ISINN-26

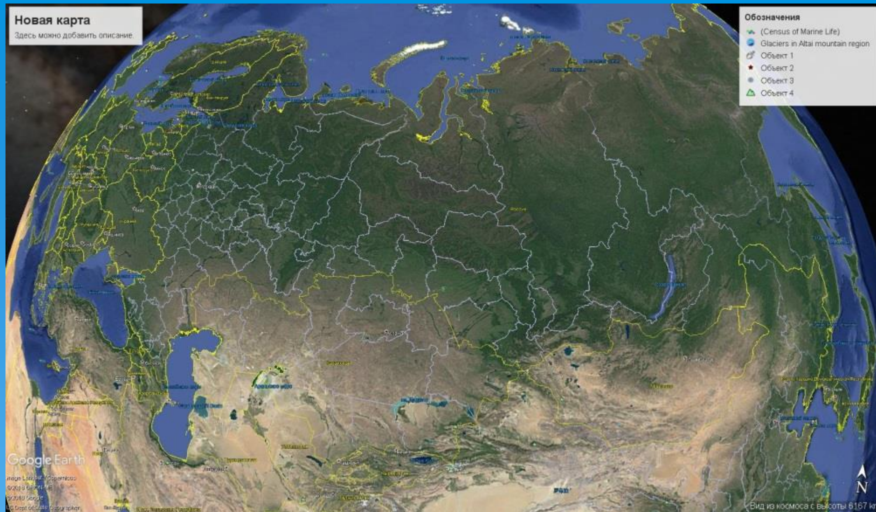
International Seminar on Interaction of Neutrons with Nuclei

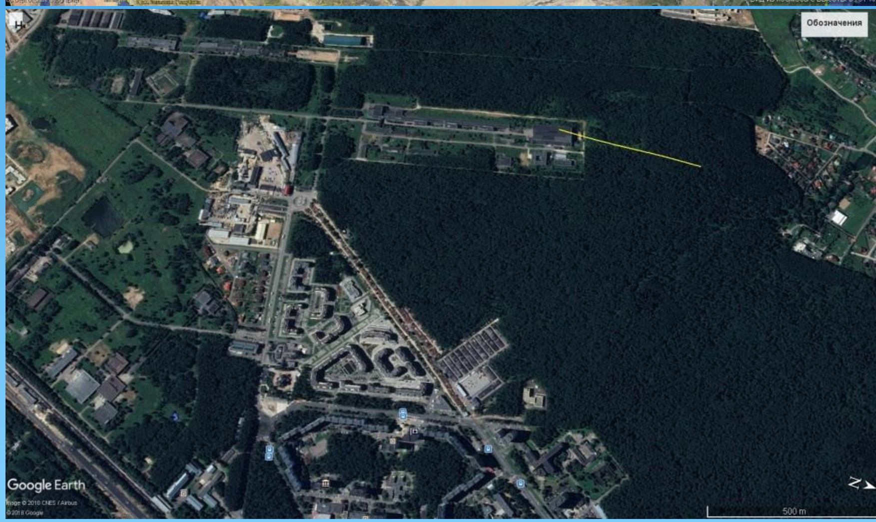
TOF Method Measurements at INR Spallation Neutron Source RADEX

Djilkibaev R.M., Khliustin D.V., Vasilev I.A.

denhlustin@gmail.com

Institute for Nuclear Research Russian Academy of Sciences
Moscow, Russia





One of the most important tasks, for which INR RAS proton linac was designed and built, were TOF measurements to provide fast neutron reactors program by exact neutron group cross sections data. Powerful Linac with one-turn beam extraction storage ring for high intensity, and long TOF bases for high $\left(\frac{\Delta t}{L}\right)$ parameter were designed. Target reloading machine allows to change proton beam target making modeling of the reactor's core and measure corresponding neutron spectrum.

Proton linac of INR Russian Academy of Sciences

Project linac parameters:

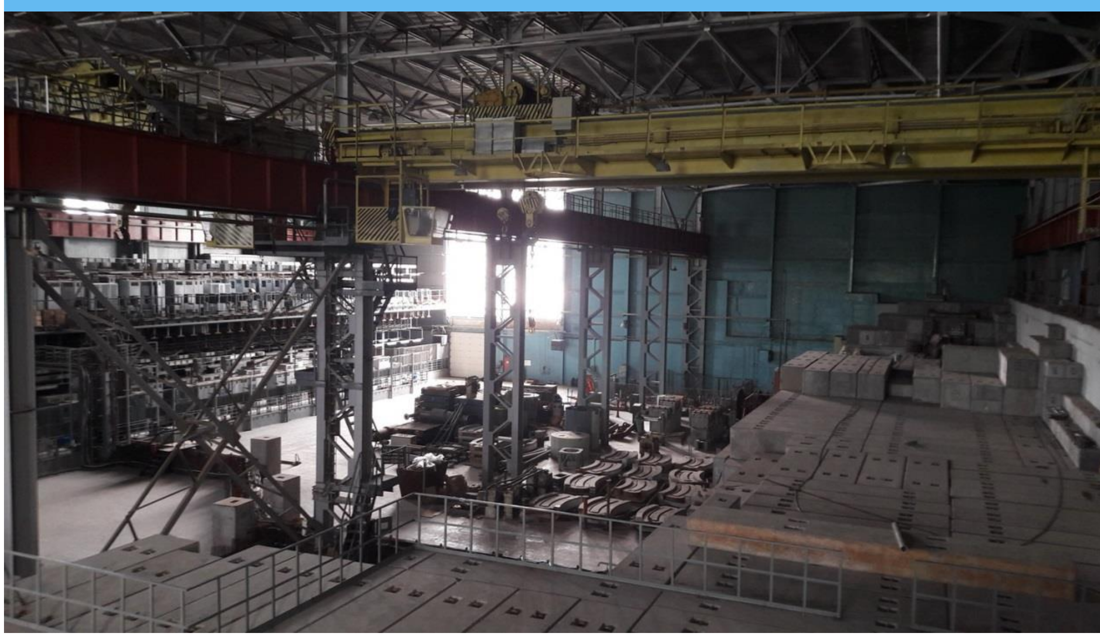
Proton energy 600 MeV, pulsed current 50 mA, frequency 100 Hz, maximum pulse duration 100 (200) mks;

Average current 0.5 (1.0) mA, mean beam power 300 (600) kW, neutron yield into angle $4\pi \sim 10^{17}$ neutrons per sec

Storage ring of INR Linac : project parameters

* Beam aperture 200 mm
* $2\pi R$ = 102.8 meters
* Proton cycling period 430 nanoseconds at 600 MeV
* Maximum pulse current, allowed by space charge: 10 Amperes at 600 MeV
* Maximum pulse intensity $2.3*10^{13}$ protons in each pulse at 100 Hz
* Average neutron flux with W target in short pulses at 100 Hz: $2.5*10^{16}$

Storage ring is now under construction.
Significant part of it's radiation sustainable equipment is already manufactured.



Requirements for exactness of group neutron cross sections:
for many types of reactors are determined by share of delayed neutrons

Reactor fuel composition	**U-235**	**U-233**	**Pu-239**	**BN-1200 nitride fuel**
Desirable exactness of criticality coefficient calculation $\left(\frac{\Delta K}{K}\right)$	0.6%	0,2%	0,2%	0.42%

Diffusion one-group approximation gives expression for critical radius

$$R_{crit} = \frac{\pi}{\sqrt{3(K_{inf}-1)\Sigma_a \Sigma_{tr}}} - \frac{0.71}{\Sigma_{tr}}$$

And expression for critical mass

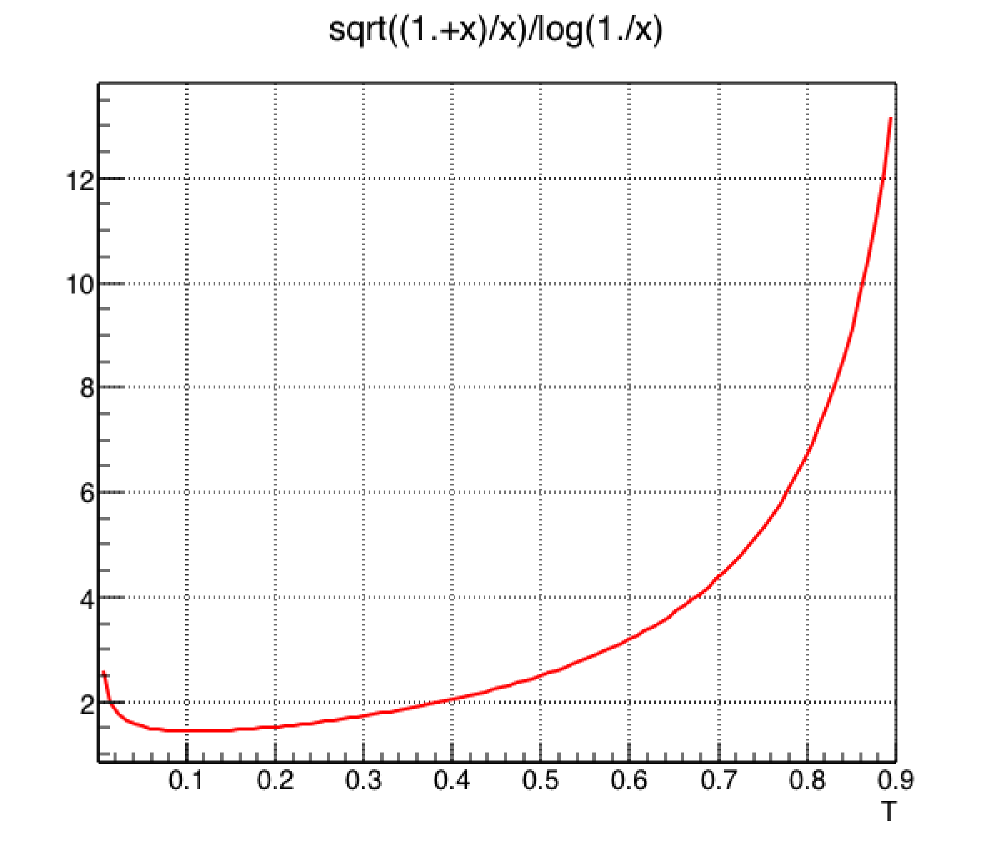
$$M_{crit} \sim R_{crit}^3 \sim (\Sigma_a \Sigma_{tr})^{\frac{3}{2}} \sim (\sigma_a \sigma_s)^{\frac{3}{2}}$$

