Capture Neutron Cross Sections Measurements of Rare Earth Isotopes

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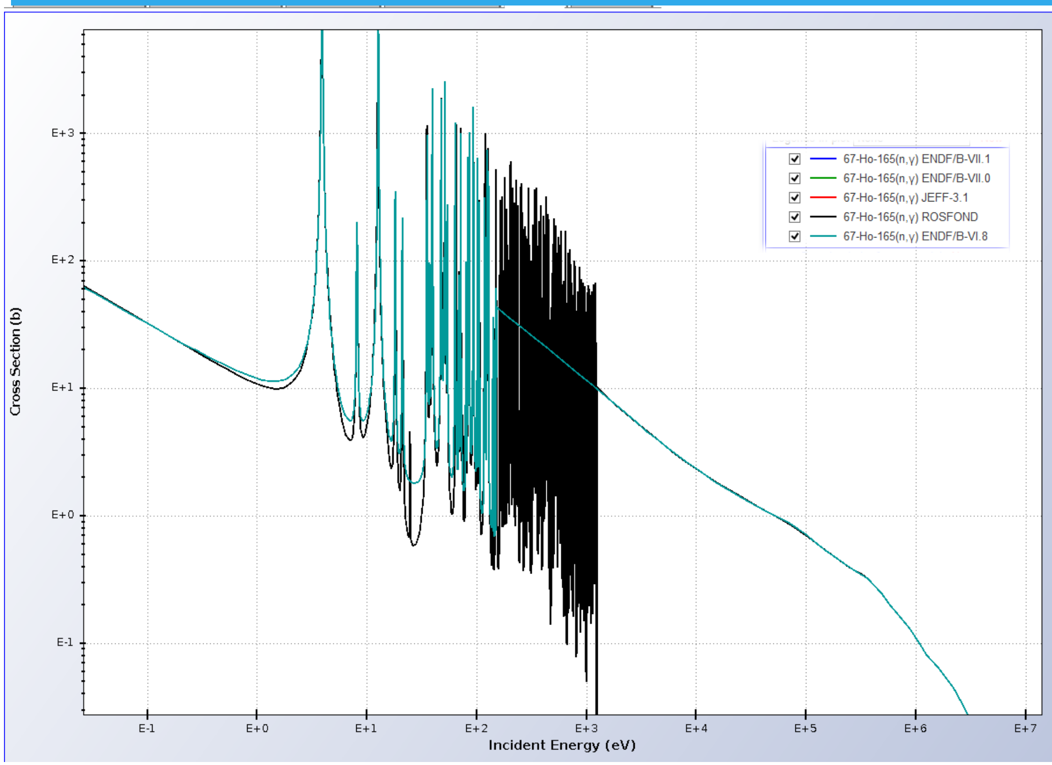
Abstract

Results of TOF measurements for total and capture neutron cross sections on isotope Ho165, conducted on pulsed spallation neutron source RADEX, are presented. Pulse duration of accelerator's proton beam 250 nanoseconds, combined with 100 nanoseconds steps of data acquisition system and 80 nanosecond pulses of (n,γ) detector provided, at 50 meter base of vacuum neutron guide, value of TOF spectrometer resolution 6 nanoseconds per meter.

Measurements were done during linear proton accelerator's work for our task in years 2020 and 2021. Beam parameters were: proton energy 247 and 305 MeV, pulsed proton current 0.01 Amperes, pulse duration 250 nanoseconds, frequency 50 Hz. Average beam power 40 W provided average neutron intensity on Ho165 pattern 4000 n/cm2sec. Recycle neutrons were cut using cadmium filter.

Experimental results were compared with 4 world neutron databases: ENDF /B-VII.1, JEFF-3.1, JENDL-4.0, and ROSFOND. New experimental data on cross section resonance structure of Ho165 were achieved and are presented.

Introduction and description of the task



- Ho165 capture cross section BNL data [1] are shown in the neutron energy range 0.0253eV<En<14 MeV.
- ENDF/B-VII.1, ENDF/B-VII.0, JEFF-3.1, ROSFOND and ENDF/B-VI.8 are compared.
- Upper energy border of resolved resonances in the best world data for Ho165 is 1250 eV.
- Several disputed resonances were found
- Experimental TOF measurements were done to determine, what variant is more true and exact.

Neutron cross section measurements are necessary both for fundamental and applied nuclear physics. For fundamental purposes it’s necessary to investigate detailed resonance structure and resonance parameters in the neutron energy region of resolved resonances, for each partial type of cross section: energy of each resonance, cross section at maximum point, it’s gamma and neutron energy width, spin, average energy distance between resonances. This requires high energy resolution of TOF measurements.
For applied purposes the task is to measure partial components of cross section for each isotope in wide energy groups: both in resolved energy area and also in the high energy area of unresolved resonances.

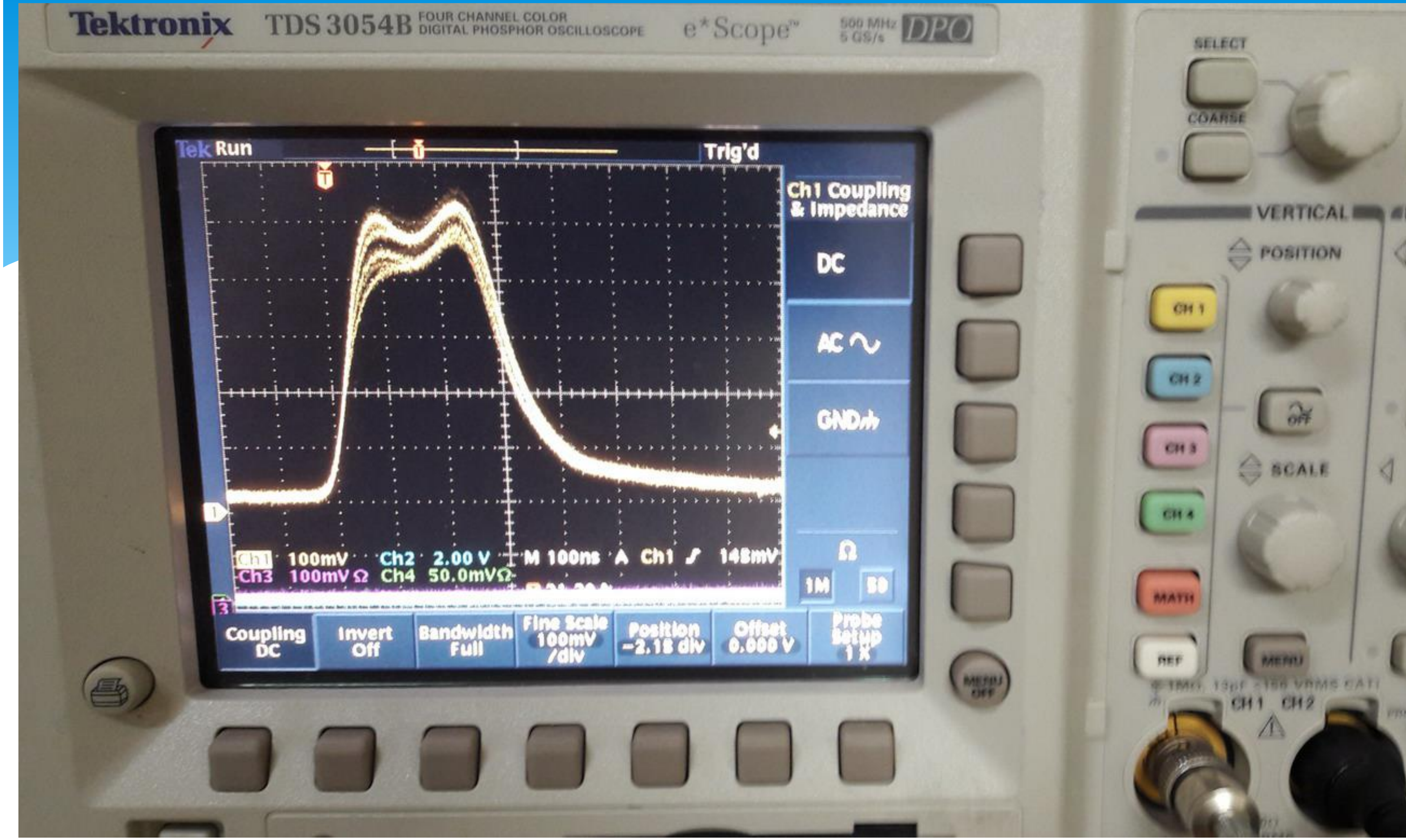
Group cross sections, like ABBN-78, are used as initial data for calculation codes during creating the core of nuclear reactors of different types and radiation shield for them. Group cross sections are used as coefficients in the system of 28 differential equations, solution of which defines neutron balance in the core of nuclear reactor. Precision for cross section measurements, requested by applied reactor physics, is determined by the share of delayed neutrons: 0.65% for U235, 0.2% for Pu239, 0.42% for fast breeder reactors. Criticality coefficient, critical mass and breeding ratio of fast neutron reactors must be calculated with precision defined by these values. This requires high statistical precision of TOF measurements.

In spite of good development of the fundamental theory of nuclear interactions, energy dependence curves for neutron cross sections with requested precision can be taken only from the experiment.

