Investigation of Spectroscopic Properties of ^{108}Ag via the $^{107}Ag(n,2\gamma)$ Reaction

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Introduction

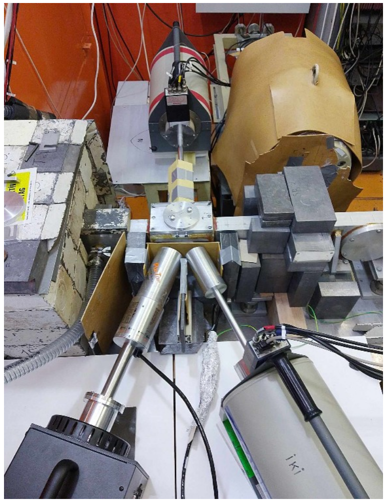
Obtaining accurate experimental values of the level scheme, level density and radiative strength functions is necessary for fission, astrophysical studies etc.

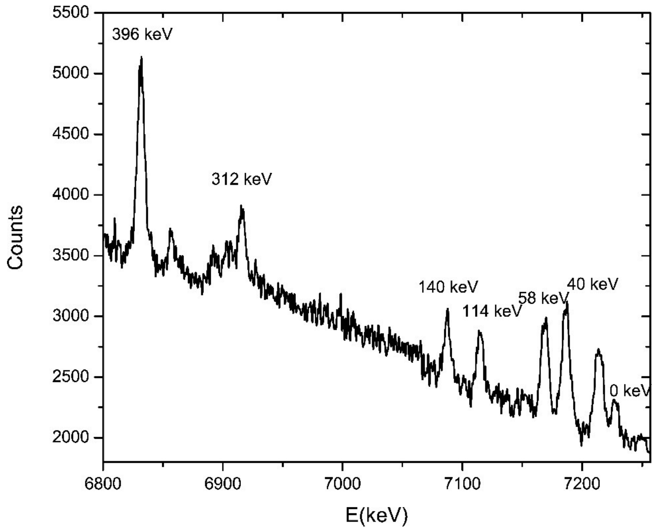
It is necessary to develop the method for determination of these parameters.

Main problem : FWHM >> D_i.

1. Two-step gamma cascades method.

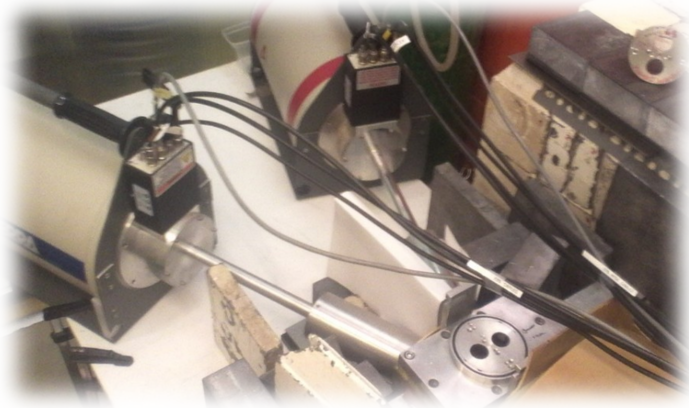
2. Practical model of the cascade gamma-decay.