Exactness of neutron cross sections must provide exactness of critical mass prediction $\left|\frac{(M_{calc}-M_{measured})}{M_{measured}}\right|$ better then value, which corresponds to maximum allowed $\left(\frac{\Delta K}{K}\right)$ value

Exactness of TOF transmittance method for measurements of total cross sections for one channel of data acquisition system:

* N(x) = $N_0 \exp(-nx\sigma_{total})$
* T = $\frac{N_x}{N_0}$
* $\sigma_{total} = \left(\frac{1}{nx}\right) ln\left(\frac{1}{T}\right)$

* $\frac{(\delta\sigma_{total})}{(\sigma_{total})} = \left(\frac{1}{\sqrt{N_0}}\right)\left(\sqrt{\frac{1+T}{T}}\right)\left(\frac{1}{ln\left(\frac{1}{T}\right)}\right)$



For total cross section exactness 0.2% it's necessary to accumulate statistics $\sim 1{,}000{,}000\ counts\ in\ each\ channel$

Achieved exactness of fast breeder reactors criticality calculation predictions $\frac{\Delta K}{K}$

Neutron Constant system	MCNP	ABBN-78	ABBN-93
$\left(\frac{\Delta K}{K}\right)$, %	2	2	0.5

During fast neutrons moderation, number of scatterings between energies E_0 and E is

$$N_{scatterings} = \left(\frac{1}{\xi}\right)\ln\left(\frac{E_0}{E}\right)$$

where $\left(\frac{1}{\xi}\right) \approx \frac{A}{2} + \frac{1}{3} + \frac{1}{18A}$

If $E_0 = 14\ Mev\ and\ E = 0.0253\ ev, for\ substance\ like\ Li^6D$ we find that 28 energy groups in ABBN-78 are enough.

Due to presence in the core of fast breeder reactor such medium atomic mass nuclides like Na, Fe, Cr, Ni, Ti, in neutron group cross section constants ABBN-93 were chosen 299 groups.

In our measurements we are working to fit ABBN-93 requirements.

Energy resolution of TOF spectrometer as function of $\left(\frac{\Delta t}{L}\right)$ parameter

$\Delta E = 2.77 * 10^{-5} * E^{\left(\frac{3}{2}\right)} * \left(\frac{\Delta t}{L}\right)$ where Δt – nanoseconds, L – meters, E - eV

$\Delta t, \left(\frac{ns}{m}\right)$	$\Delta E, eV$						
	E=10 eV	E=100 eV	E=1 Kev	E=10 KeV	E=100 KeV	E=1 MeV	E=10 MeV
100	0.09	2.8	88	2800	88000	2800000	88E6
50	0.04	1.4	44	1400	44000	1400000	44E6
10	0.009	0.28	8.8	280	8800	280000	8.8E6
5	0.004	0.14	4.4	140	4400	140000	4.4E6
1	0.0009	0.028	0.88	28	880	28000	880000
0.5	0.0004	0.014	0.44	14	440	14000	440000
0.1	0.00009	0.028	0.088	2.8	88	2800	88000

Influence of Doppler-effect and cross sections self-shielding of multi-isotope compounds on reactor criticality and other parameters on example of one-group diffusion theory

$$D\Delta\Phi - \Sigma_a\Phi + \upsilon\,\Sigma_f\,\Phi = 0 \qquad (1)$$

$$D\Delta\Phi + (\eta - 1)\,\Sigma_a\,\Phi = 0 \qquad (2)$$

thus we get differential equation with Laplasian and buckling parameter

$$\Delta\Phi + (\eta - 1)\left(\frac{\Sigma_a}{D}\right)\Phi = 0 \qquad (3)$$

or the same equation in ordinary form

$$\Delta\Phi + \left(\frac{\eta-1}{L^2+\tau}\right)\Phi = 0 \qquad (4)$$

where D – diffusion coefficient, Φ – neutron flux, Σa – macroscopic absorption cross section, τ – Fermi's age of neutron flux, L2 – square of diffusion's length.

Lower resonance levels have mainly neutron capture properties. Doppler-effect and internal block-effect influence on value of Σa and are measured by gamma-detectors.
Upper resonance levels are mainly scattering neutrons without absorption them. At the same time Doppler-effect and multi-isotope alloy's interference of resonance levels influence on value D.
Thus, leakage from fast neutron reactor's core into reflector also changes at different temperatures and delutions. This effect if researched by transmission functions measurements in TOF experiments.
Both first and second effects are able to change effective L2 and τ.

In TOF experiments transmission and self-indication functions must be measured in unresolved resonance area, that is possible using multiplicity coincidence method.

Group Energy width Energy $\Delta E, eV$ of the ABBN-78 neutron constants

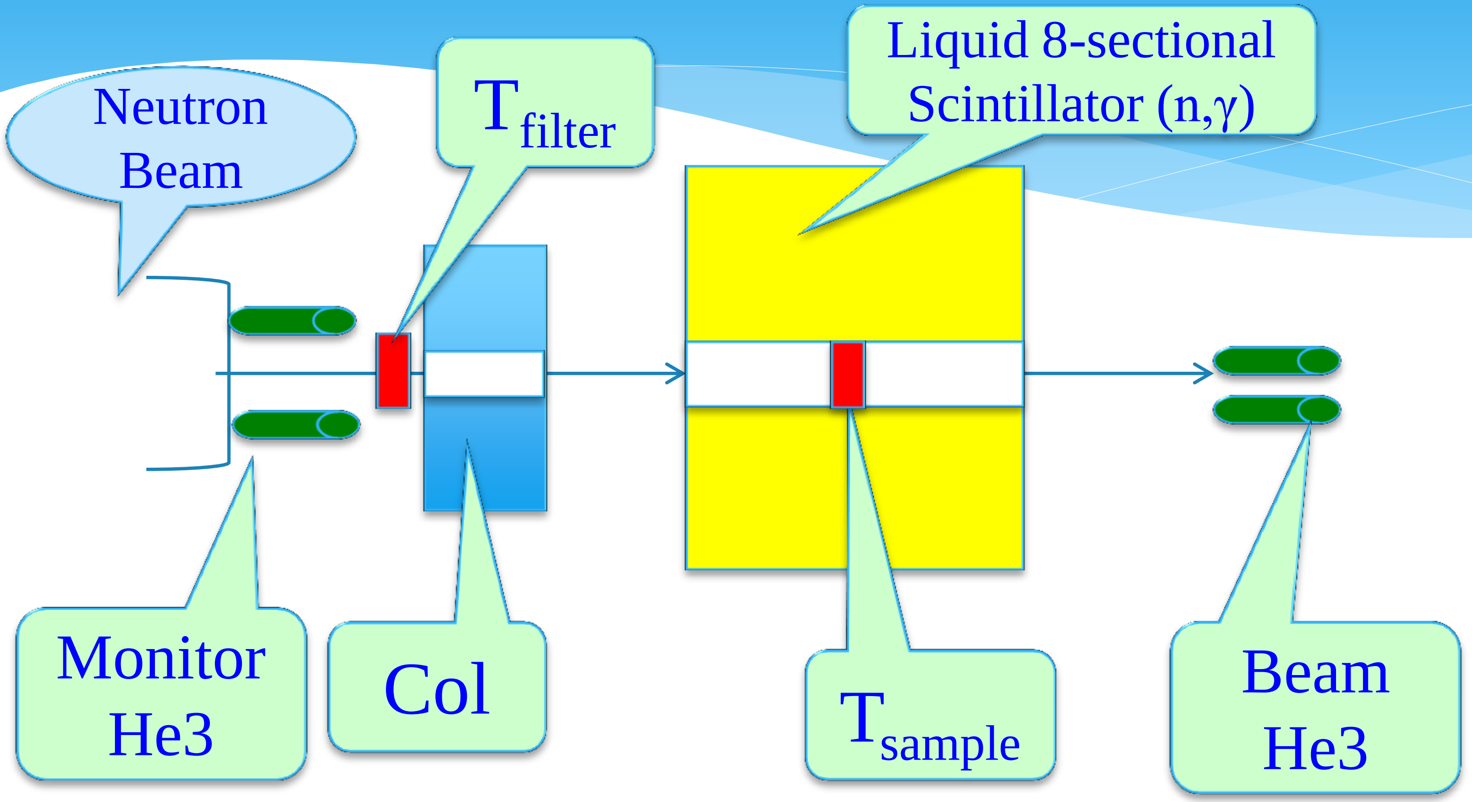
	Energy width $\Delta E, eV$ of group number N						
	E=10 eV	E=100 eV	E=1 Kev	E=10 KeV	E=100 KeV	E=1 MeV	E=10 MeV
Group's number	21	18	15	12	9	6	1
Width	11.5	115	1150	11500	115000	600000	3500000