Experimental equipment

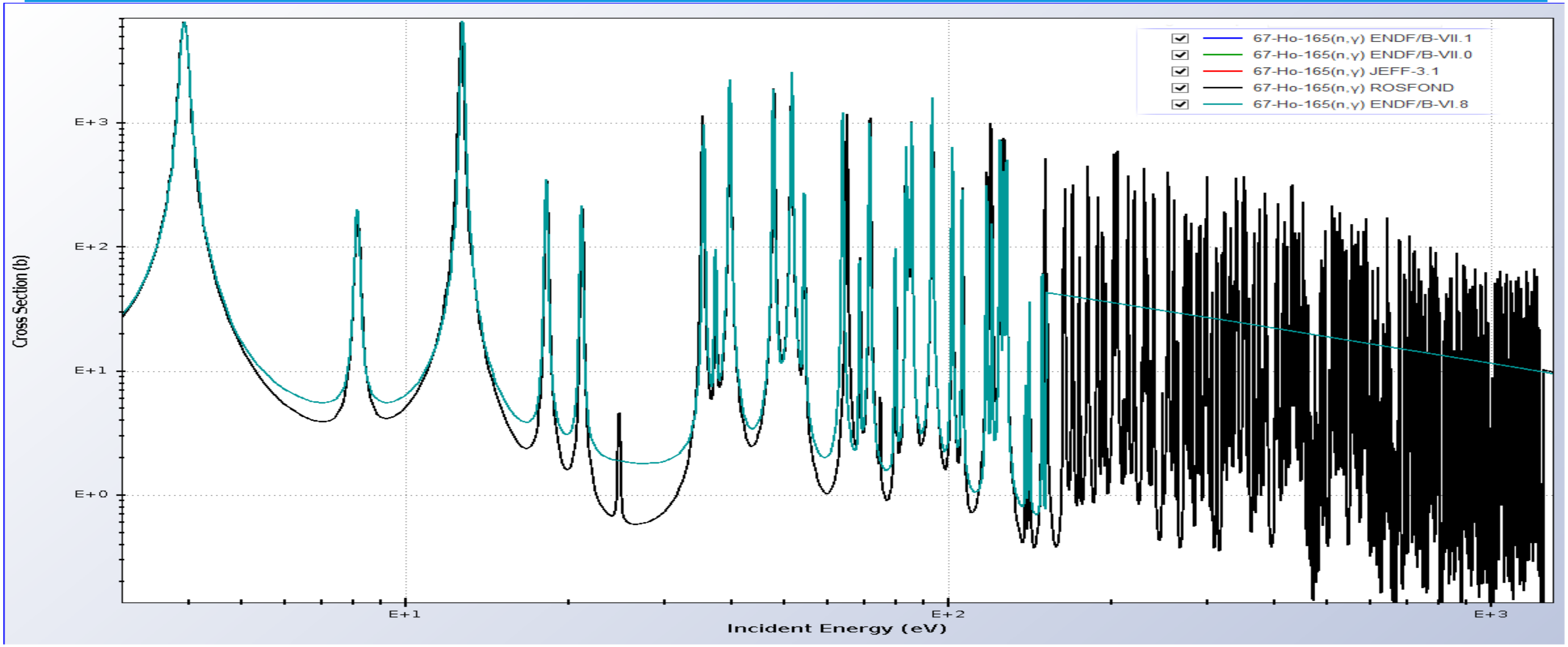
- During measurements of Ho165 resonance structure, total cross section was measured by 4 Helium-4 based counters SNM-18.
- Another four counters SNM-18 with 4 atmospheres of He3 were used as monitors of intensity of the pulsed spallation neutron source RADEX.
- Capture cross section was measured by 40-liter 8-sectional liquid (n,gamma) detector of the installation ‘INES’.
- To cut the recycle neutrons, cadmium beam filter was used.
- To determine the background layer of experimental histograms in the low neutron energy area, Mn55 beam filter was used.
- For background determination at high energies, aluminum Al27 filter was used. It allowed to determine the background up to neutron energy 140000 eV.

Detailed description of the equipment, applied in this measurements, can be found in the sources [2], [3], [4], [5],[6].



- Accelerator’s proton pulse is shown. It had duration 250 nanoseconds on half-altitude.
- Measurements were done during years 2020 and 2021 at the pulsed spallation fast neutron source RADEX, based on tungsten proton beam target of INR RAS 600 MeV proton linac.
- Ho165 radiator pattern was installed inside the 8-sectional liquid (n,gamma) detector, at the 50 meter TOF base.
- Duration of proton pulse, detector’s (80 ns) and data accumulation system’s (100 ns steps) duration, at 50 meter TOF base provided spectrometer resolution factor: 6 nanoseconds per meter.

Ho165 capture cross section structure in the energy region of resolved resonances

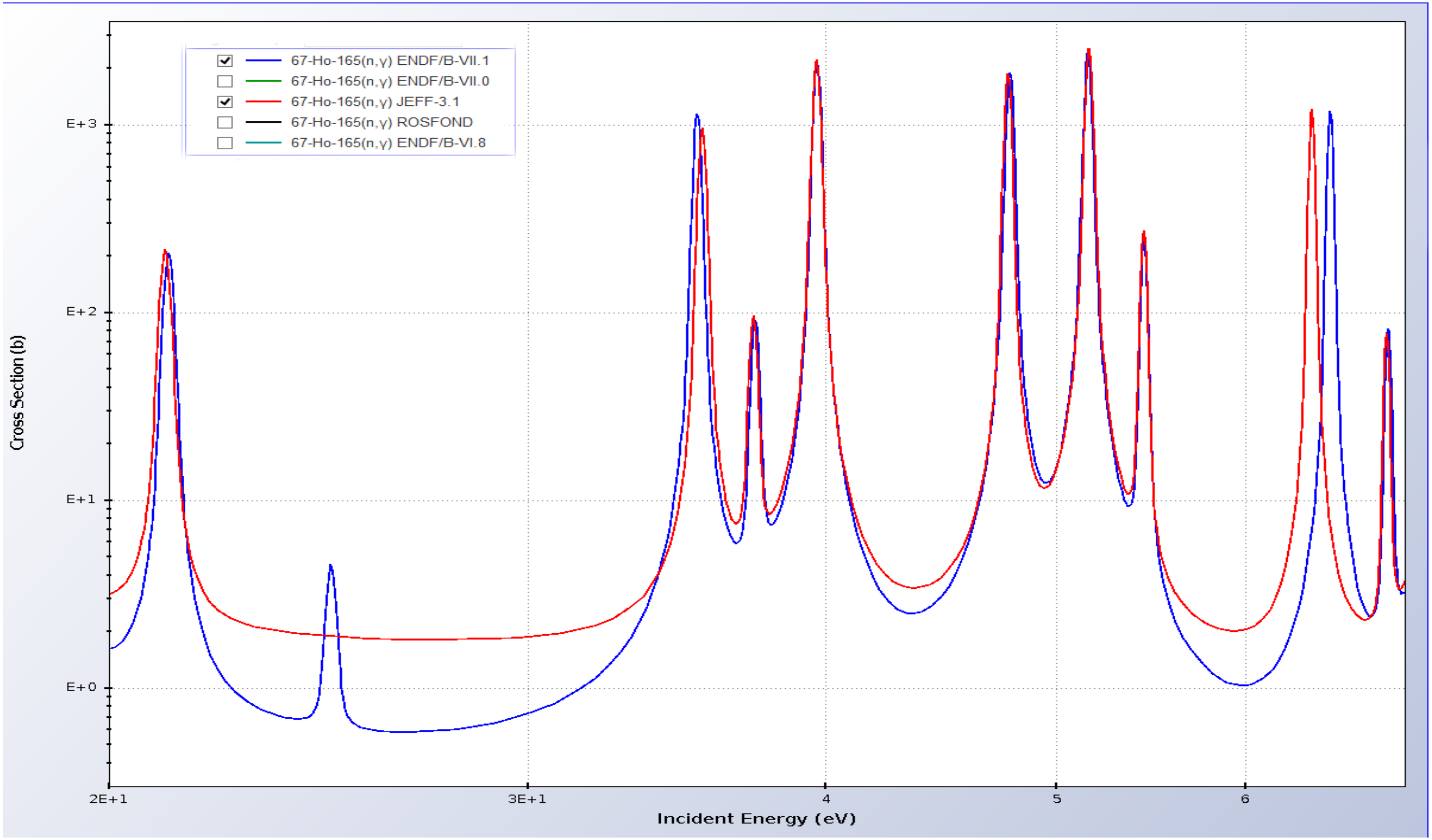


Comparison showed that

* ENDF/B-VII.1, ENDF/B-VII.0 and the ROSFOND data for Ho165(n,gamma) are similar to each other, and have upper border of resolved resonances at neutron energy 1250 eV;
* JEFF-3.1 and ENDF/B-VI.8 are similar to each other and have resolved area up to 152 eV;

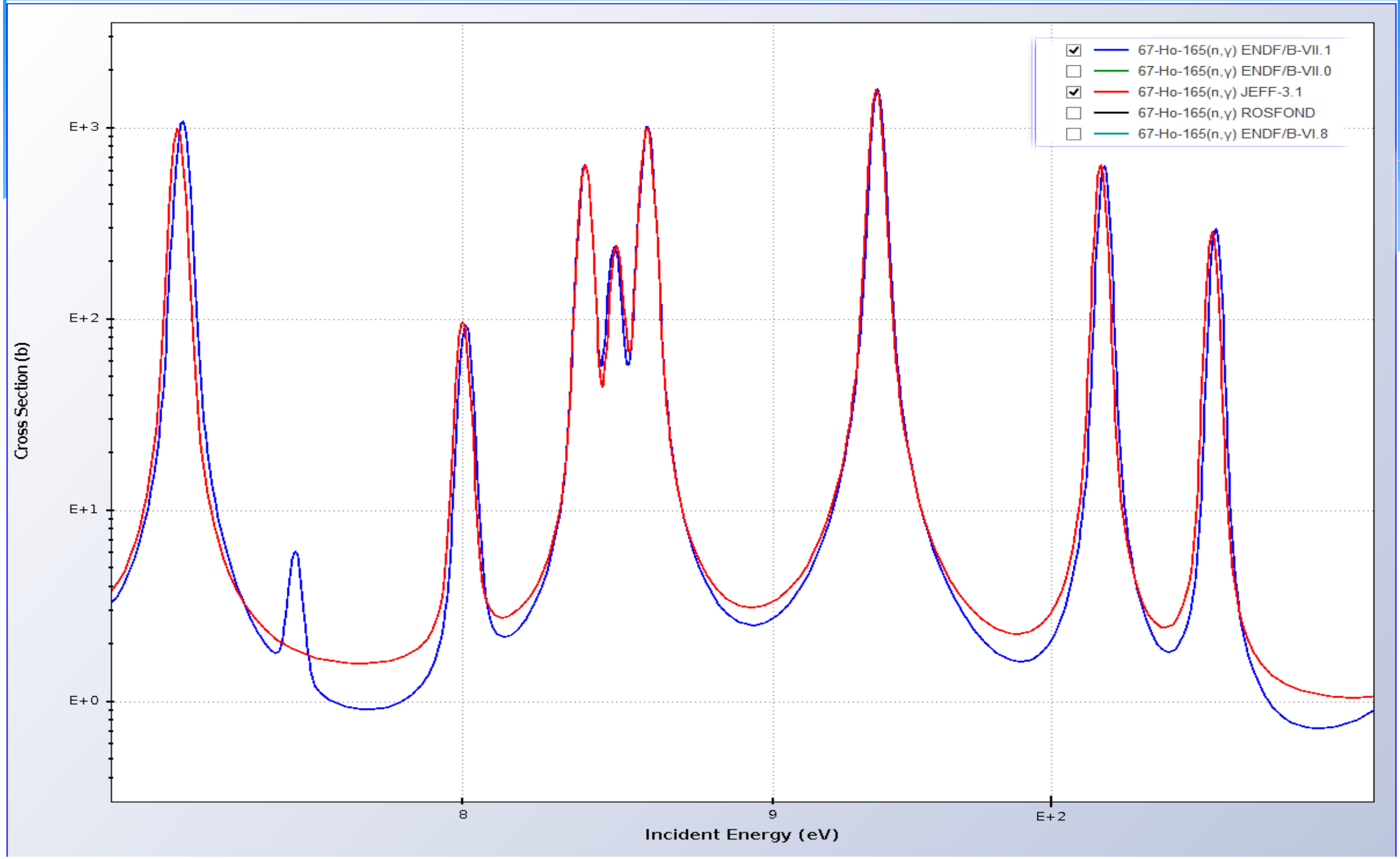
* To resolve resonances at higher energies better energy resolution of spectrometer is necessary. At the same time, all differences are below 152 eV. Between 152 eV and 1250 eV all world data are similar.

