IAEA
International Atomic Energy Agency

INDC (NDS)-0493
Distr. IN

INDC International Nuclear Data Committee

Resolution Broadening of Measured Leakage Spectra from IPPE Spheres

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January 2006

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Produced by the IAEA in Austria
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Abstract

An IPPE ^{232}Th sphere leakage spectrum measurement from a D-T 14-MeV source is a candidate benchmark for the OECD/NEA compilation of IPhRe benchmark experiments. Various aspects of resolution broadening of the results of Monte Carlo calculations were addressed to enable direct comparison with the experimental data.

January 2006

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1. INTRODUCTION

Neutron leakage spectra from thorium shell were measured at the Institute of Physics and Power Engineering (IPPE) at Obninsk by the time-of-flight technique using a 14-MeV neutron generator and ^{252}Cf fission chamber. A Cockroft-Walton type accelerator, the KG-0.3 pulse neutron generator, was used to accelerate deuterons to a kinetic energy of 280 keV to produce 14-MeV neutrons in T(d,n) reaction. A thin wall fast ionization chamber with ^{252}Cf layer was used to produce spontaneous fission neutron spectrum.

These experiments were performed in the period 1987 to 1992. The purpose was to benchmark nuclear data for its use in the analysis of fusion reactors. The thorium sphere had outer radius of 13.0 cm, inner radius of 3.0 cm and hole of 2.5 cm to accommodate either 14-MeV or ^{252}Cf neutron sources. The sphere were made from 100% thorium with nuclear density of 2.93×10^{22} atoms/cc.

The available experimental information was compiled and analysed by S.P. Simakov for inclusion in the SINBAD benchmark collection at the NEA Data Bank.

The purpose of the present document is to review different approaches to the resolution-broadening effects to enable comparison between measured and calculated neutron leakage spectra. The analysis is limited to the case with the 14-MeV source.

2. BASIS FOR RESOLUTION BROADENING

2.1. Time resolution

The measurements involved recording number of pulses from a neutron detector in predefined time bins to measure the time the neutrons travel from the source to the detector. Knowing the distance their speed can be calculated, which in turn defines the energy of the neutrons. Uncertainties in the measured time originate from the following:

- Finite duration of the source pulse.
- Finite size of the detector, affecting the length of the flight path.
- Finite size of the target.
- Uncertainties and drift in the electronics.
- Finite width of the time bins for collecting the measurements.

The last three items above can usually be neglected.

2.2. Conversion from time to energy domain

If all neutrons travelled along the shortest path, the conversion from time to energy domain would be exact. Unfortunately, this is not the case due to:

- Multiple scattering.
- Final size of the spheres surrounding the source.

If time-of-arrival spectra from the measurements are available, it is much easier (and more accurate) to simulate in a calculation such a spectrum for the purpose of comparison with experiments. If comparison in the energy domain is essential, the calculated spectrum and the measured one can be converted to the energy domain by the same procedure. The comparison would involve some uncertainty in the energy, but the spectrum values at any energy would be directly comparable.

2.3. Modelling of the experimental setup

Simulation of the experimental setup by Monte Carlo techniques can accurately take into account practically all features of the experimental setup, but would result in very complex models and long computational times. Very often approximations are made.

3. ANALYSIS

3.1. Available experimental information

The details of the target assembly and the surrounding spheres are adequately described. The details of the collimator and the experimental hall are only given in figures. The pulse width is given, but the intensity profile of the pulse is not.

The measured spectra were converted to the energy domain, making approximate corrections for background and multiple scattering. Two spectra are given:

- without the sphere being measured (i.e. measurement of the source spectrum),
- with the sphere in place.

3.2. Modelling approximations

Input model for the MCNP Monte Carlo transport code was provided. The input model accurately describes the geometry of the target assembly and the surrounding sphere, but the air, the collimator and the detector are not modelled at all.

Two tallies are defined: the first gives the total leakage spectrum from the sphere at a distance of detector location and the second represents a point detector at the actual detector location. Ideally, the two would be equivalent if the source was isotropic. In the present setup the neutron energy from the source has a distinct angular dependence. The total leakage spectrum tally is therefore excluded from further consideration.

A “point detector” tally may cause problems in certain types of calculations. In this particular case with no collimator and no air modelling, the point detector tally seems a good approximation.

3.3. Scope of analysis

Resolution broadening approximations were first tested on the spectrum without the thorium sphere in place. Another tally was added to the input to produce a time-of-arrival spectrum at the point-detector.

