experimental[7] and evaluated total cross sections of p + ^{56}Fe

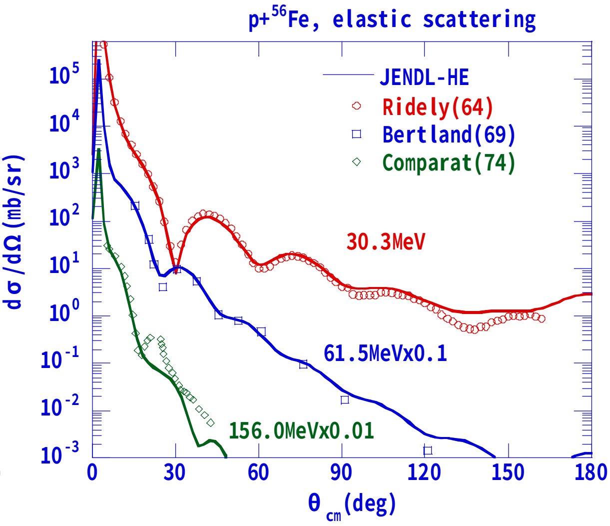
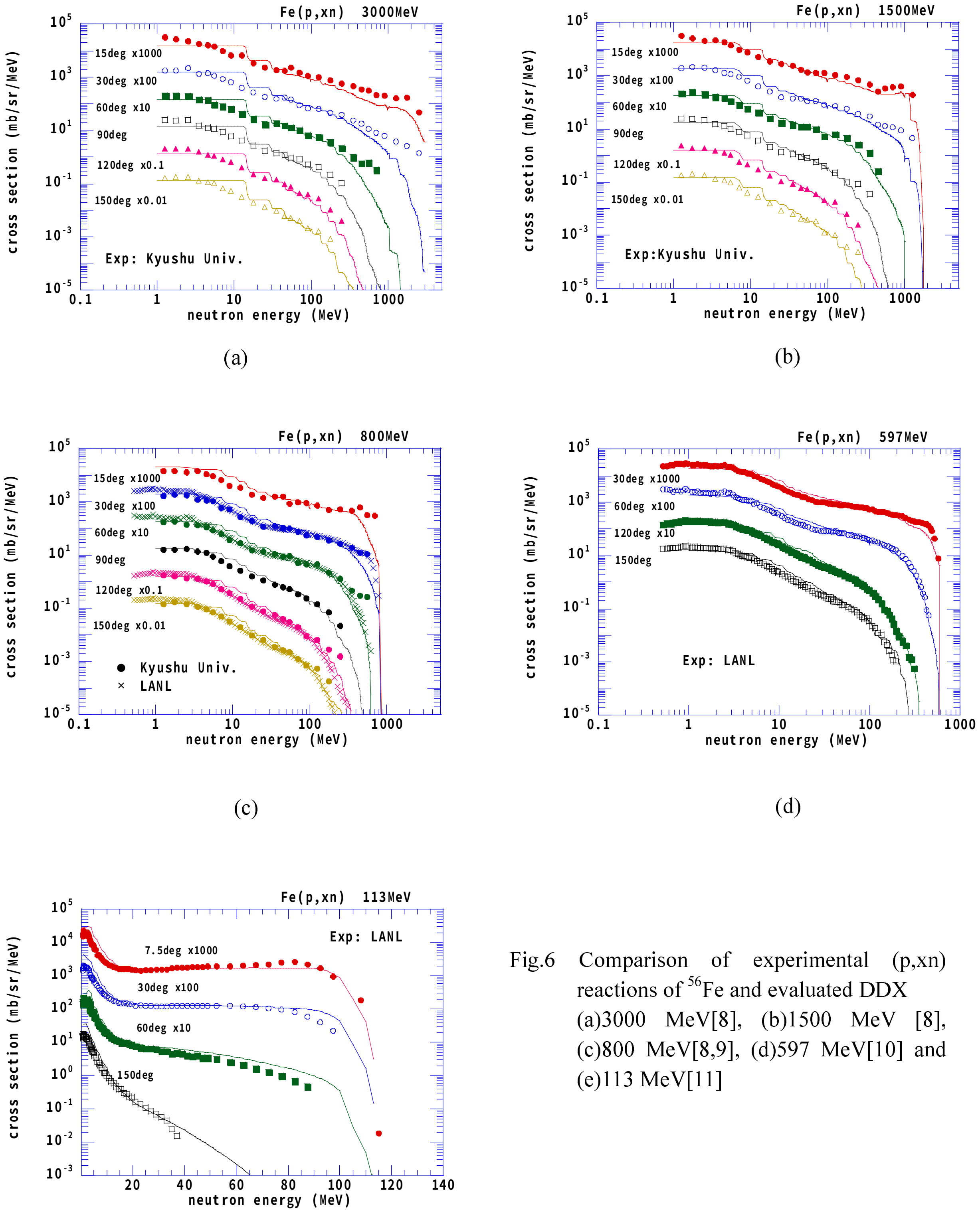