Ho165(n,gamma) between 20 eV and 70 eV in world data bases



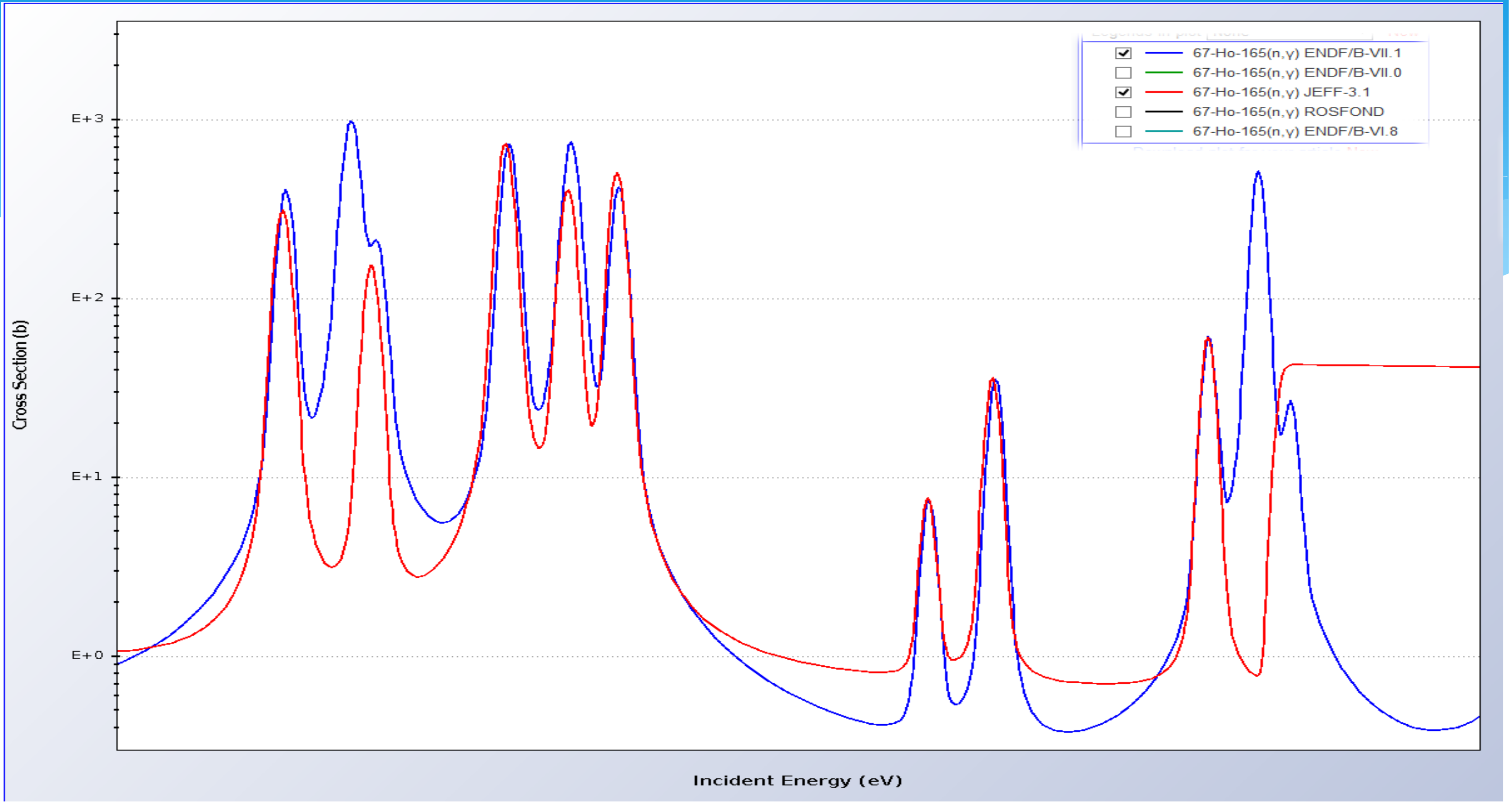
- Existence of 24,9 eV resonance is disputed;
- Energy position of resonance at 64 eV or at 65.18 eV is disputed

Ho165(n,gamma) between 70 eV and 113 eV in world data bases



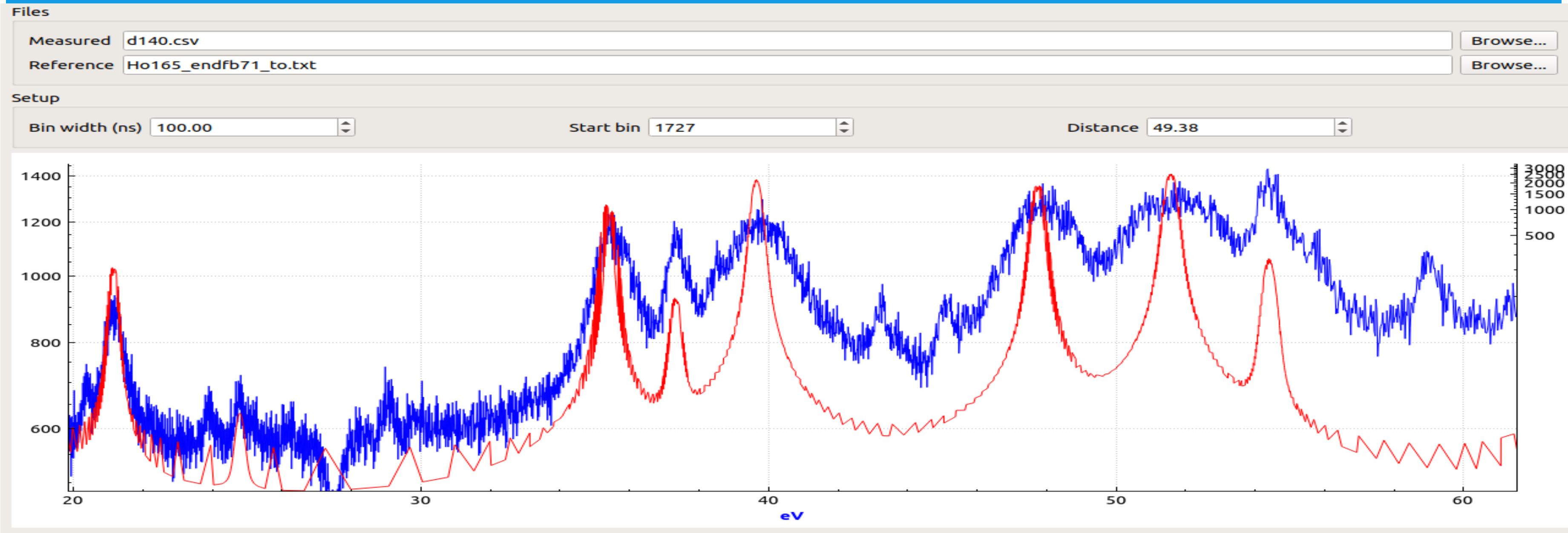
* Existence of resonance at 75.07 eV is disputed

Ho165(n,gamma) between 113 eV and 160 eV in world data bases

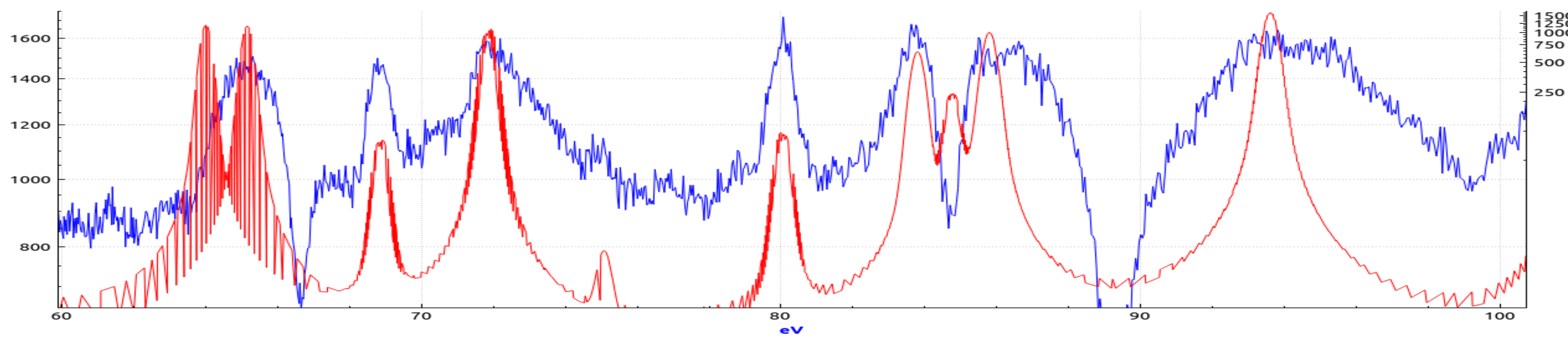


- Existence of the resonance at 120 eV is disputed
- Amplitude at 126.9 eV is disputed