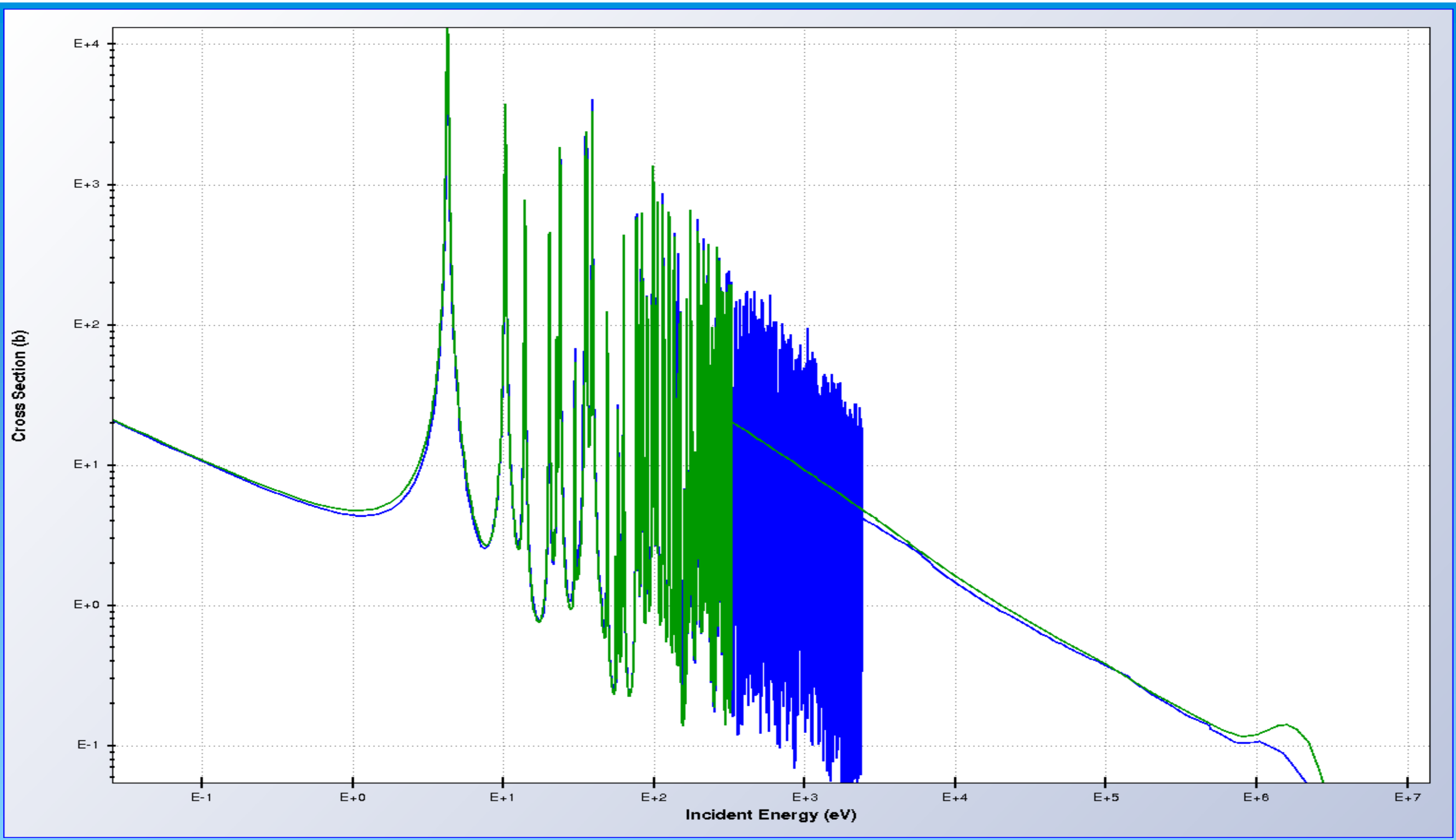
Compared to resonance structure measurements, where energy level's width Γ_γ is approximately constant in wide energy range and is about 0.1 eV for heavy nucleus, group cross sections measurements allow to measure up to higher upper energy level using the same TOF spectrometer with the same energy resolution $\left(\frac{\Delta t}{L}\right)$ measured in nanoseconds per meter.

Also important that number of counts per channel, in expression for accuracy of measurements, corresponds not to single data acquisition system channel, but to energy group where present many histogram channels.

At the same time, capture cross sections measurements must be done in the energy area of unresolved resonances using multiplicity coincidence method, which gives an opportunity to distinguish effect and background.