Fig.5 Comparison of experimental[7] and evaluated elastic cross sections of p + ^{56}Fe



(a)

(b)

(c)

(d)

(e)

Fig.6 Comparison of experimental (p,xn) reactions of ^{56}Fe and evaluated DDX (a)3000 MeV[8], (b)1500 MeV [8], (c)800 MeV[8,9], (d)597 MeV[10] and (e)113 MeV[11]

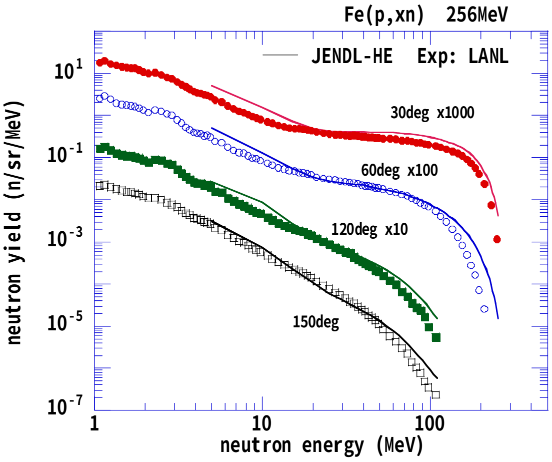


Fig.7 Comparison of experimental[13] and calculated 256 MeV proton TTY from Fe

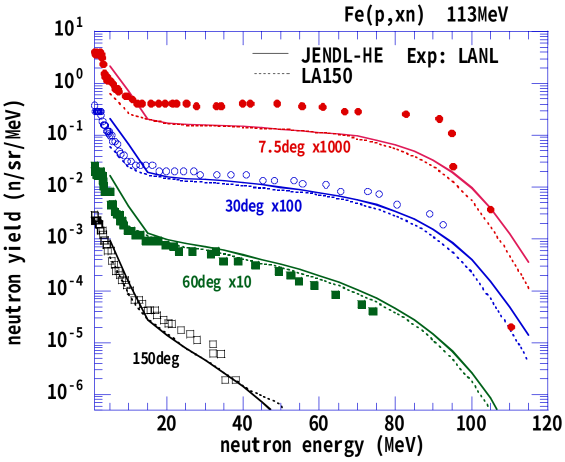


Fig.8 Comparison of experimental[11] and calculated 113 MeV proton TTY from Fe

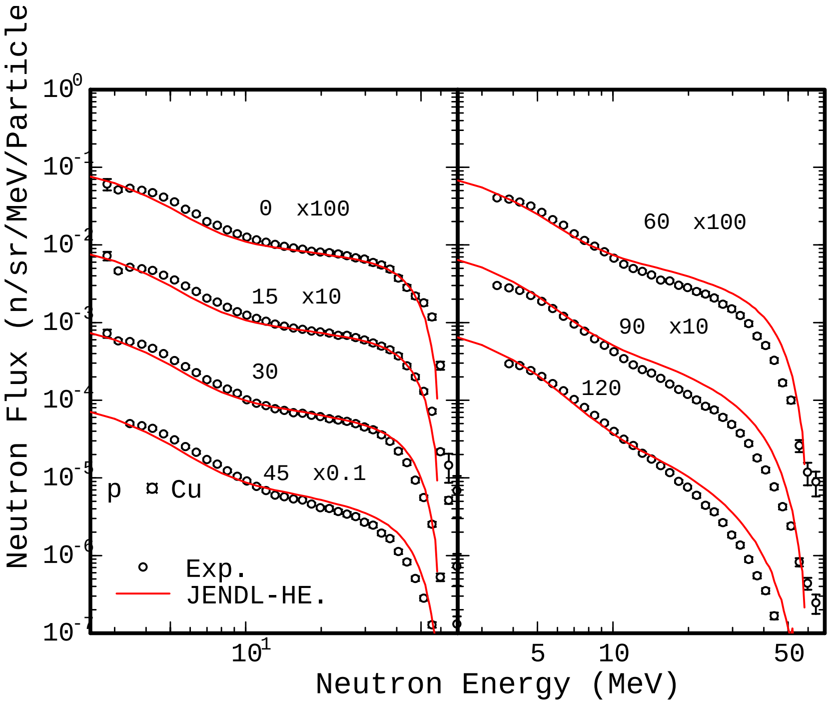


Fig.9 Comparison of experimental[14] and calculated 68 MeV proton TTY from Cu