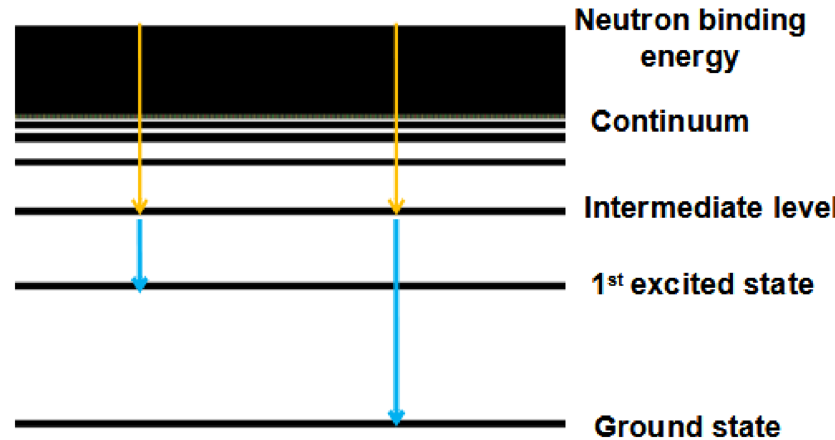


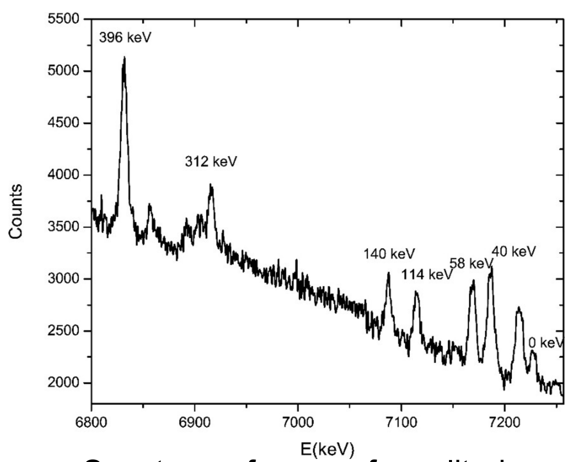


Two-step gamma cascades: Basic principles

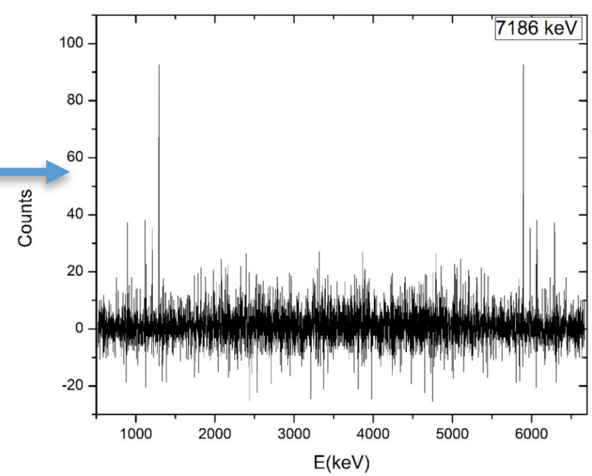
Detecting two consecutive gamma rays emitted from the binding energy to the ground state or one of the low-lying excited levels after neutron capture: (n,2γ) reaction.