A post-processing code was extended to implement various resolution-broadening options to tallies in MCNP output. Resolution broadening is governed by

$$F(E) = \int F_m(E - u)\, p(u)\, du$$

Where

F	resolution-broadened spectrum,
F_m	calculated spectrum,
$p(u)$	resolution-broadening function.

The resolution-broadening function can be defined in tabular form, with zero argument at the peak of the distribution. The argument values are scalable to simulate energy-dependent resolution broadening. Alternately, a Gaussian resolution broadening function can be defined. Its width is specified in terms of percent of the argument value at half-maximum. If conversion from time to energy domain is requested, the uncertainty in the flight path due to finite size of the detector can be taken into account.

The various resolution-broadening options on the calculated spectrum without thorium sphere can be compared in Figures 1 and 2 as follows:

Energy/Point: is the directly calculated tally for a point detector in the energy domain. Note the distinctly high peak at the source energy of 14.8 MeV.

TOA-E: is obtained by converting the time-of-arrival spectrum into energy domain. It agrees very well with the directly calculated energy spectrum, Small differences can be attributed to multiple scattering and partly to different binning.

TOA-E/Detector size: includes resolution-broadening due to final size of the detector. Note that the effect is rather small.

TOA-E/Pulse width: includes resolution-broadening due to final time-width of the source pulse. The resolution broadening effect is significant very near the peak energy, but decreases rapidly at lower energies.

TOA-E/Gaussian: arbitrarily a Gaussian resolution-broadening function was applied after conversion to the energy domain. Its width was 3% of the energy value at any point. This choice reproduces the shape of the peak around the source energy, but deviates significantly at lower energies.

Energy/Source: refers to the point-detector tally in energy domain where the measured spectrum distribution itself was used as the detector response function. The argument of the function was scaled proportionally to energy such that nominal distribution was attained at 14.8 MeV. The curve shows that this procedure results in a sufficient reduction in the range of the resolution-broadening function so as not to distort the observed spectrum.

Energy/Leakage: refers to the total leakage current spectrum at the distance of the detector. Due to the angular dependence of the source neutrons the peak is shifted. The curve demonstrates that at energies near the source the total leakage spectrum is not representative of the measurement at a fixed detector location.

The *Energy/Source* option seems the only one that produces reasonable results. This option was applied to compare the results of calculations using different evaluated nuclear data for

^{232}Th. The results are shown in Figures 3 and 4. The data from the IAEA-CRP reproduce the measured spectrum extremely well, except in the energy range between 2 and 7 MeV. This is consistent with the comparison of measured neutron emission spectra and is specific for the energy range around 14-MeV. To improve the data a better theoretical understanding of the direct and pre-equilibrium contributions to the continuum is required. Other libraries, namely JEFF-3.1 and ENDF/B-VI.8 show large deviations at lower energies, and just below the source peak, which are consistent with the observations in comparing neutron emission spectra with measured values. An example is shown in Figure 5. Contributions to the total neutron emission spectrum from individual reactions is shown in Figure 6, from which it is evident that in the region of interest the fission and the (n,2n) reactions are the dominant contributors.

4. CONCLUSIONS

Physically justifiable resolution-broadening effects are not strong enough to reproduce the observed shape of the spectrum. Arbitrarily chosen Gaussian broadening may reproduce the spectrum shape around the source energy, but not at lower energies. This suggests that most likely the physical model of the experiment is inadequate. Possible improvements would include:

- direct comparison of the measured time-of-arrival spectra, avoiding the uncertainties associated with the conversion into the energy domain,
- accurate representation of the pulse shape – a square shape was assumed at present,
- explicit modelling of the collimator, air and any other structures that might affect the results,
- improved modelling of the detector to avoid drawbacks of the “point detector” tally in MCNP.

Considering that it might not be possible to obtain the necessary information to improve the modelling of the experiment as suggested above, the use of the measured source spectrum (i.e. without the thorium sphere in place) as the resolution-broadening function seems reasonable.

Although the calculations using ^{232}Th data from the IAEA-CRP exhibit a dip in the spectrum between 2 and 7 MeV, these data provide by far the best agreement between measurement and calculations.