Experimental results for Ho165(n,gamma) in the energy area of resolved resonances

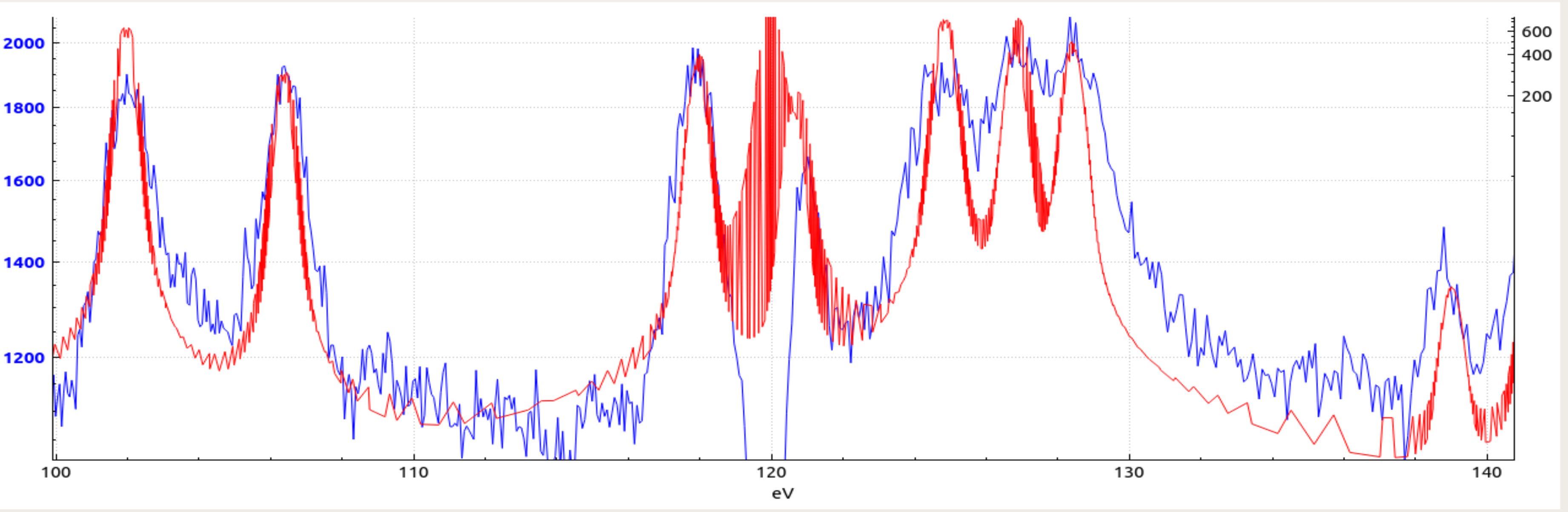


* Resonance at 24.8 eV exists.
* Resonance at 64 eV does’nt exists, at 65.18 eV exists.
* Resonance at 75.07 eV exists.

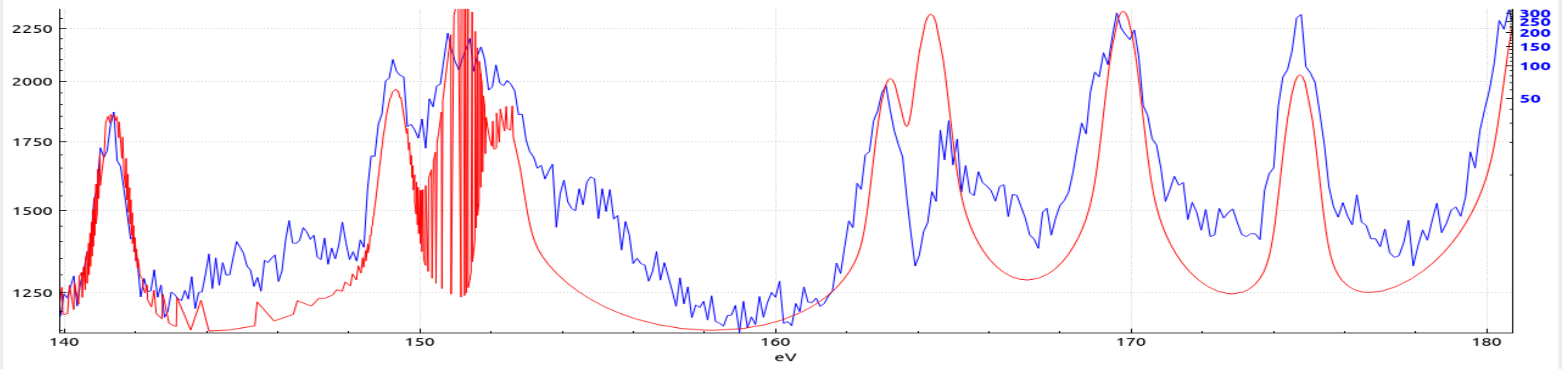


* Blue line – experimental TOF histogram, counts per channel on left vertical axis;
* Red line – BNL ENDF/B-VII.1 data for Ho165(n,gamma), cross section in barns on right axis, logarithmic scale;
* Neutron energy in eV on horizontal axis.

Experimental results for Ho165(n,gamma) in the energy area of resolved resonances



* Resonance at 120 eV originally exist, on this curve neutrons at 120 eV are absorbed by one of beam filter’s isotopes;
* Cross section of the 126.9 eV resonance coincidences with the ENDF/B-VII.1 variant.



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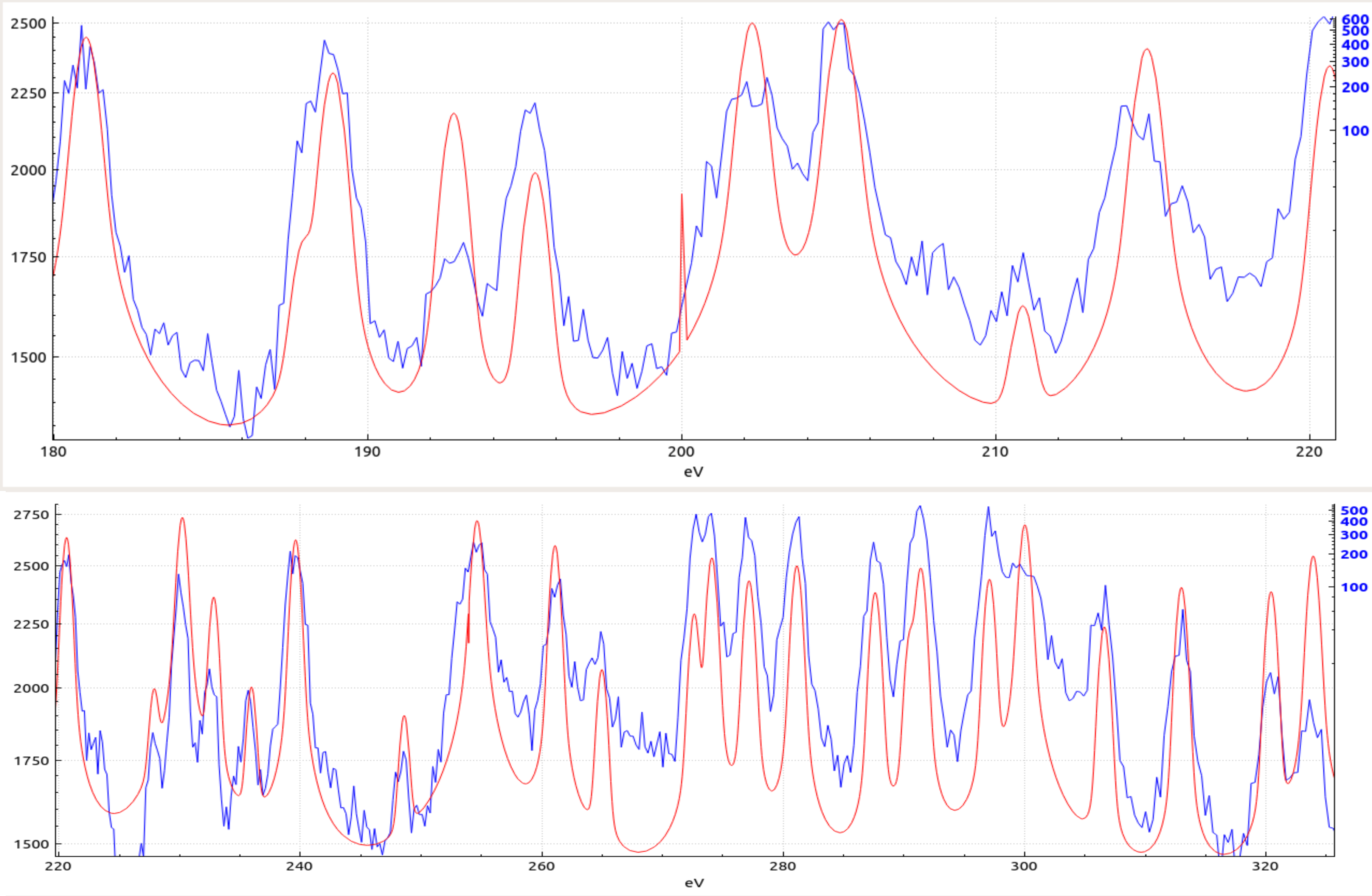
* Neutron energy in eV on horizontal axis.