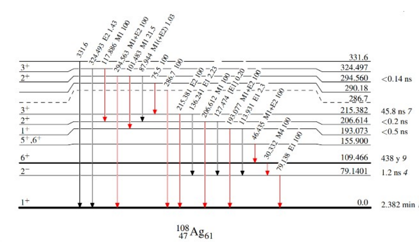


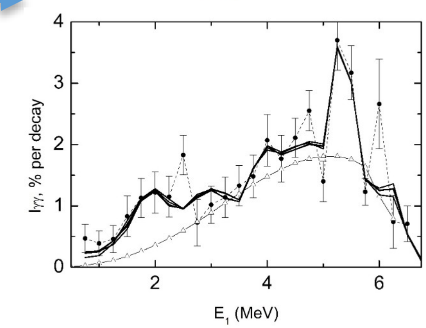


Spectrum of sums of amplitudes for coincident pulses

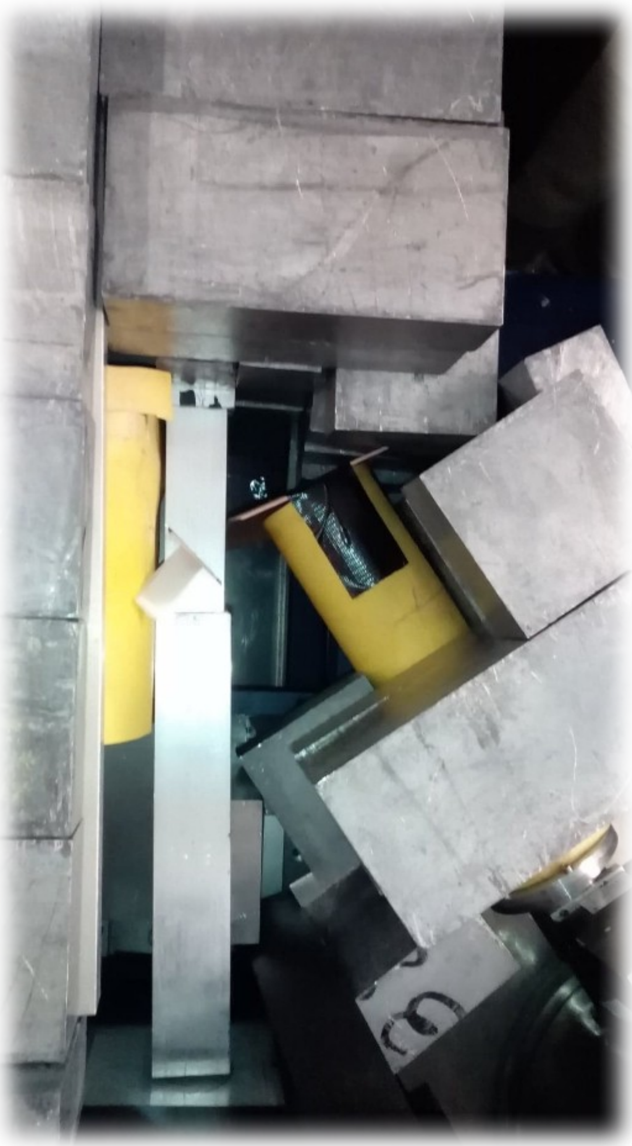


Two step gamma cascade (TSC) spectra



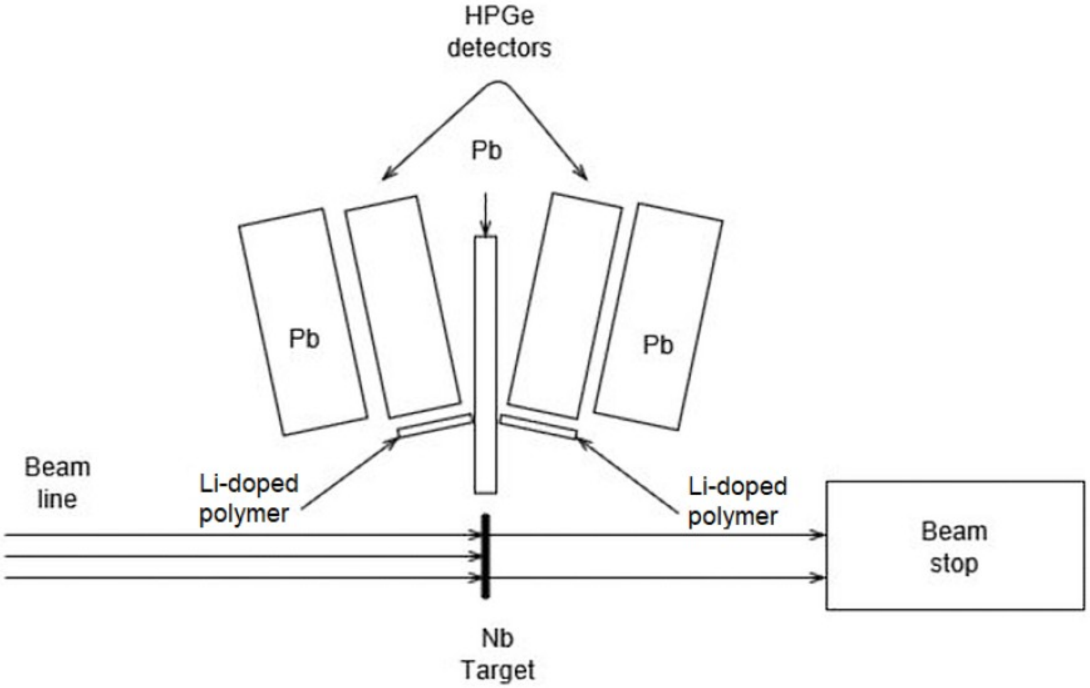


Measurement