Installation INES:
Investigations of Neutron Experimental cross Sections





Ta181 BNL

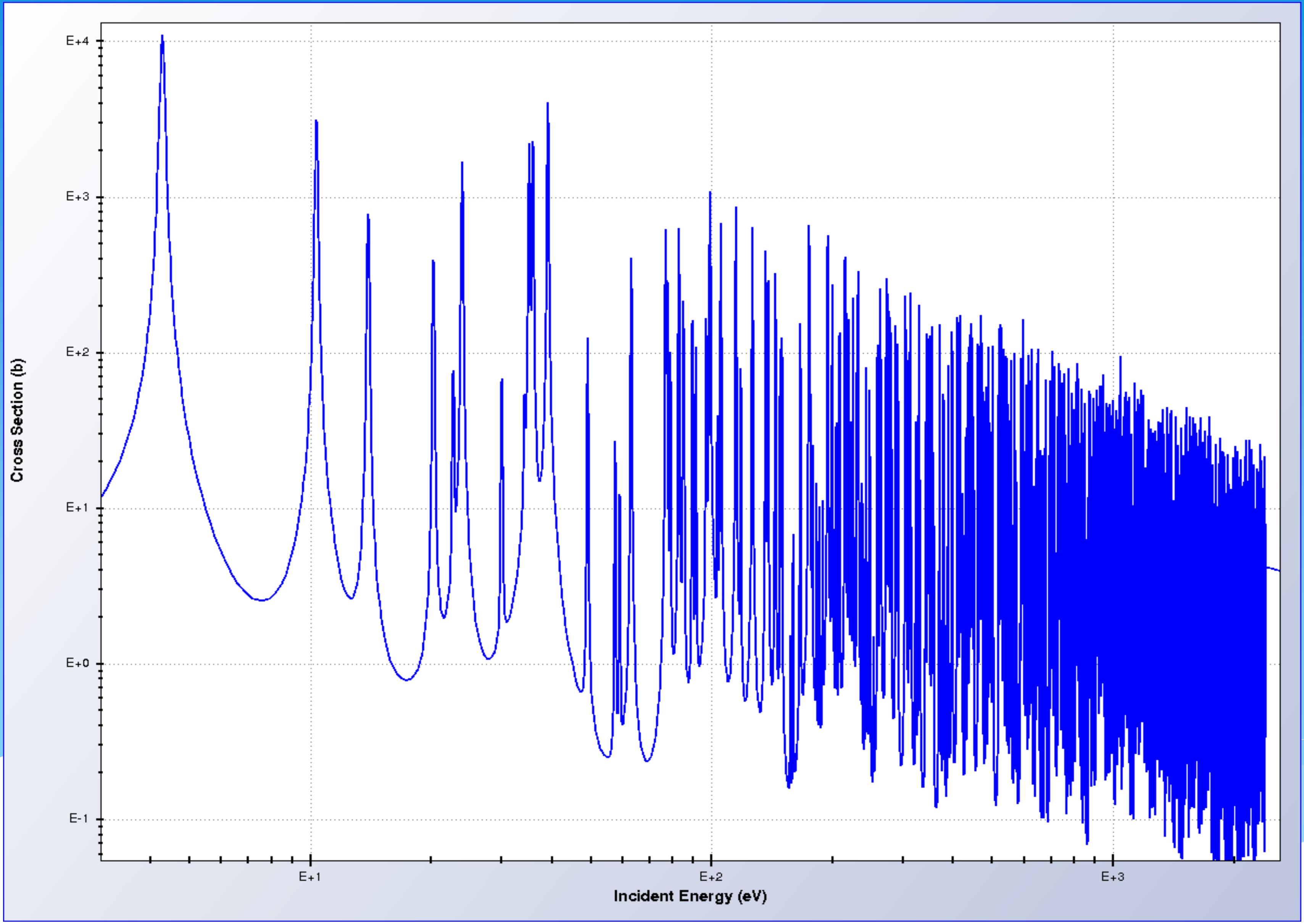
Resolved resonances up to 2500 eV

Unresolved Resonances 2.5e3-1.e5

Green 73-Ta-181(n,γ) ENDF/B-VII.1

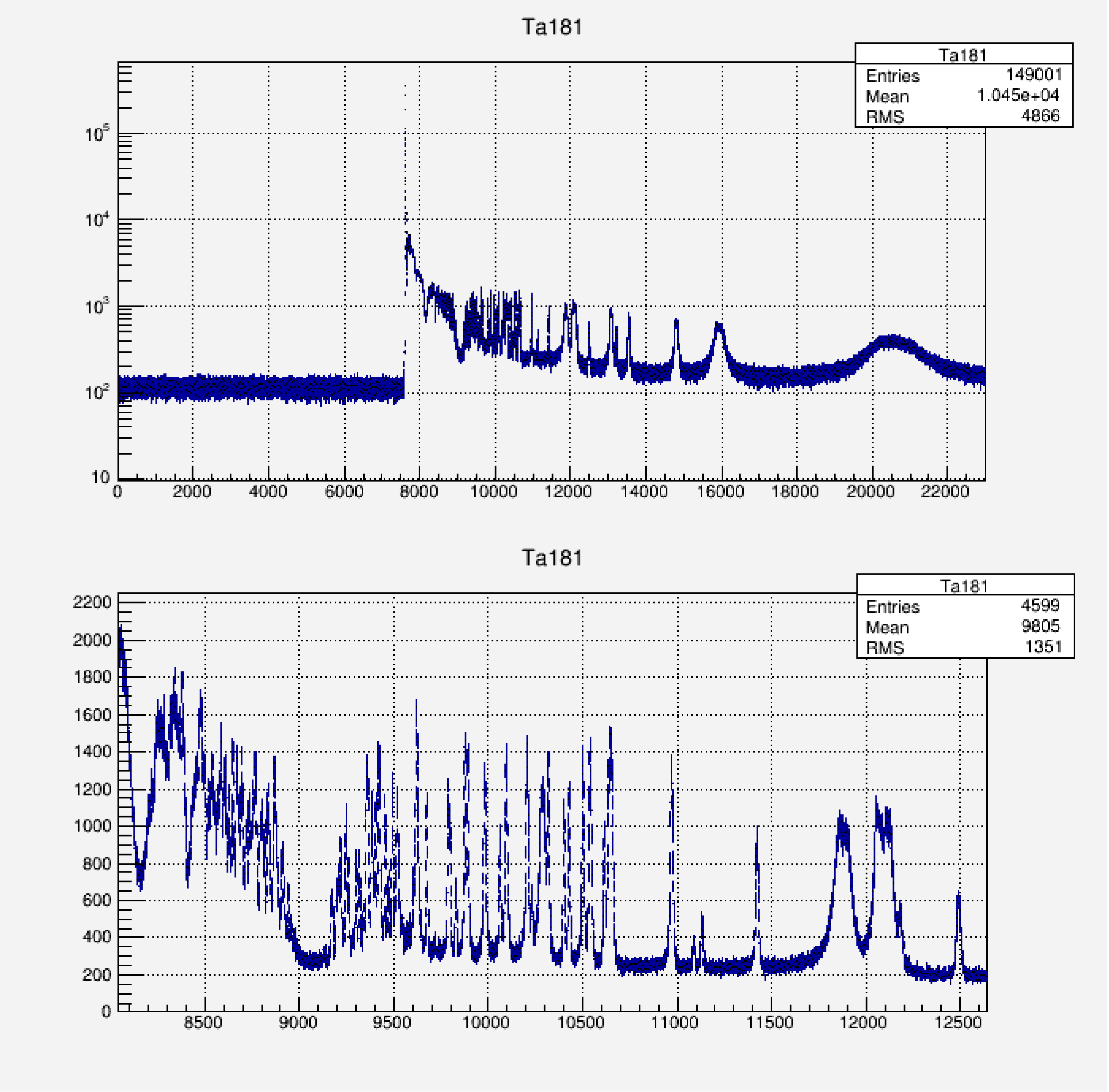
Blue 73-Ta-181(n,γ) JENDL-4.0

Ta181 cross capture from 3.0 to 2500 eV

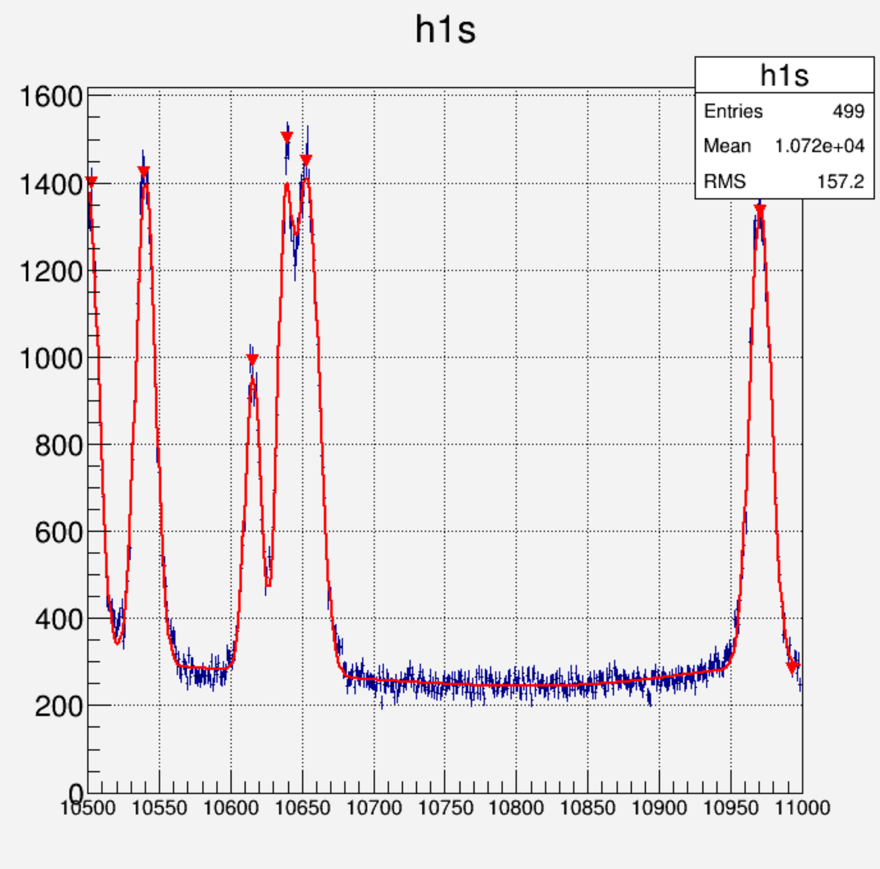


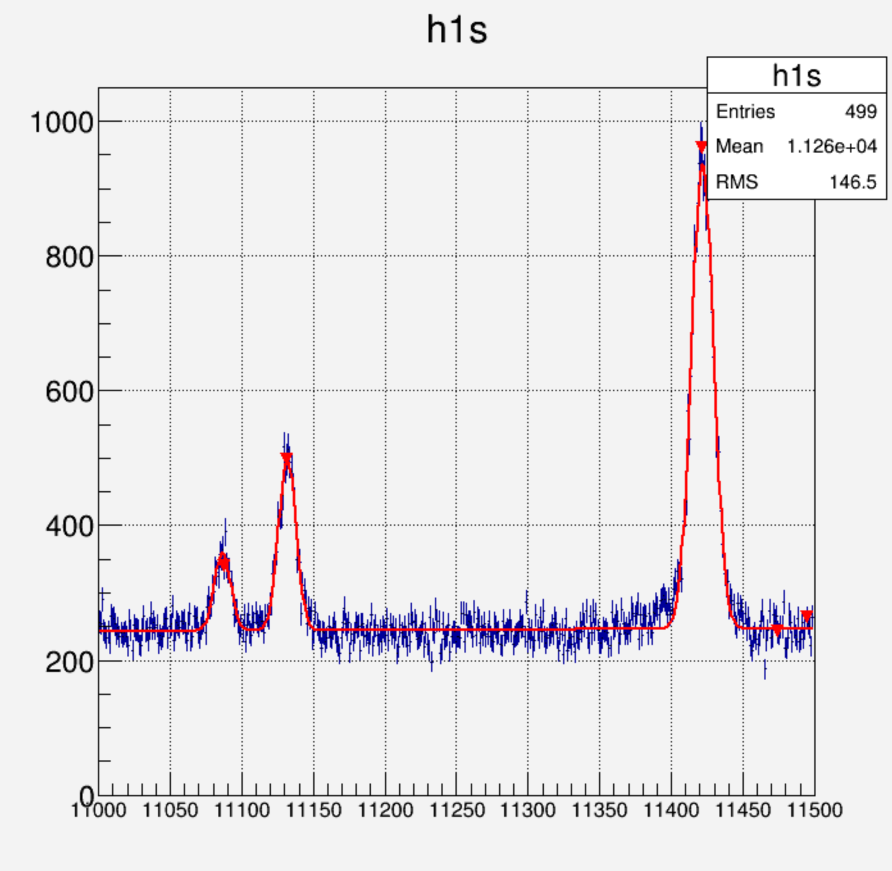
Ta181 our measurements

TOF base L=50 meters
Beam filter = Mn^{55}
Accelerator was working with proton beam parameters:
$E_p = 209\ MeV$
$J_{pulse} = 10\ mA$
$\tau_p = 1 mks$
ν =50 Hz