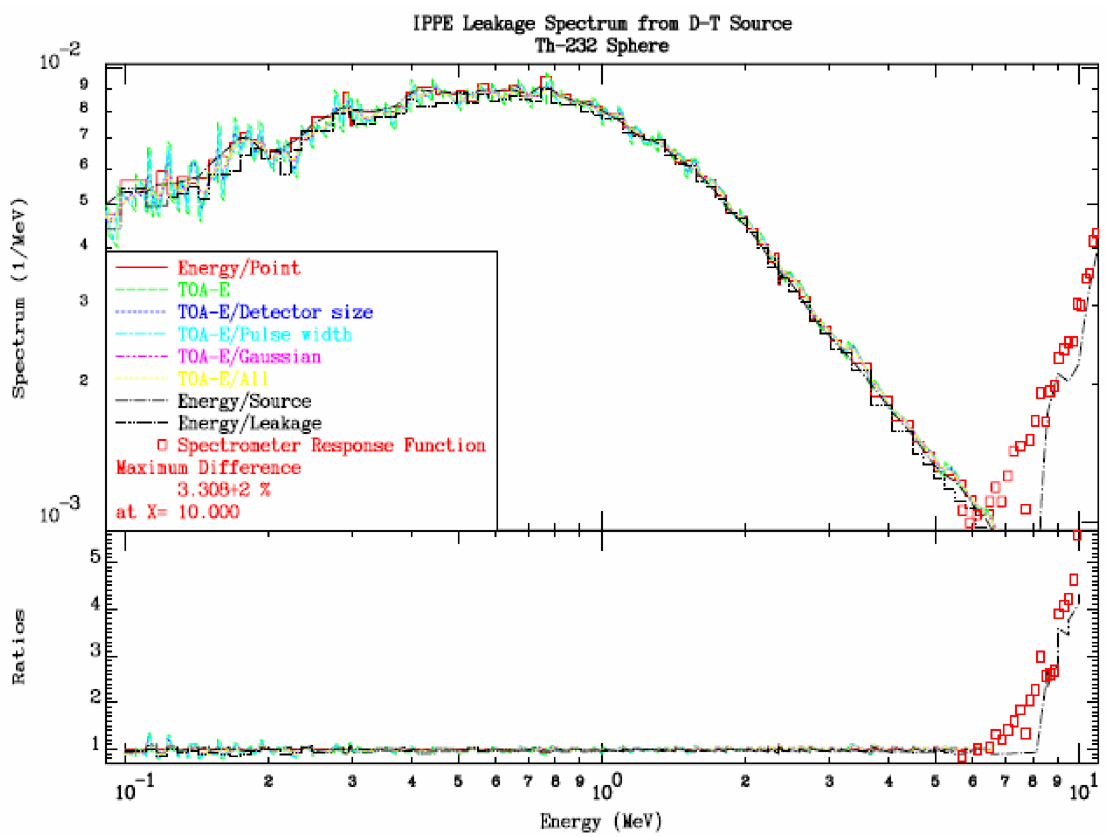

Figure 1: Comparison of measured source spectrum with calculations using different resolution-broadening assumptions (low energy part).