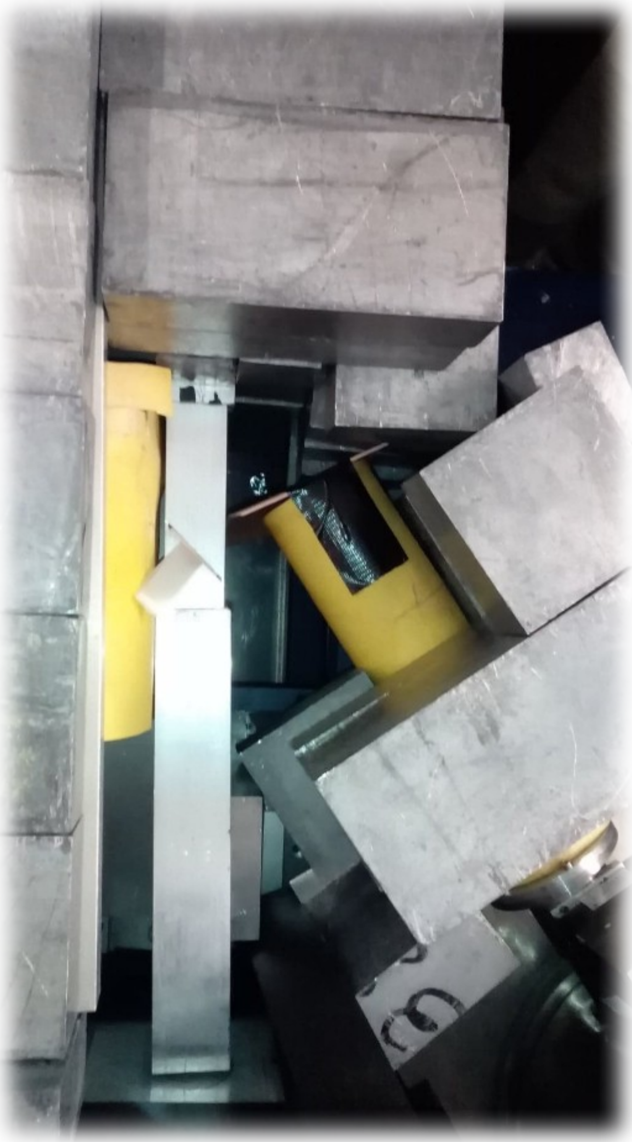


Thermal (cold) neutron capture (n_{th},2γ) reaction.

Experimental setup is fairly simple: thermal neutron beam, two HPGe detectors, target and an acquisition system capable of recording channel and time stamps of the event.