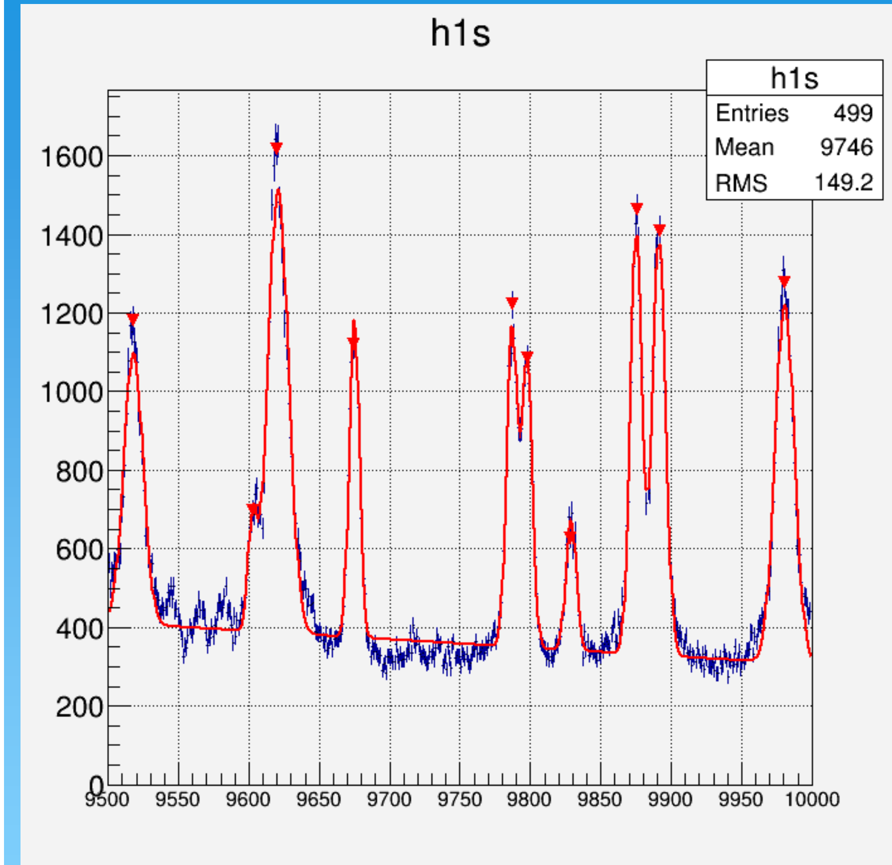
Ta181 our measurements

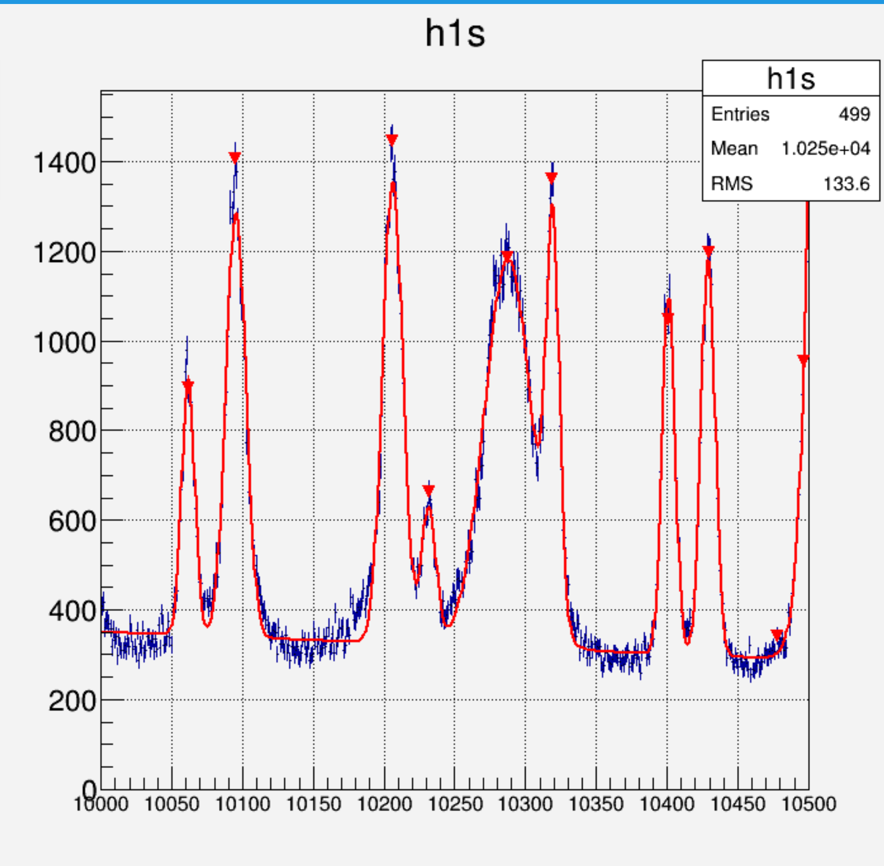




Experimental spectral histograms can be transformed into cross section curves by main two methods. Below few hundreds eV for heavy atoms with high resonance level densities, where ΔE of spectrometer resolution function is smaller then Γ_γ which is about 0.1 eV, the method of form can be used. At higher neutron energies in the resolved area it's necessary to use method of square areas.

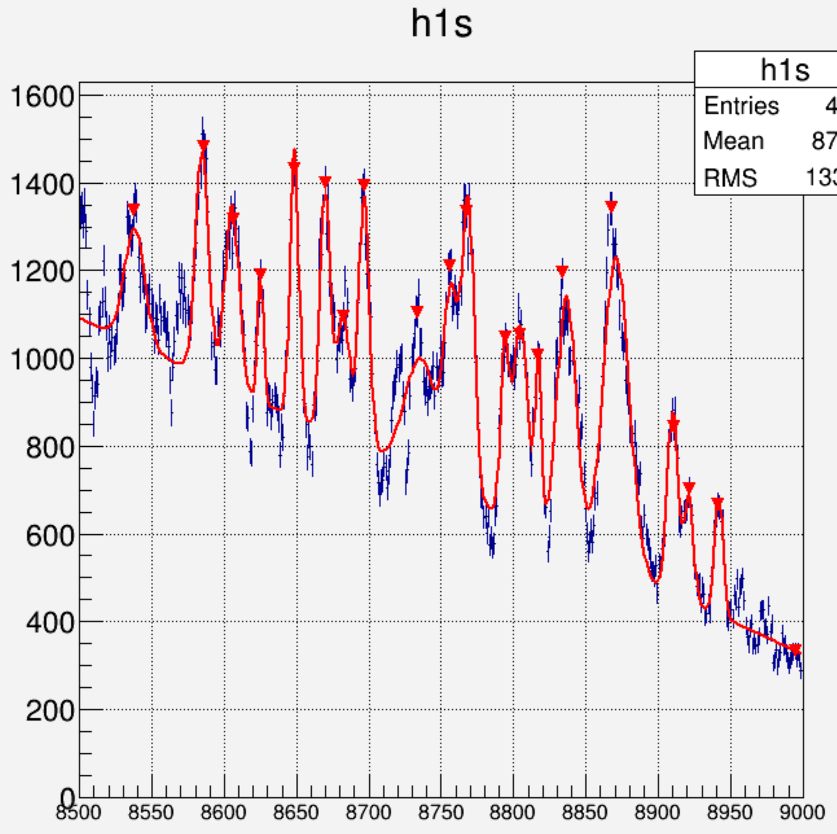
Ta181 our measurements

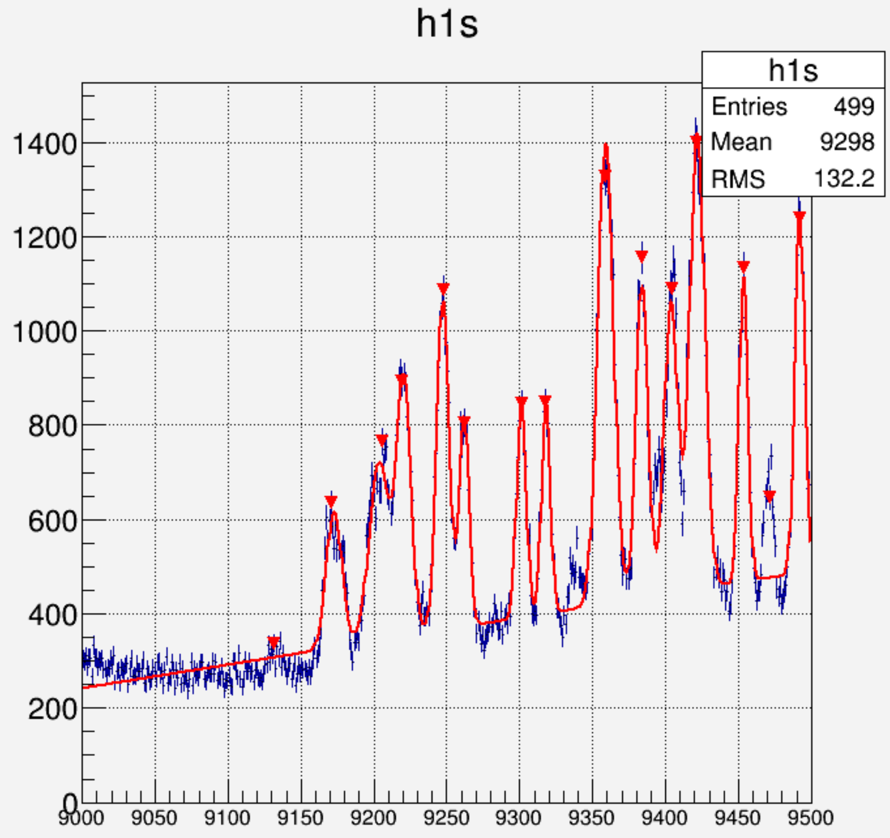




Program for resonance parameters definition automatically calculates:
* Background level as function of neutrons energy on experimental histogram
* Energy of the center of resonance area
* Width of resonance on half-altitude
* Area of the resonance