Experimental results for Ho165(n,gamma) in the energy area of resolved resonances



- Blue line – experimental TOF histogram, counts per channel on left vertical axis;
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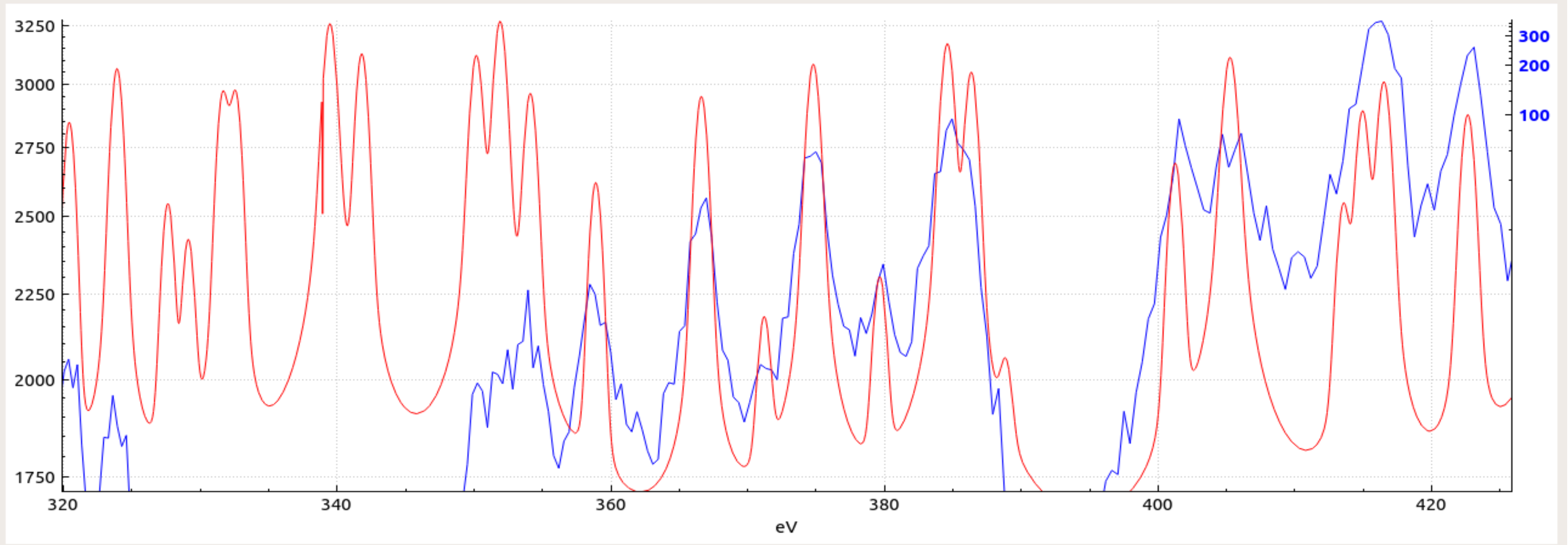
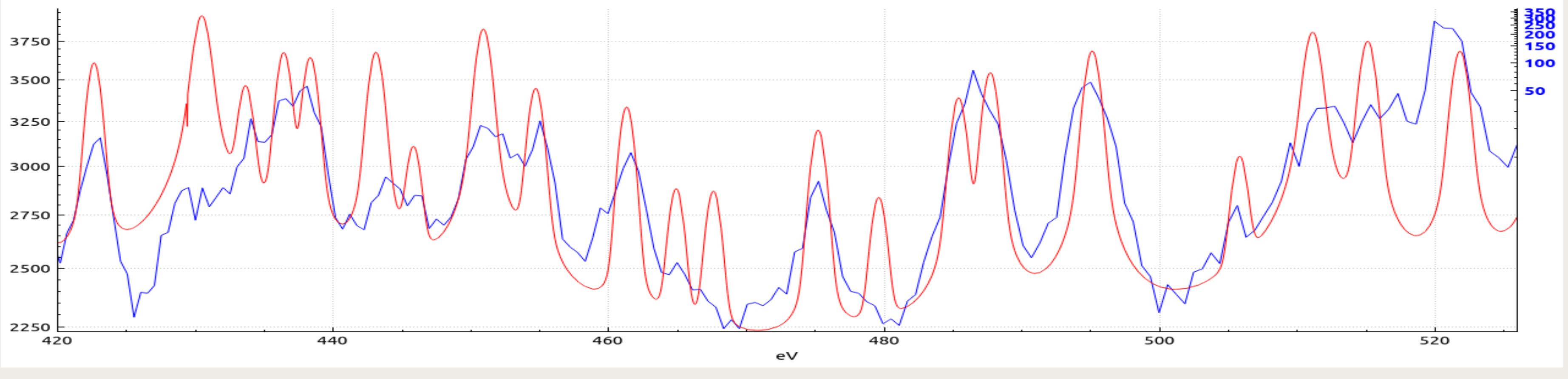
Experimental results for Ho165(n,gamma) in the energy area of resolved resonances

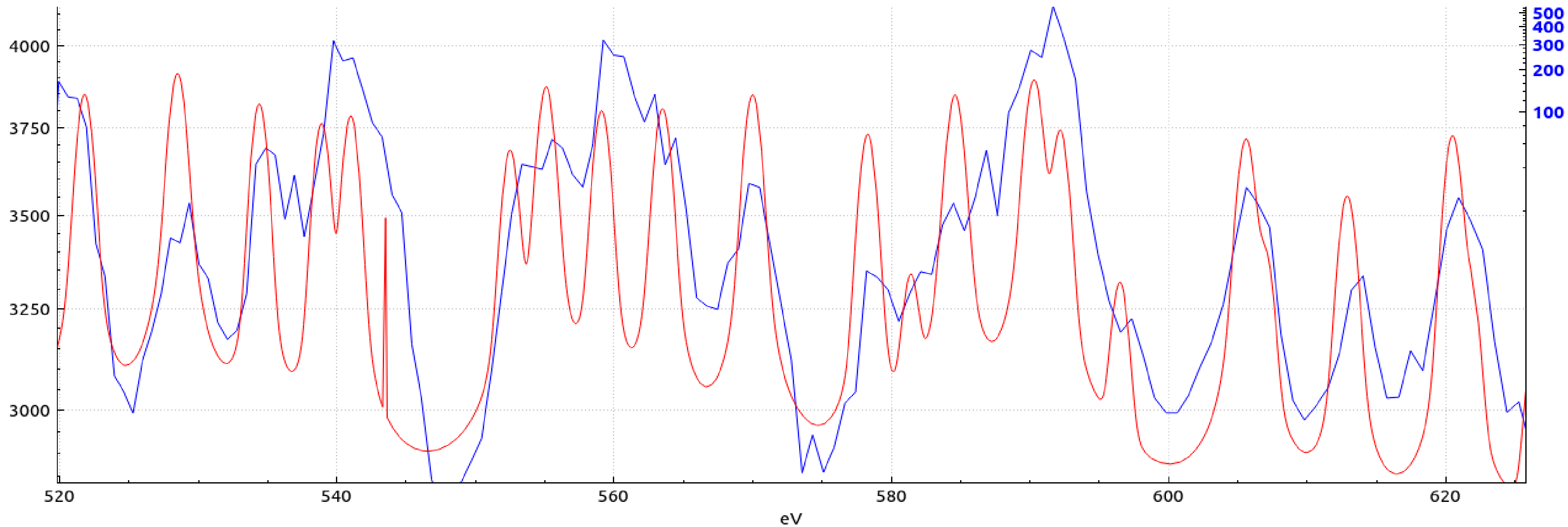


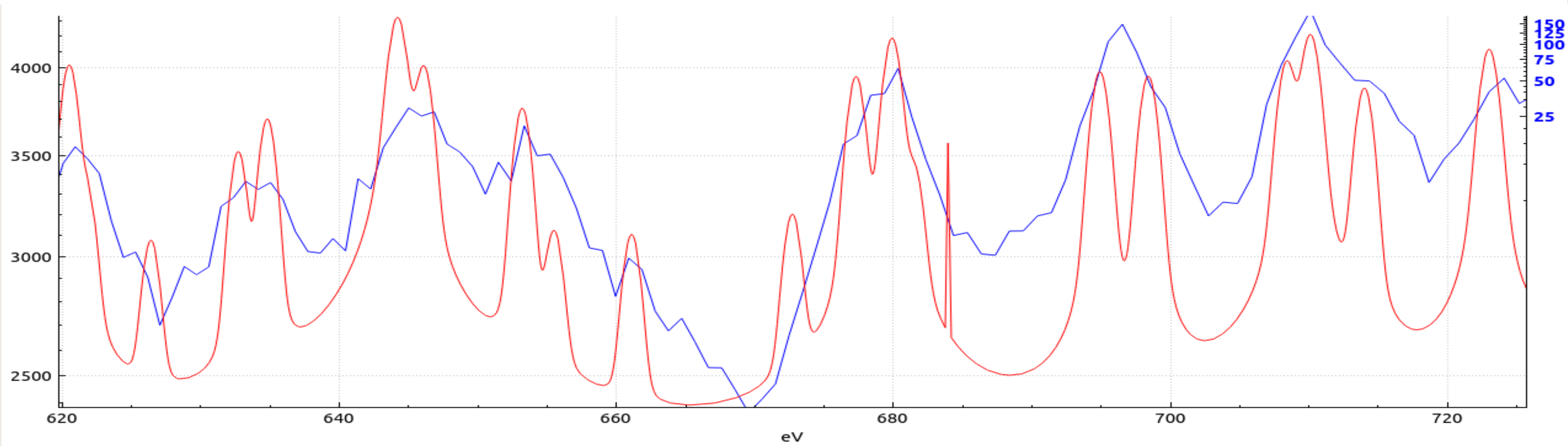
* Neutrons between 325 and 348 eV are abcent due to using Mn55 beam filter for determination of the background, so as Mn55 has strong capture resonance at the neutron energy 336 eV.



* Blue line – experimental TOF histogram, counts per channel on left vertical axis;
* Red line – BNL ENDF/B-VII.1 data for Ho165(n,gamma), cross section in barns on right axis, logarithmic scale;
* Neutron energy in eV on horizontal axis.