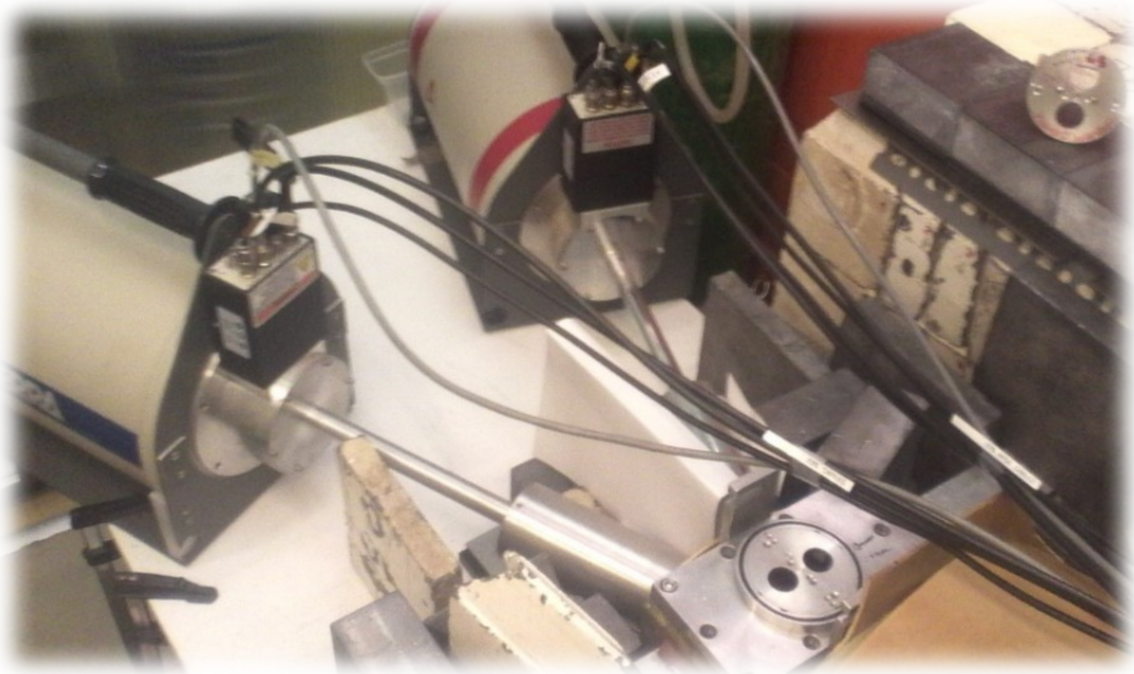


Measurement

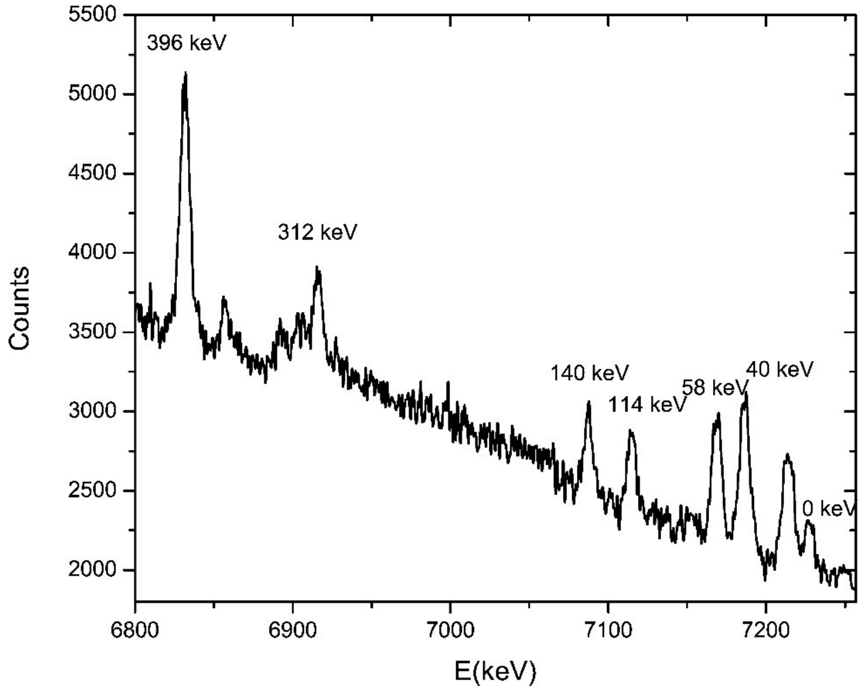


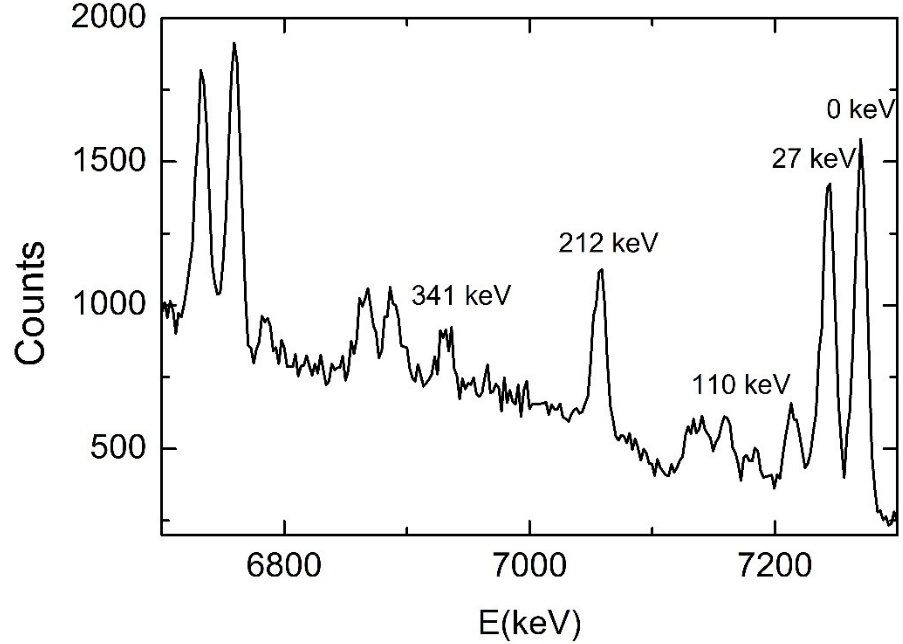
^{94}Nb, ^{104}Rh and ^{108}Ag: PGAA facility of Centre for Energy Research (MTA EK), Budapest, Hungary (down).

^{56}Mn: Technische Universität München, Forschungsneutronenquelle Heinz Maier-Leibnitz (FRM II), Garching, Germany (left).



Spectrum of sums of amplitudes for coincident pulses (SACP)





Gamma cascade total energy (keV)	Final level (E_f) of the cascade(keV)	Spin of level E_f	Part of resolved cascade intensity	Full intensities % per decay
7227	0	6+	0.25(2)	5.4(20)
7186	40.9	3+	0.71(2)	6.2(15)
7168	58.7	(4)+	0.60(1)	7.0(11)
7114	113.4	(5)+	0.42(2)	5.3(15)
7087	140.3	(2)-	0.84(1)	2.7(9)
6916	311.8	(4,5)+	0.57(3)	3.2(10)
6831	396.2	(3)-	0.51(3)	5.4(11)
Sum of total			0.56(2)	35.2(40)

^{94}Nb

Gamma ray cascade total energy (keV)	Final level (E_f) of the cascade(keV)	Spin of level E_f	Part of resolved cascade intensity	Full intensities % per decay
7270	0	3+	70(5)	17(3)
7243	26.5	2+	70(7)	13(3)
7160	110.4	1+	51(9)	5.0(10)
7058	212.0	4+	49(5)	16.0(20)
6929	341.0	3+	40(6)	6.0(10)
Sum of total			56(3)	57(5)