Ta-181 our measurements

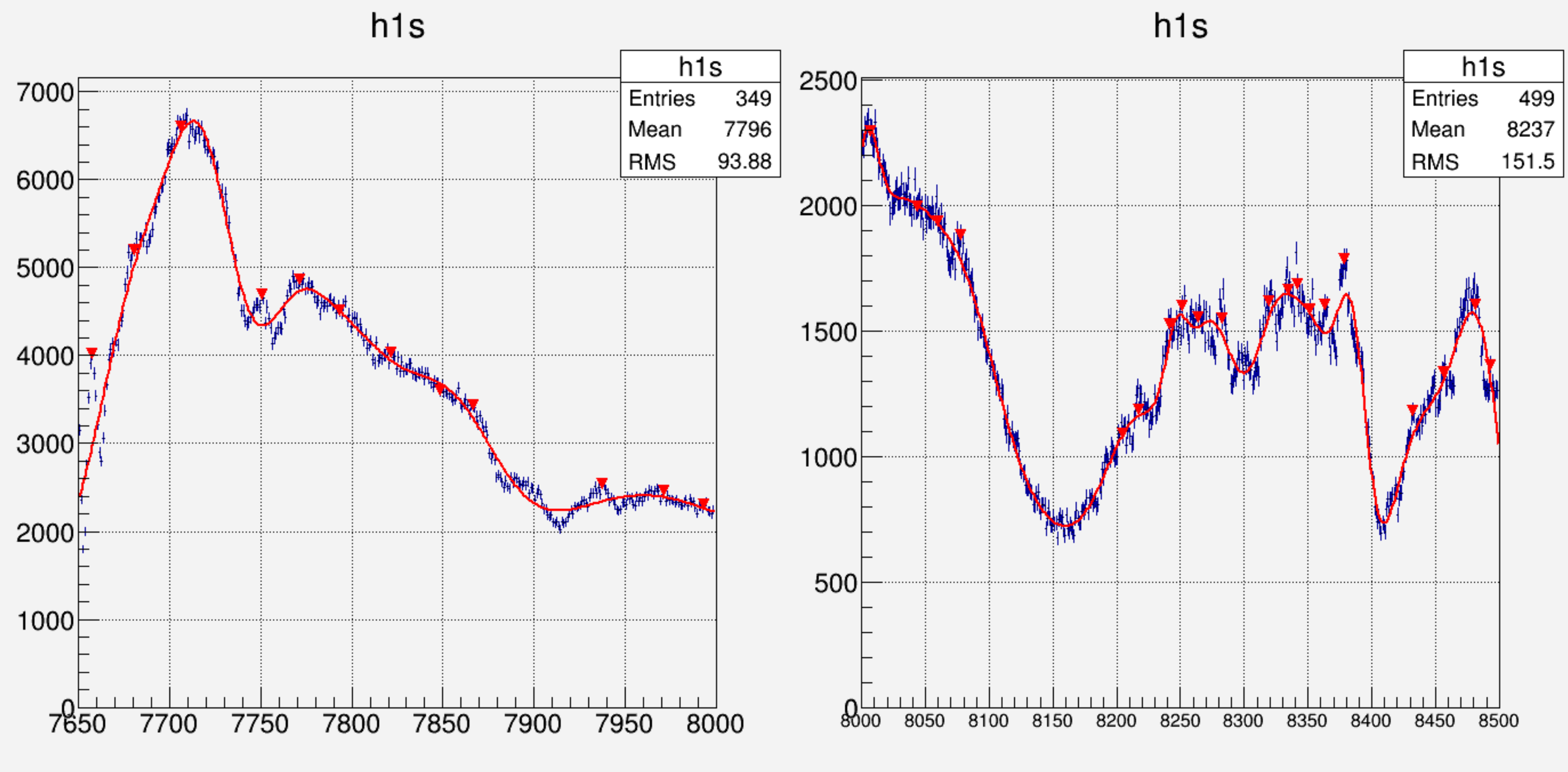




At energies upper then fe hundreds eV, in the case of heavy nuclides with most dense energy level system and the smallest intervals between resonances, spectrometer resolution function's value is much larger then energy width Γ_γ with doppler-effect.

Due to this, experimental histogram gives us Gauss resonance parameters. When we know them, using another program for each resonance we transform the curve into the cross section curve descripted by Breit-Wigner parameters.

Ta-181 our measurements



Nuclides which we measured for calibration of installation INES are:

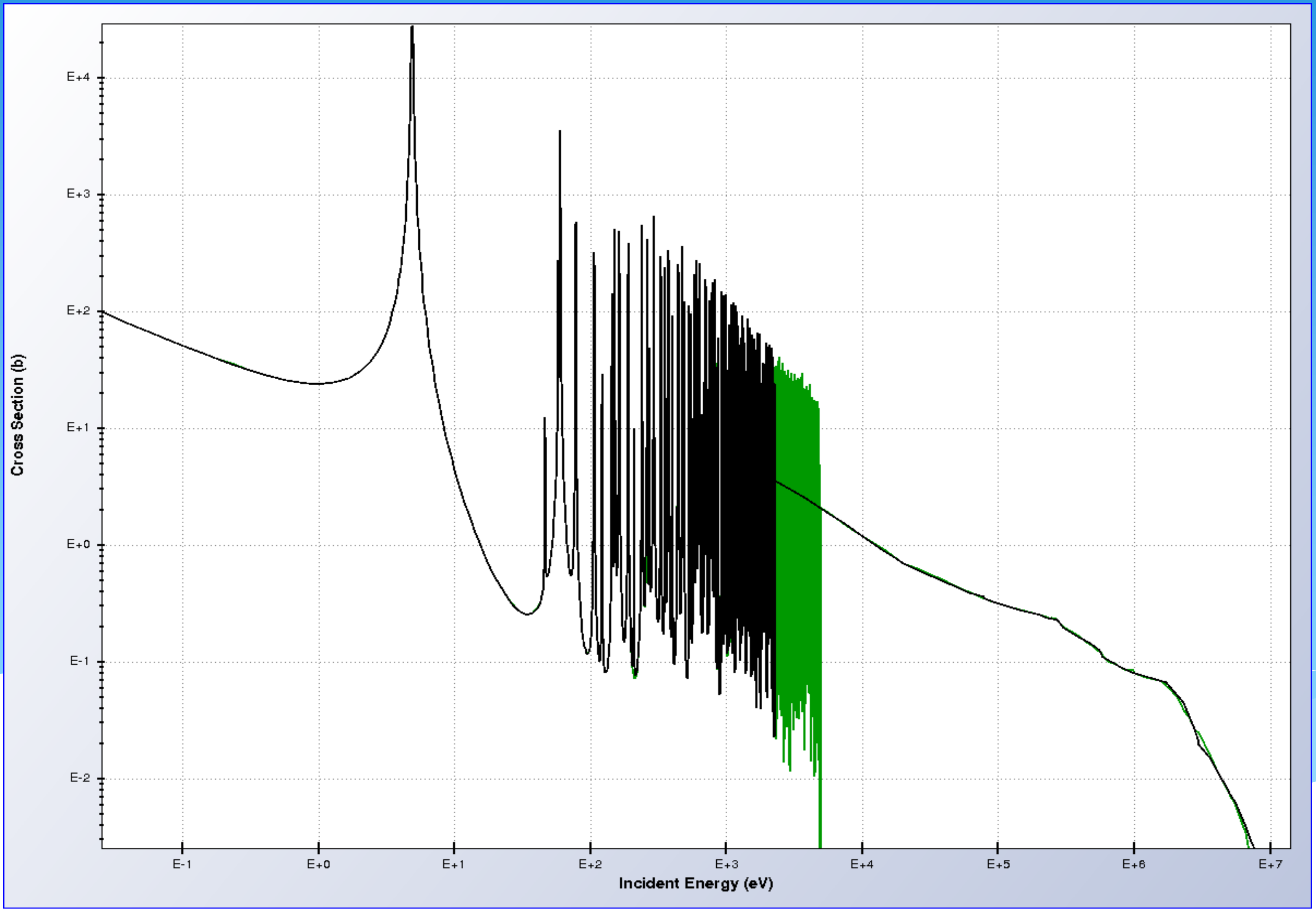
Isotope	D_0, eV	Isotope (A+1)	$T_{1/2}$ of (A+1)
Ta^{181}	1.13	Ta^{182m2}	15.8 minutes
In^{115}	1.9	In^{116m1}	54 minutes
Au^{197}	1.15	Au^{198}	2,7 days