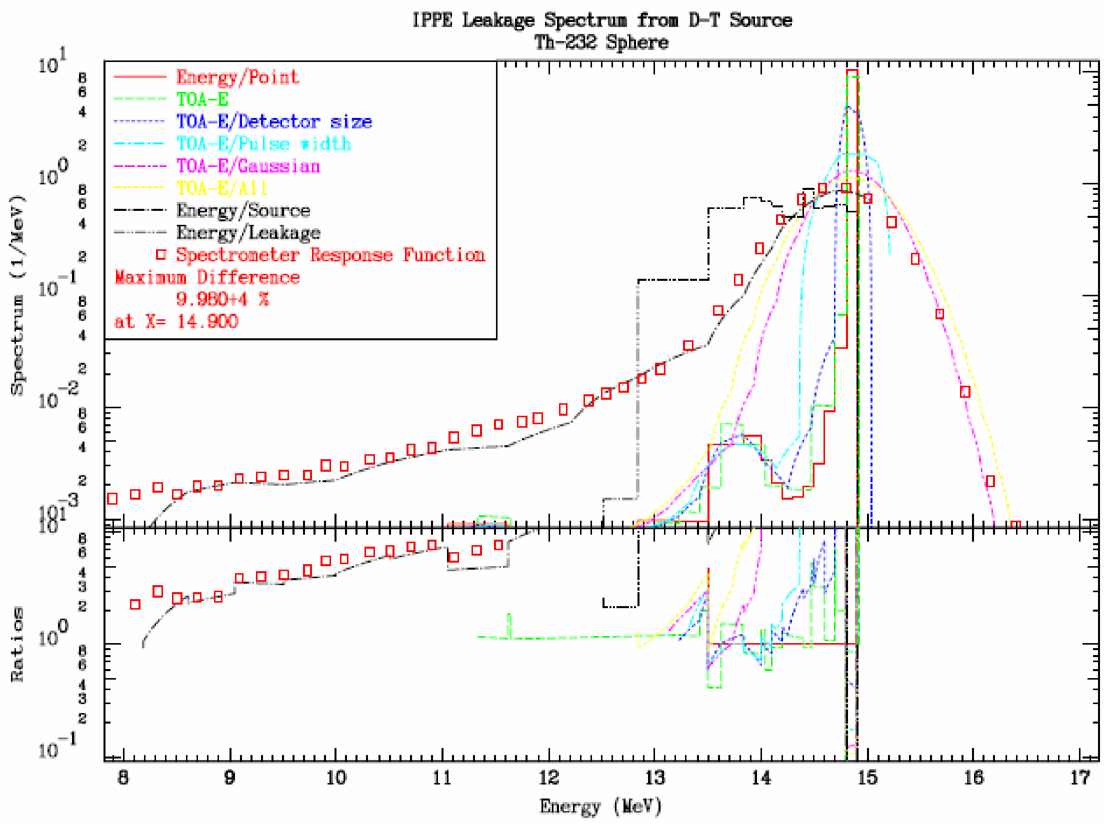

Figure 2: Comparison of measured source spectrum with calculations using different resolution-broadening assumptions (high energy part).

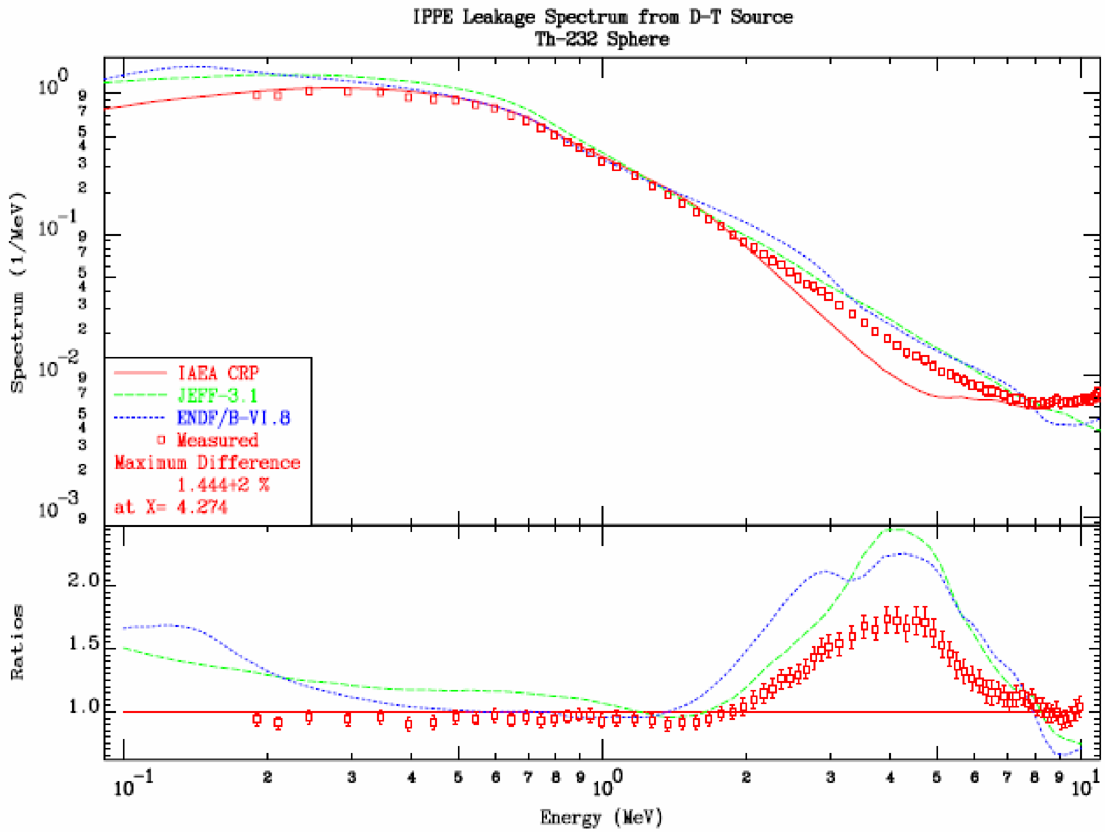

Figure 3: Comparison of measured leakage spectrum from thorium sphere with calculations based on different evaluated data libraries (low energy part).