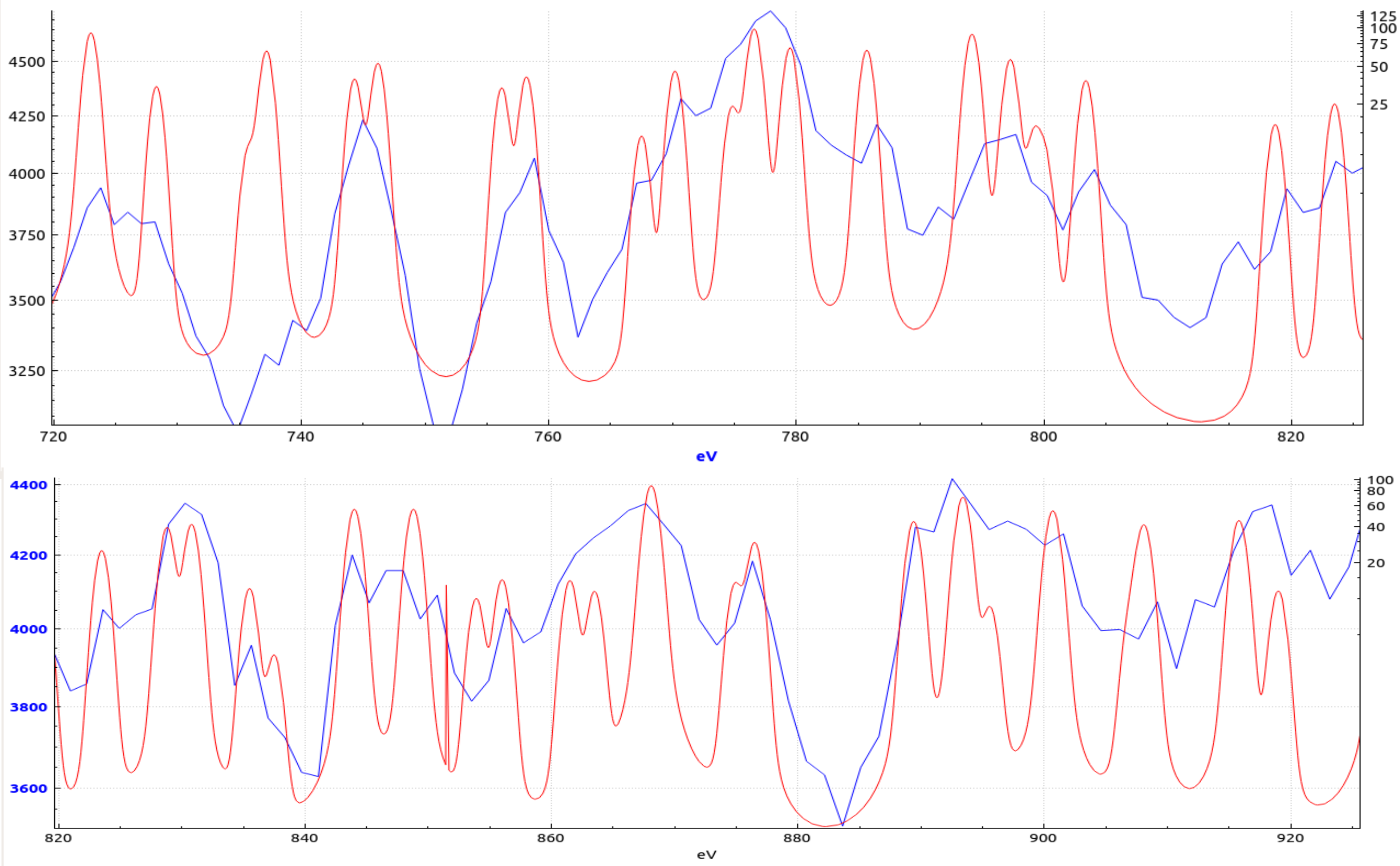
Experimental results for Ho165(n,gamma) in the energy area of resolved resonances





- Blue line – experimental TOF histogram, counts per channel on left vertical axis;
- Red line – BNL ENDF/B-VII.1 data for Ho165(n,gamma), cross section in barns on right axis, logarithmic scale;
- Neutron energy in eV on horizontal axis.

Experimental results for Ho165(n,gamma) in the energy area of resolved resonances



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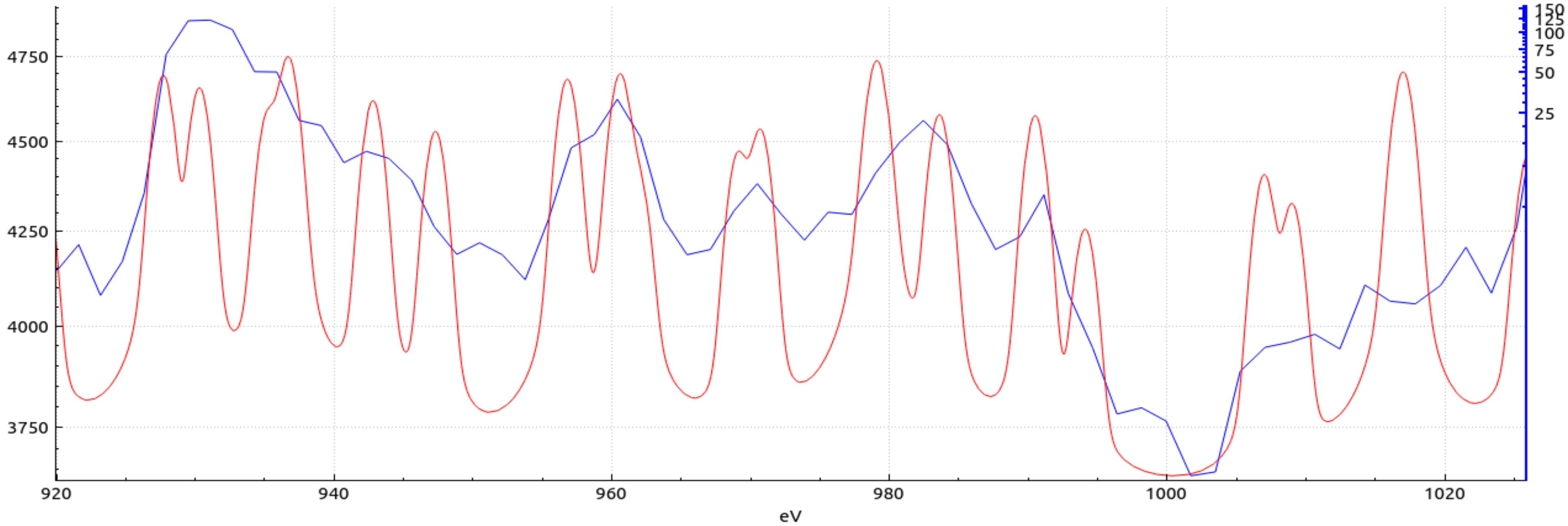
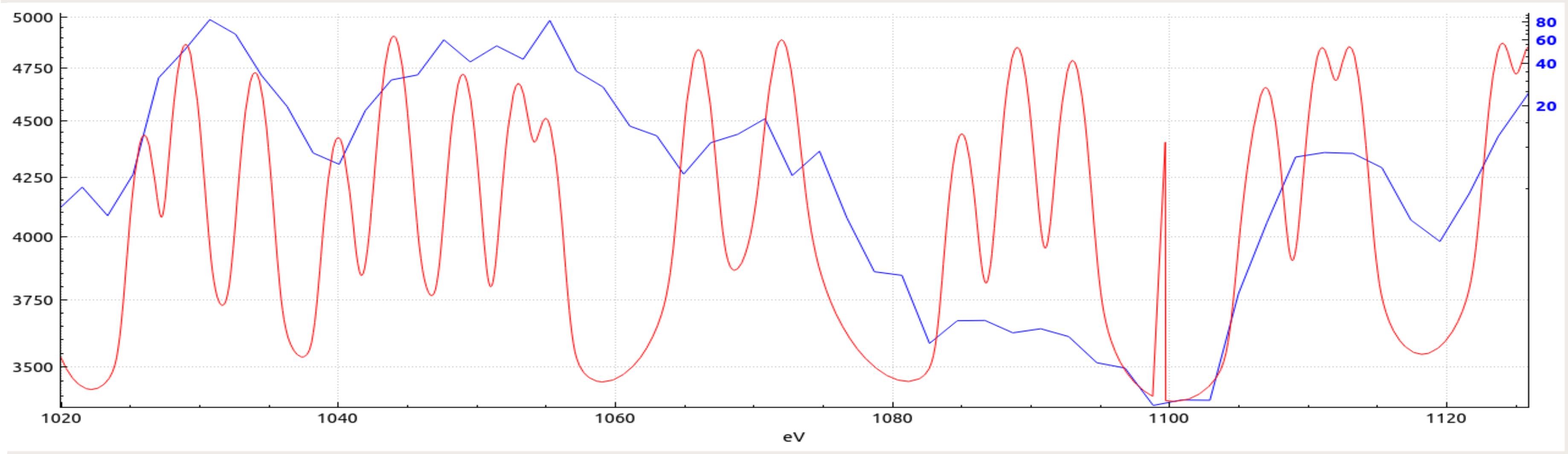
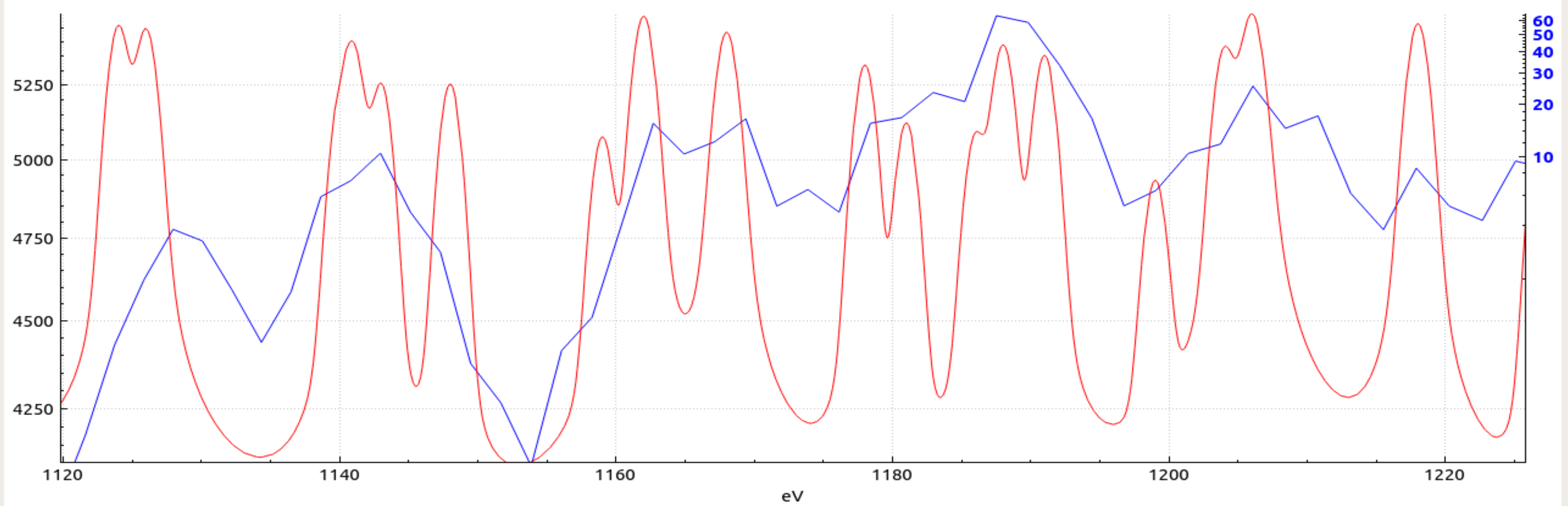
Experimental results for Ho165(n,gamma) in the energy area of resolved resonances