Au197

Resolved resonances up to 5000 eV

Black line = JENDL-4.0

GREEN line = ROSFOND

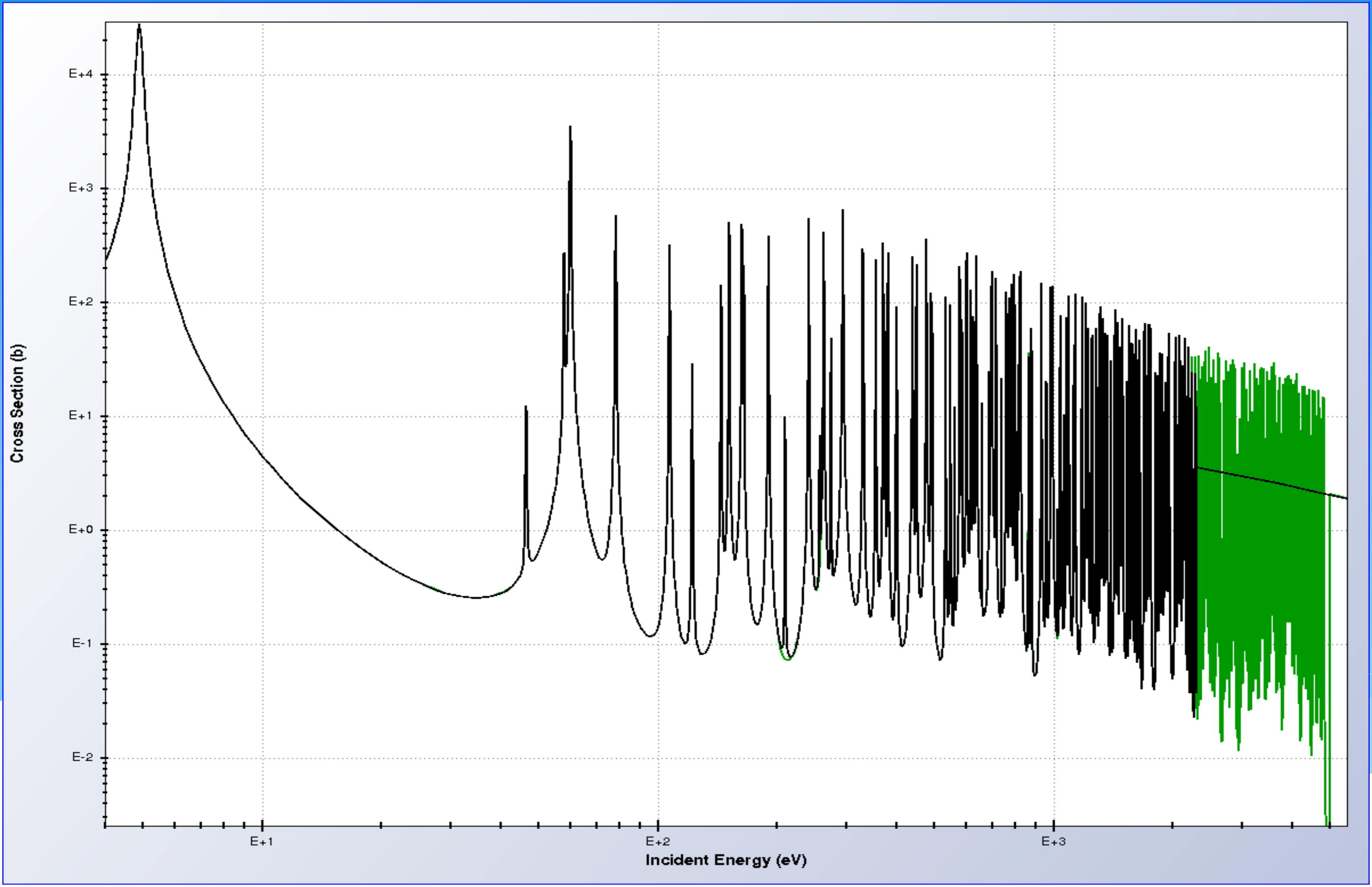


Au197 BNL

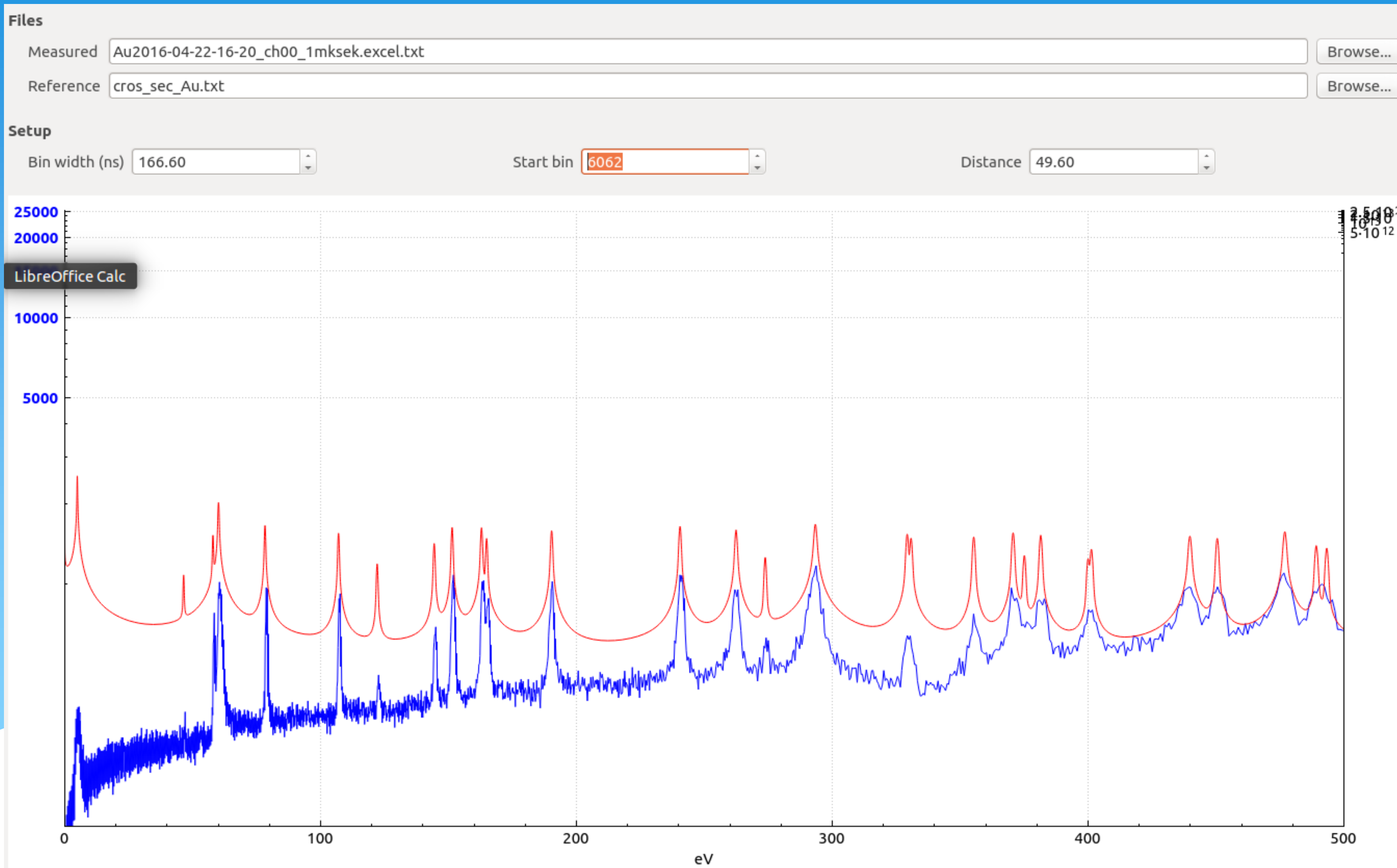
Resolved resonances up to 5000 eV, unresolved resonance region: 5 keV – 100 keV

Black = JENDL-4.0

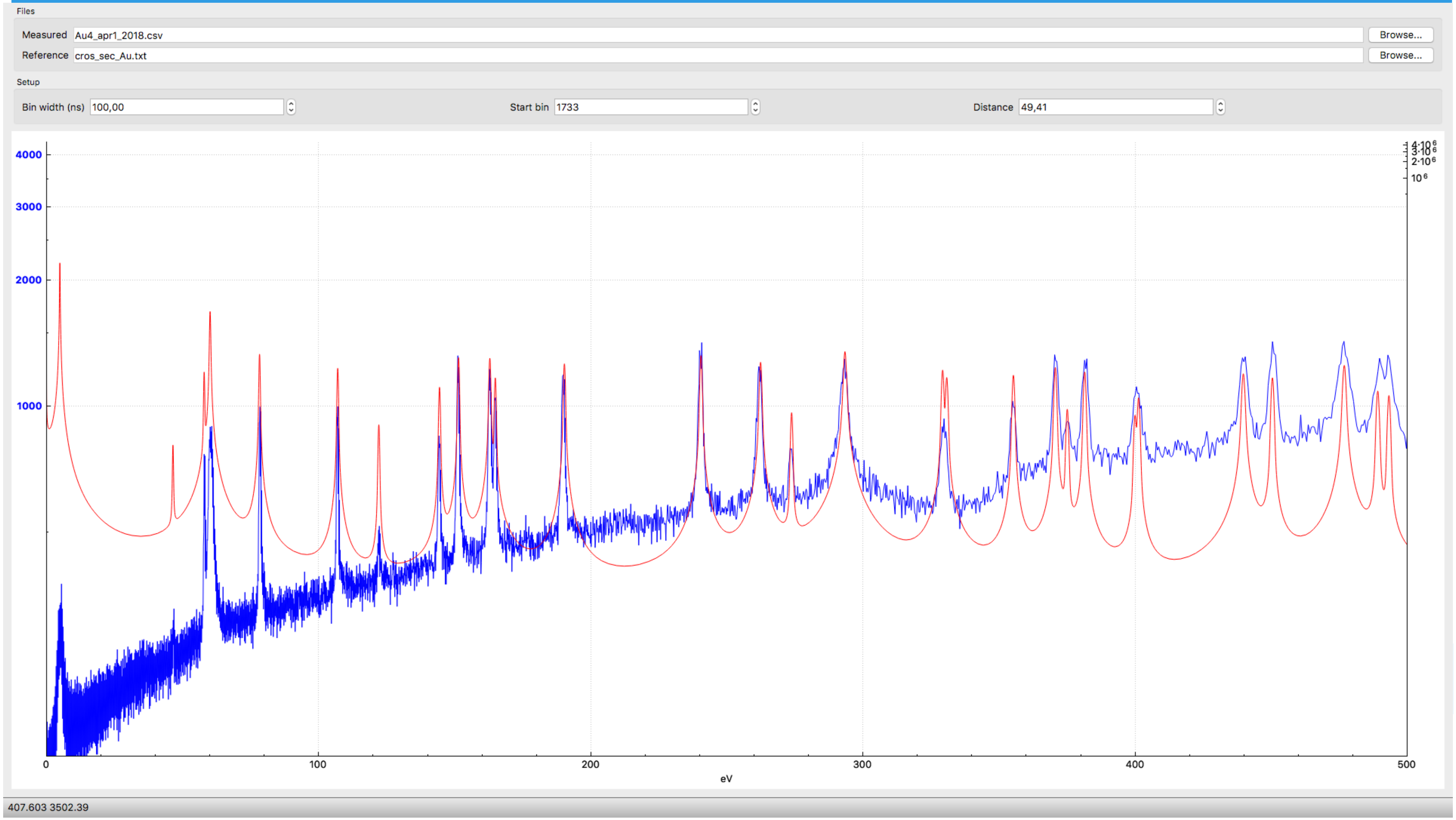
GREEN = ROSFOND



79-Au-197 our measurements
L= 49.6 meters, t=1 mks,
measured during year 2016 by installation INES based on Spallation Neutron Source RADEX



79-Au-197 our measurements
L= 49.6 meters, t=0.5mks,
measured during year 2018 by installation INES based on Spallation Neutron Source RADEX