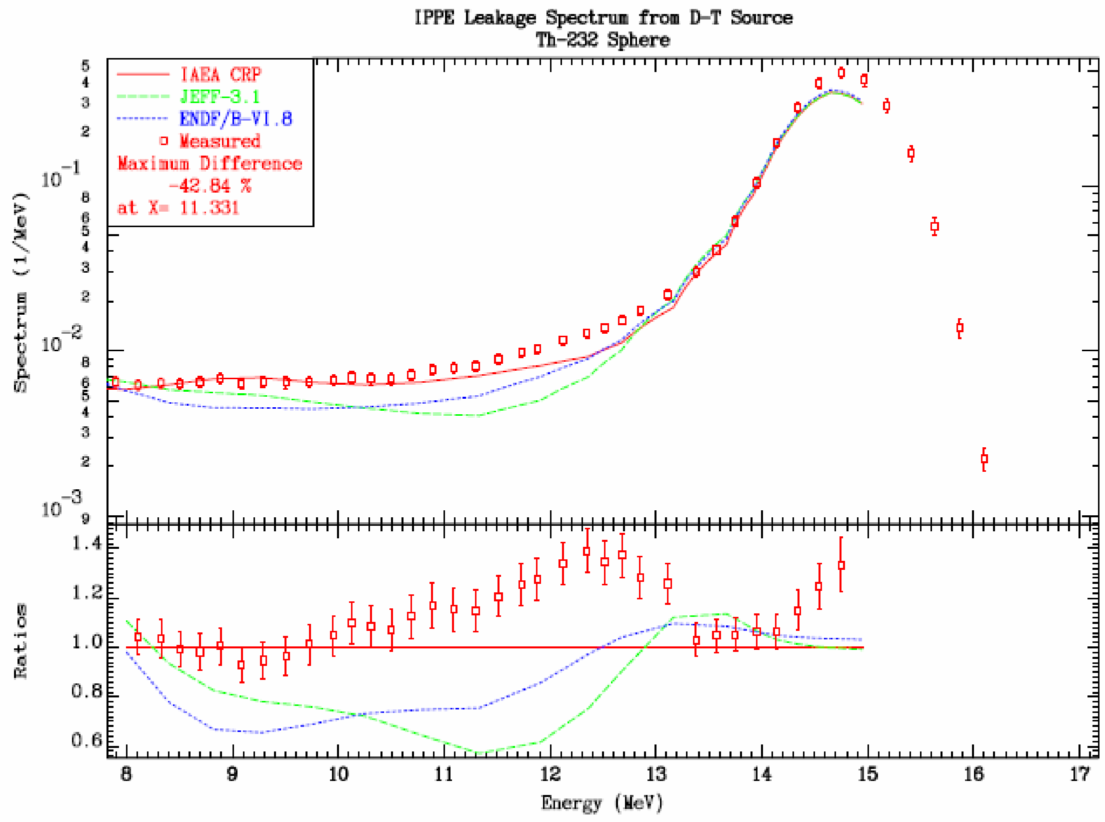

Figure 4: Comparison of measured leakage spectrum from thorium sphere with calculations based on different evaluated data libraries (high energy part).