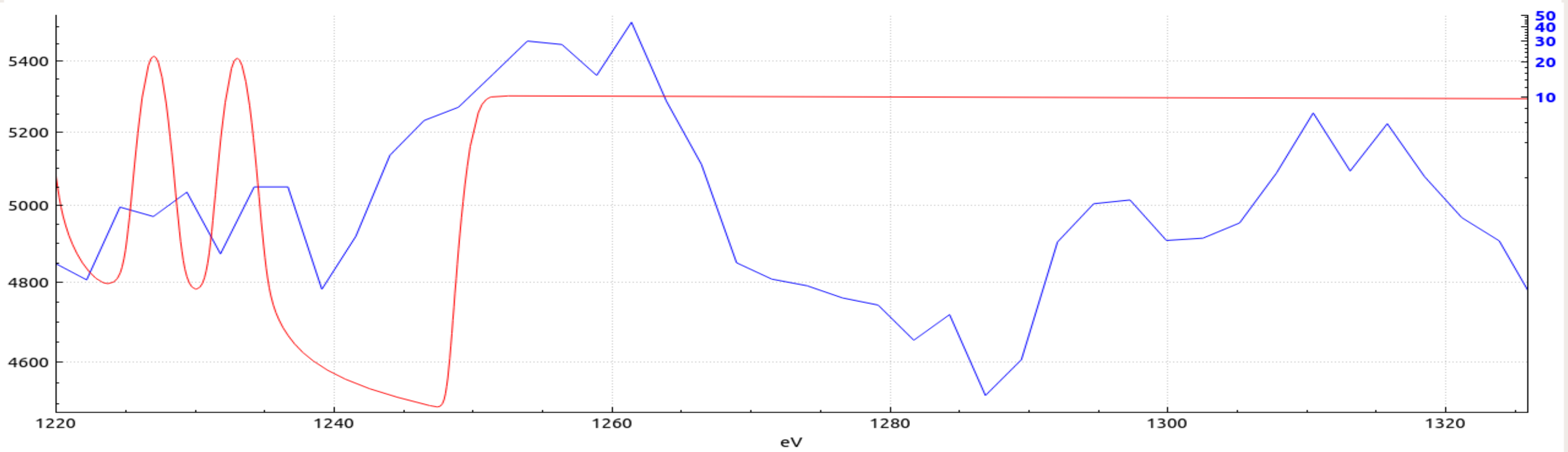




- Blue line – experimental TOF histogram, counts per channel on left vertical axis;
- Red line – BNL ENDF/B-VII.1 data for Ho165(n,gamma), cross section in barns on right axis, logarithmic scale;
- Between 1080 eV and 1105 eV resonances absent due to beam filter Mn55, which has capture resonance here for background determination.

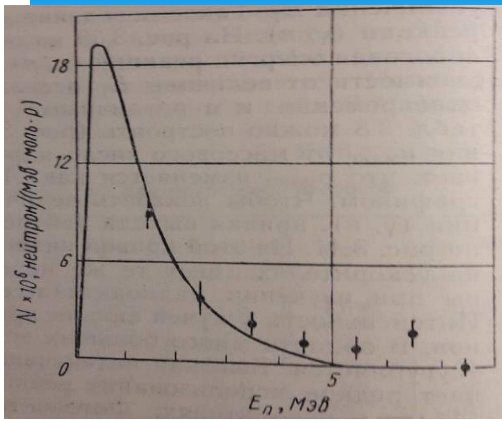
Experimental results for Ho165(n,gamma) in the energy area of resolved resonances



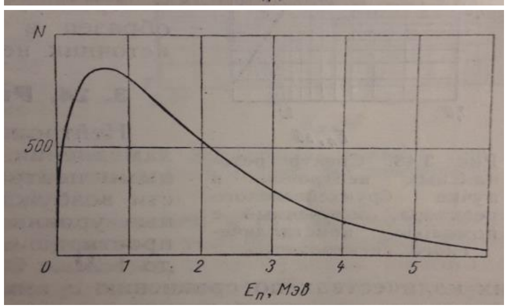


- Resolved resonances region for Ho165 currently ends at neutron energy 1250 eV in the best world data.
- At higher energies, resolution of our RADEX INES spectrometer allows to see some structure which consists of groups of resonances.
- Separate resonances are mostly not observable, because above 1300 eV energy resolution of spectrometer delta(E) is bigger then distance between Ho165 resonances.

High neutron energy area of unresolved resonances. Types of neutron sources



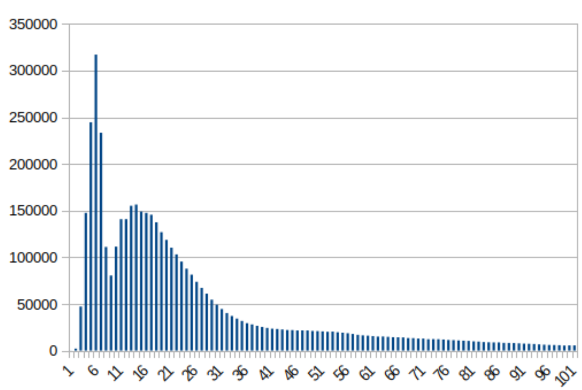
* Electron accelerators produce neutrons using (gamma,n) reaction, which is emmitting much softer neutron spectrum [7] compared to initial neutrons emitted by fission reaction. On the picture classical L. Curtiss data are shown, they corresponds to gamma rays from 22 MeV electron accelerator. Majority of neutrons have initial energies at few hundreds of KeV. Reaction (gamma, fission) also can be used to raise average energy of neutron spectra. If natural uranium is used as electron beam target, U238 has share of delayed neutrons 1.5% resulting in constant background layer on experimental histograms.



* Fission reaction has average neutron spectrum energy 2 Mev and energy of distribution’s peak 650 KeV.
* Lower energy border of prompt fission neutrons can be practically determined as 140 KeV, at energy where is available Al27(n,total) resonance, used for calibration of background curve on TOF spectra.

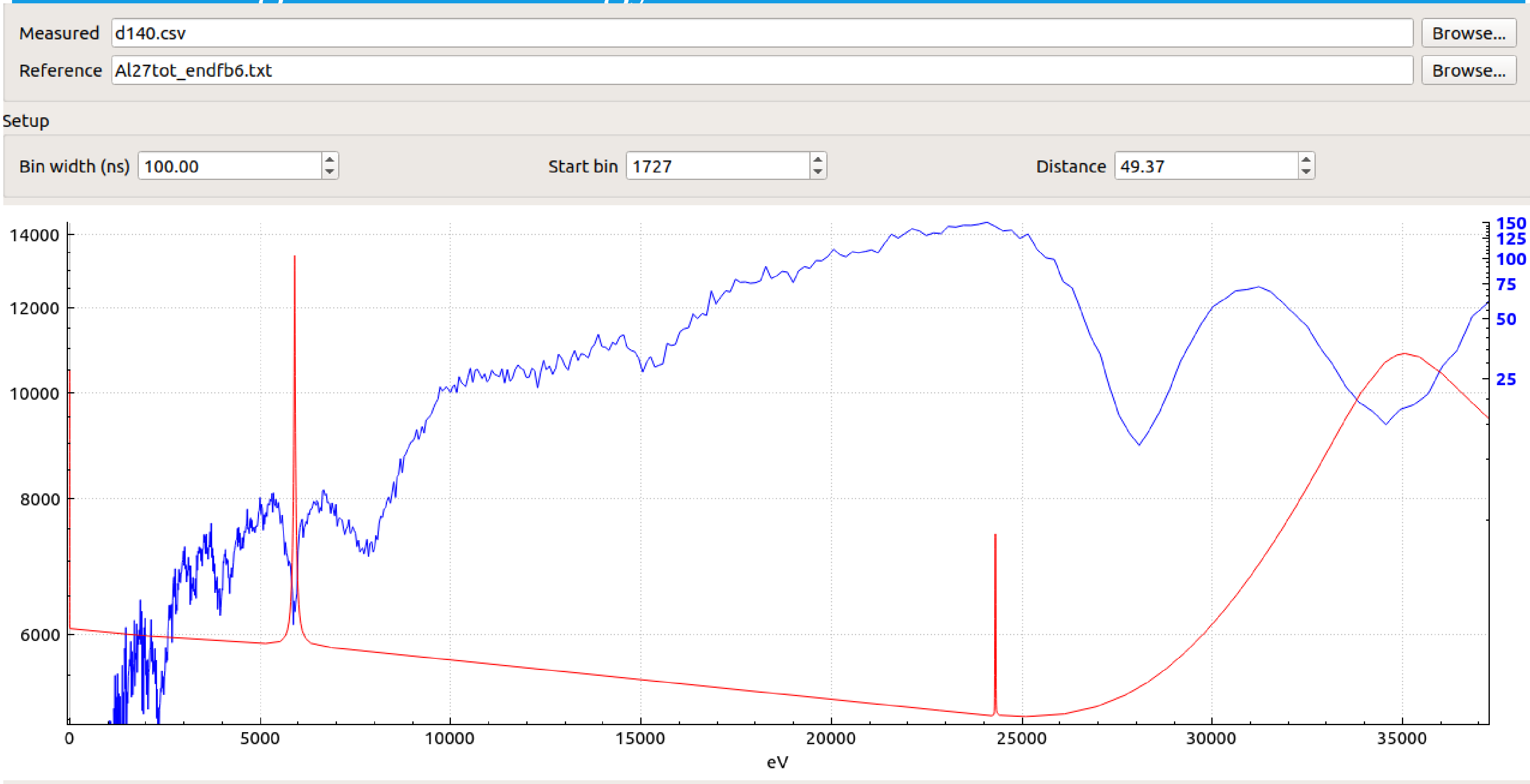
* D + D => T + p + 4,03 MeV
* D + D => He3(0.82 MeV) + n(2.45 MeV)
* D + T => He4(3.52 MeV) + n(14.1 MeV)

* Reaction of thermonuclear synthesis in plasma which consists of deuterium and tritium, produces neutrons with initial energies 2.45 MeV and 14.1 MeV. Cross sections for all 286 stable isotopes at this energies, for peaceful purposes can become actual after future successful launch of the ‘ITER’ thermonuclear reactor.