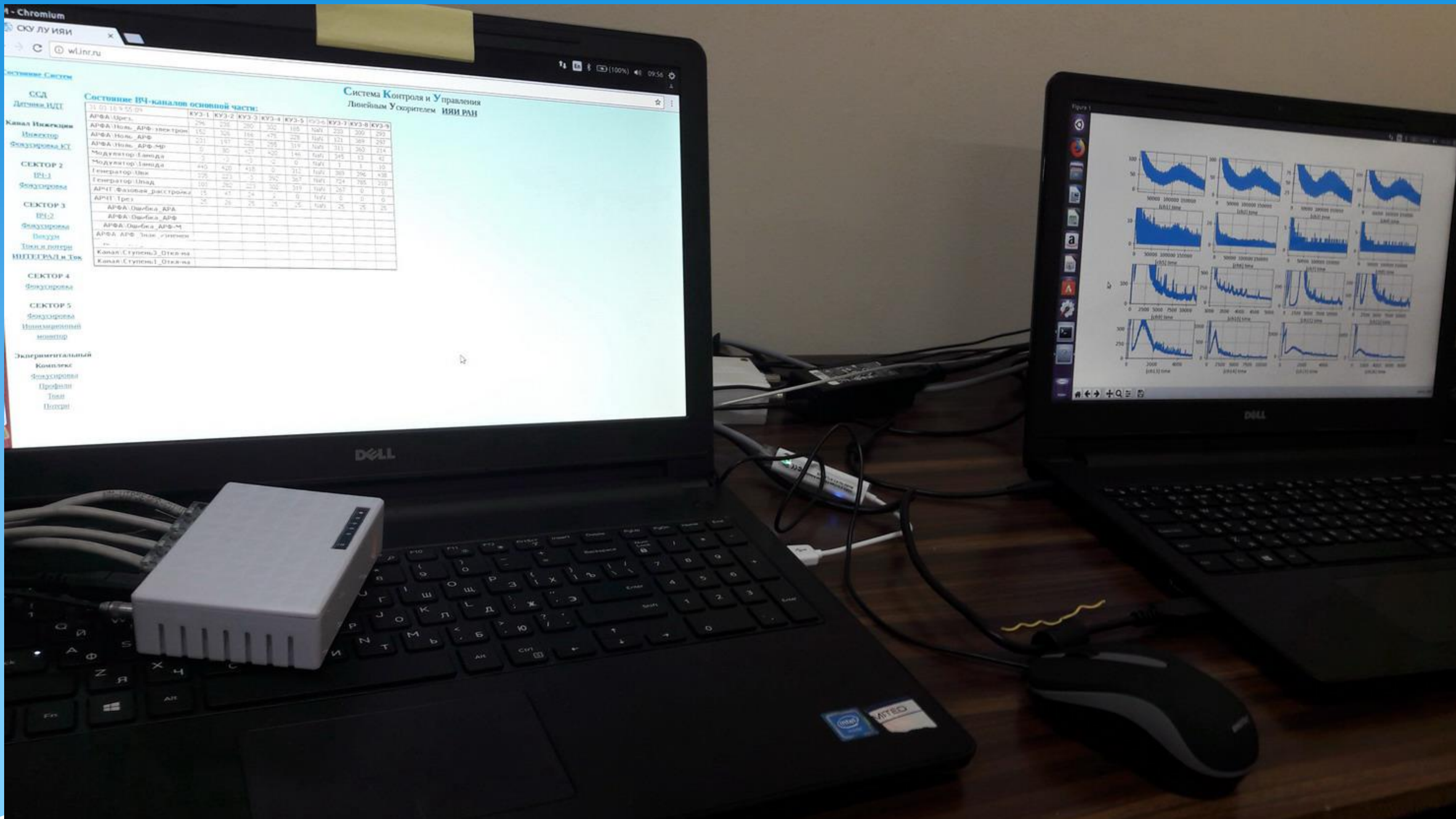


New equipment

During years 2017 and 2018, in our group new data acquisition system was designed, manufactured, tested and used in measurements.

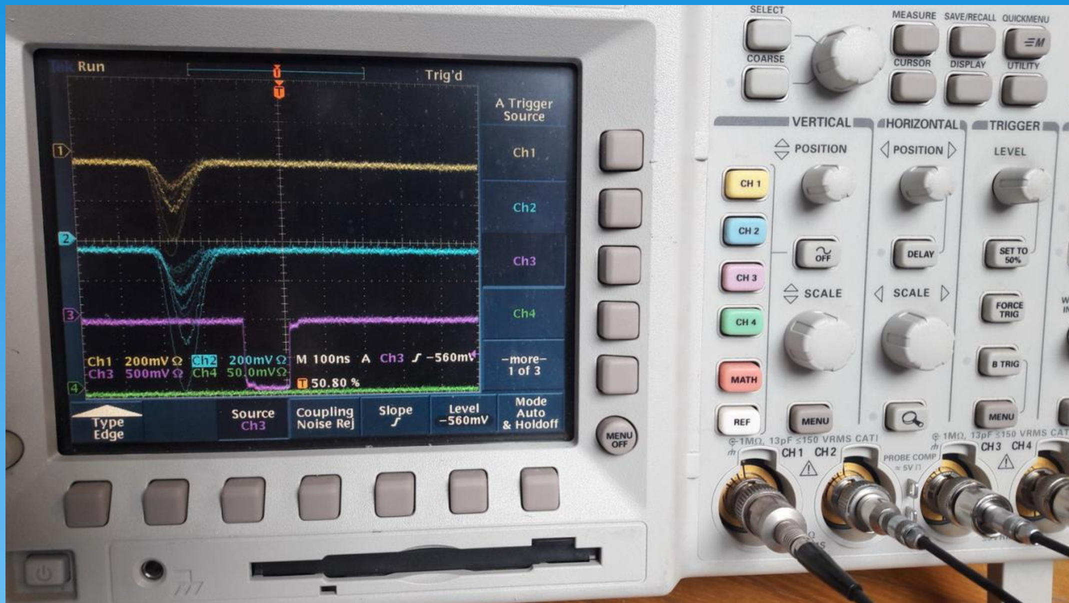
* Two modes: 16 channels at 100 ns channel width and
  8 channels at 50 ns channel width
* Number of histogram channels 200,000 in the first and
  400,000 in the second mode is optimized for spectra measurements at 50 Hz
* Multiplicity measurements can be made in both modes

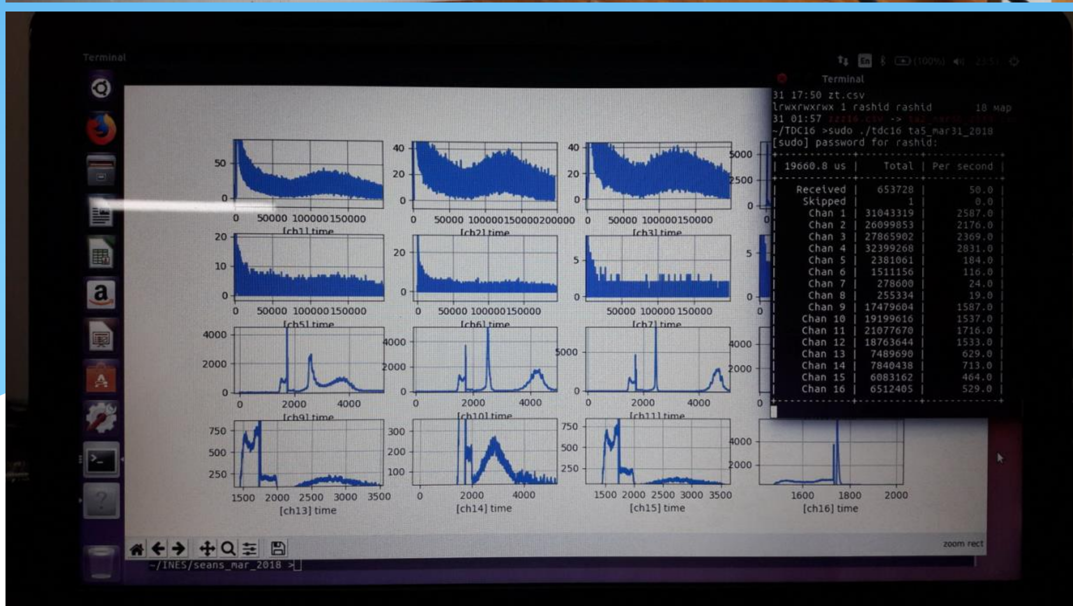
New equipment



Software for new 16 channel multiplicity data acquisition system is also written in our group using PYTHON. Program allows to interactively observe data on all 16 channels in detail.

New equipment





New 16-channel multiplicity data acquisition system was tested at first using Co^{60} gamma source and Cf^{252} spontaneous fission neutron source, then it was tested on pulsed beam.

During turning, high sustainability to radio frequency transients was achieved.

After turning and testing, 16-channel multiplicity system was used in measurements at TOF base 50 meters during accelerator's work with proton bean duration 500 ns. TOF histograms of Ta^{181}, In^{115}, and Au^{197} were successfully measured using 40 liter liquid scintillator gamma detector, four He-3 counters SNM-18 as neutron beam monitors and four He-3 neutron counters SNM-17 as transmission detectors.

Conclusion

* Installation INES has properties, high enough for measurements of total and capture cross sections of reactor and construction materials in energy groups of ABBN-78 and ABBN-93 neutron constants, which are used for core criticality calculations during construction of fast breeder reactors BN-800 and BN-1200.

* Internal block-effects for reactor alloys and radiation shield materials resonance cross section structure, also as Doppler-effect, can be measured.

* Measurements can be done both for separated isotopes of natural multi-isotope mixtures, and for multi-isotope mixtures of many chemical elements like stainless steel.

Measurement plans:

* Measurements of new reactor alloys group cross sections, including burning absorber reactor materials for isotope separation quality control
* Measurements of total and capture cross sections of separated isotopes
* Measurements at different thicknesses and temperatures in ABBN-93 energy group intervals

Linac progress plans:

* Increase of Linac operation proton energy to 423 MeV
* Increase of Linac pulse proton current to 16 mA is planned for 2019 year
* TOF measurements with 300 nanosecond proton beam are planned for 2019
* Frequency 100 Hz achievement is in progress
* TOF stations at 250 meters and at 500 meters are discussed
* Proton storage ring is under construction

Thank you for your attention!