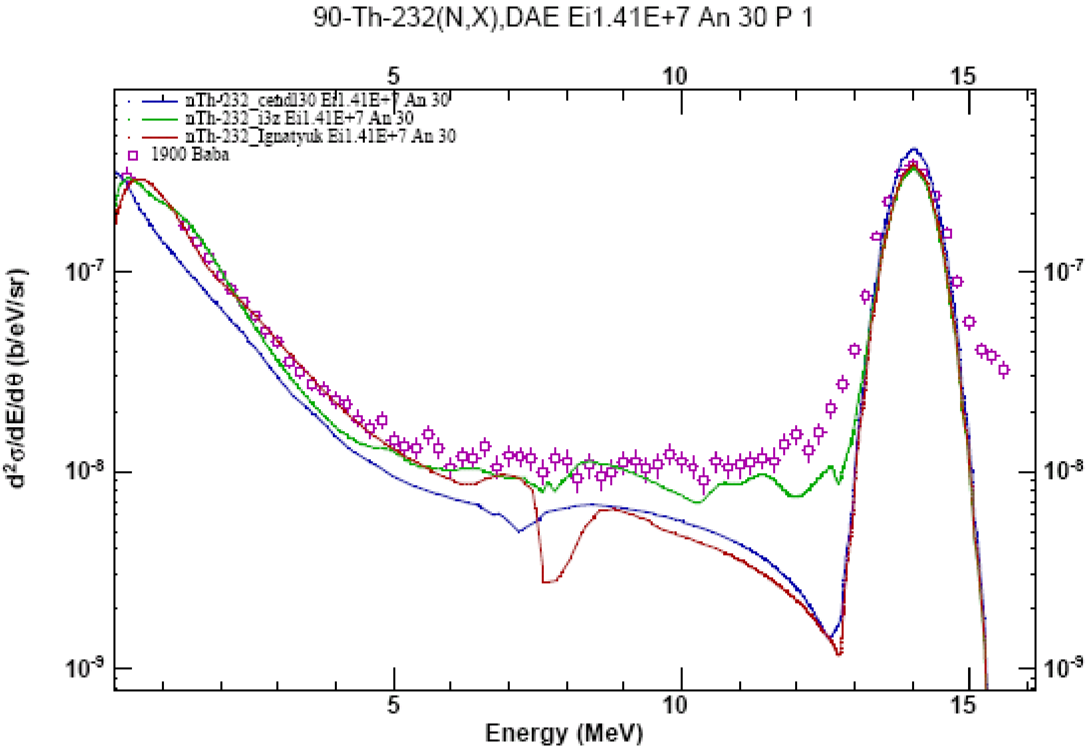

Figure 5: Comparison of neutron emission spectra at 30 degrees from 14-MeV incident neutrons measured by Baba (2000) with evaluated data libraries. The CENDL-3.0, BROND-2 (labelled “Ignatyuk”) and this work (labelled “i3z”) are shown.

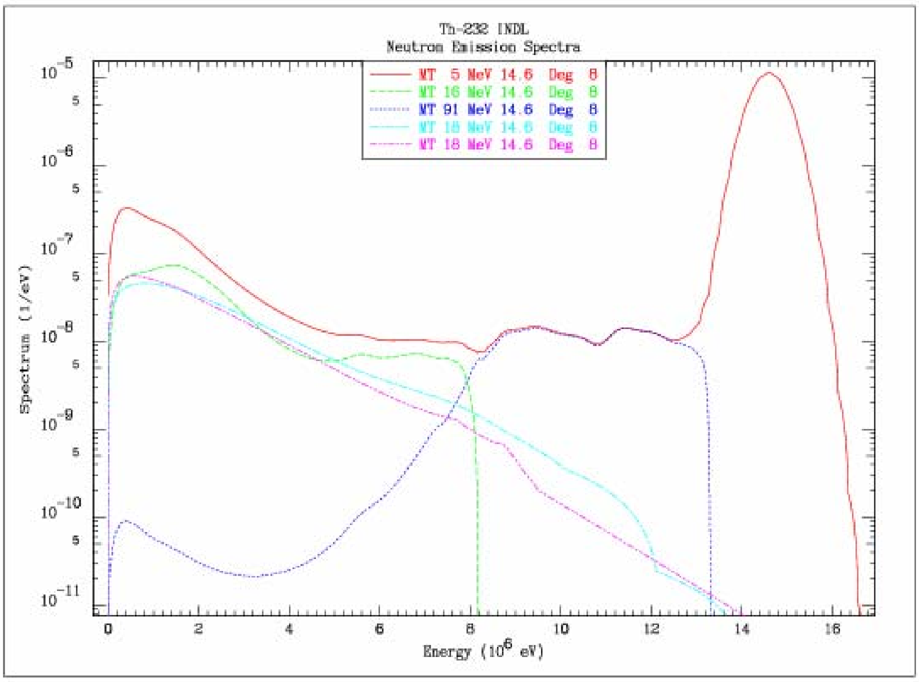

Figure 6: Contributions to the total neutron emission spectrum (labelled MT5) from different reactions: MT16=(n,2n), MT91=(n,n’-continuum), MT18=fission. The last fission curve corresponds to the spectrum by Maslov and is given for comparison only.

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