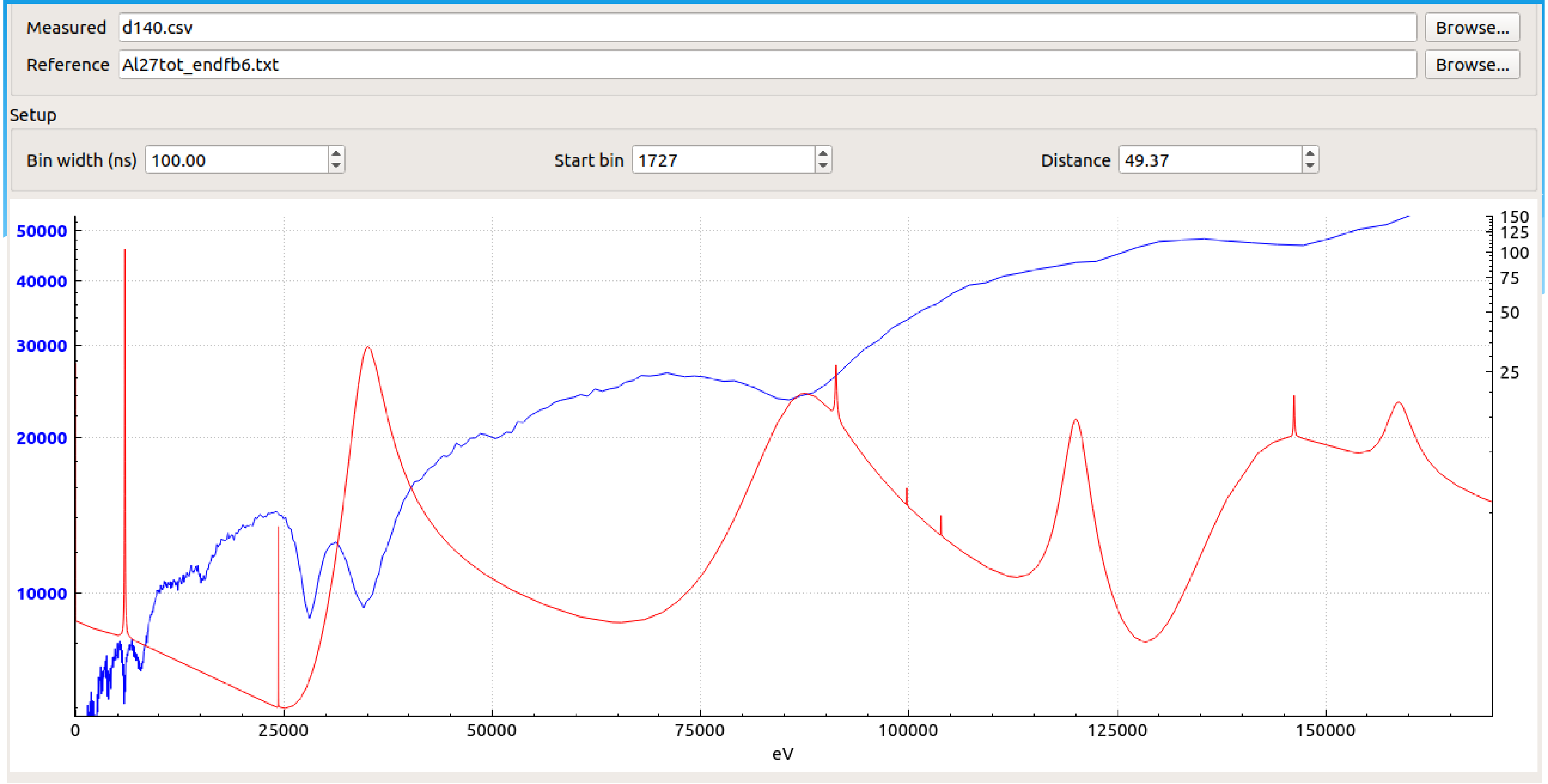
* Spectrum of spallation neutron sources, based on proton accelerators, consists of 2 components.
* Share of cascade neutrons is 8% of all initial neutrons, they have energy up to energy of protons, in our case 305 MeV.
* Another 92% of neutrons are spallation neutrons, they have average spectrum energy 3 Mev and, compared to fission reaction, less amount neutrons at En < 1 Mev.
* Share of delayed neutrons is 10^-5 and background layer by this factor is very small compared to fission reaction as a neutron source.

High neutron energy area of unresolved resonances



* Blue line is Ho165 experimental histogram, counts per channel on the left axis;
* Red line is Al27(n,total) BNL data;
* Al27 resonances at neutron energy 5900 eV and at 35000 eV are exactly observable and were used for calibration of the background curve at these energies.
* Spectrometer energy resolution allows to make measurements on this energy interval, of neutron group cross sections: both for ABBN-78 which has 28 groups,
* And for group constants based on ABBN-93, like ABBN-RF, which has 299 energy groups and is being developed in Russia for fast breeder reactor calculations.

High neutron energy area of unresolved resonances

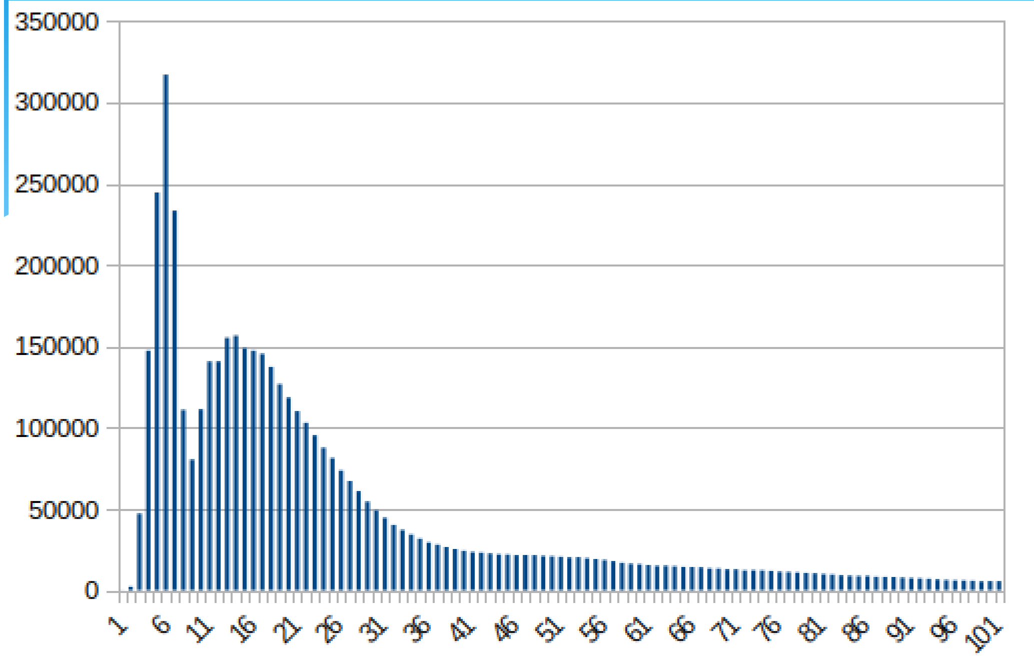


* Al27(n,total) resonances, used as beam filter, are exactly observable at 5900 ev, 35000 ev, 87000 eV
* Resonance at 147000 eV is also observable on experimental curve. This allows to calibrate the background curve in the region 140 – 170 KeV and extrapolate it higher.

High neutron energy area of unresolved resonances

* Neutron energy region up to 0.5 MeV includes main part of spectra of fast breeder reactors.
* Al27 resonance at 147000 eV is exactly observable on this scale.
* New method for background determination in the MeV region is currently investigated.
* Good statistical precision of measurements (counts on the left axis) in high energy region, allows to provide precision of experimental data, requested by reactor requirements.

Conclusion



* Ho165 capture resonances were experimentally confirmed at 24,8 eV; at 65.18 eV; at 75.07 eV; at 120 eV.
* Amplitude value for 126.9 eV resonance coinsidences with ENDF/B-VII.1 data file.
* Energy resolution of the spectrometer INES, based on neutron beam of the INR RAS pulsed neutron source RADEX, allows to observe all resolved area of Ho165 capture cross section. Up to 1250 eV, according to the best world data files.

* At resolution 6 nanoseconds per meter we achieved separation between cascade neutrons and spallation neutrons. On the picture first 100 histogram channels of (n,gamma) detector are shown, 100 ns each step, energy of minimum point between components is 8 MeV.
* Energy resolution of modern TOF spectrometers allows to make measurements in all practically important neutron energy region: 0.0253 eV < En < 14 MeV.
* It allows to resolve the resonance structure, of all 286 stable nuclides, up to energy, where Doppler-effect makes intersection of neighbor resonances at the temperatures of the core of nuclear reactors and radiation shield.
* The same high energy resolution is necessary to make possible measurements in wide energy groups for multi-group neutron reactor constants.

Literature and cited sources

* 1. Brookhaven National Laboratory http://www.bnl.gov
* 2. http://isinn.jinr.ru/past-isinns/isinn-27/presentations/12/Khliustin.pdf
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* 4. http://isinn.jinr.ru/past-isinns/isinn-25/24/Hliustin.pdf
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* 7. L.F. Curtiss ‘Introduction to Neutron Physics’. D. van Nostrand Book Company, Inc. Princeton, New Jersey.

Thank you for your attention !