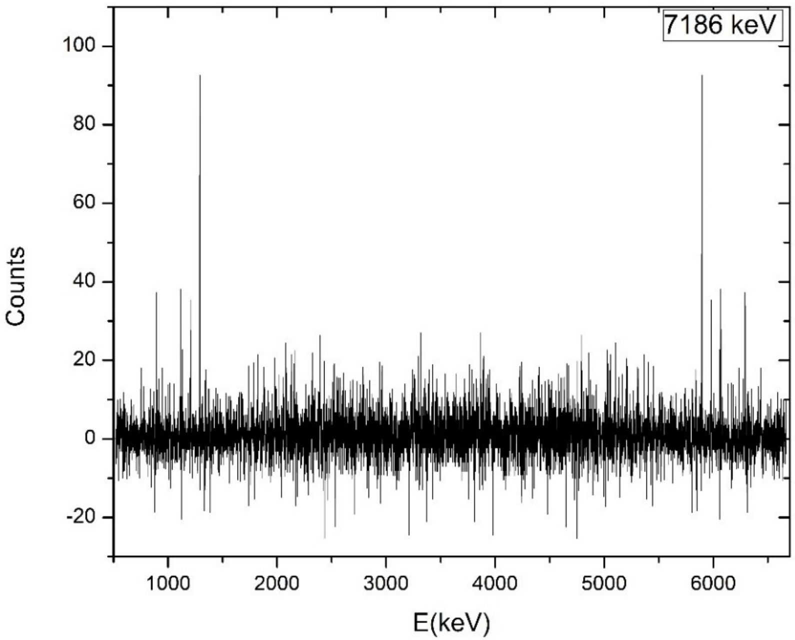
^{56}Mn

Determination of the level scheme

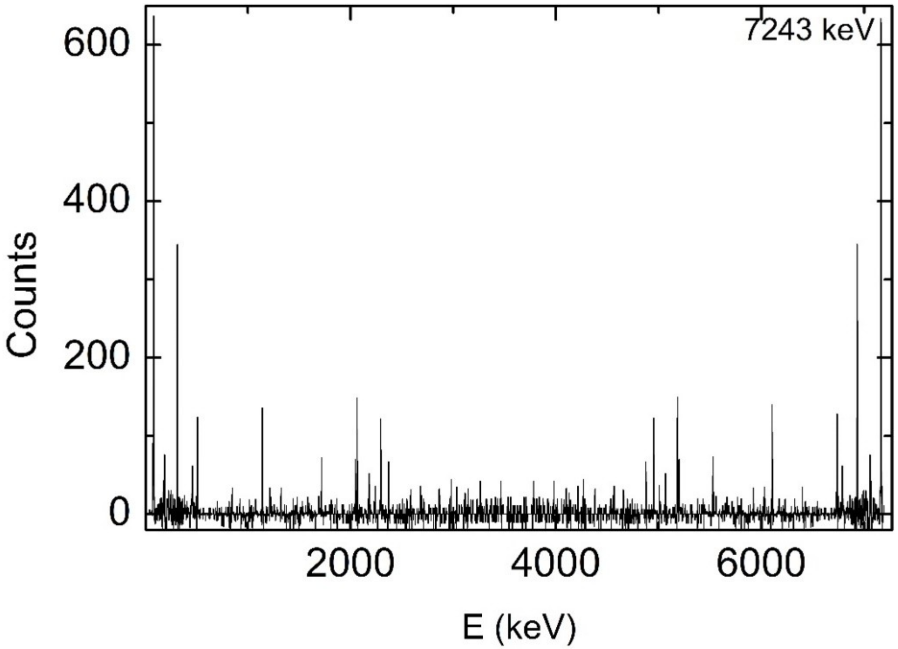
Two step gamma cascade (TSC) spectra

TSC spectra represent the cascades from the initial state to the defined final levels of the nucleus. The elimination of Compton background and random coincidences was done by gating on the region nearby the peaks of interest in the SACP spectrum.

The mirror-symmetrical peaks in the TSC spectra represent primary and secondary transitions of the investigated two-step gamma cascade.



^{94}Nb



^{56}Mn

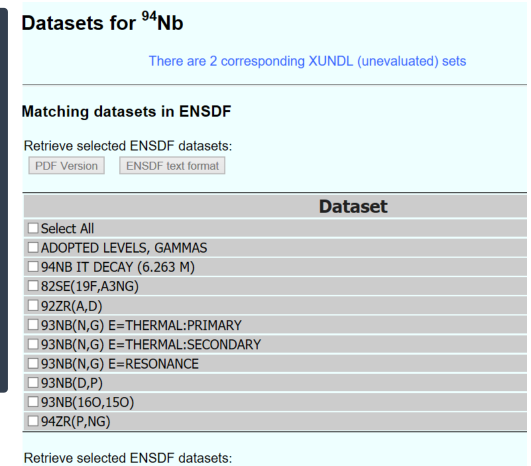
Determination of the level scheme

The order of the gamma quanta

The order of the gamma quanta in the cascade was determined using the maximum likelihood function.

Results obtained in this way were checked with two rules:

1. If the same gamma ray appears in multiple cascades, it is assumed that it is the primary gamma in the cascade.
2. If the primary or secondary gamma recorded is already included in the ENSDF database, its place in the cascade is assigned accordingly.


Datasets for ^{94}Nb

There are 2 corresponding XUNDL (unevaluated) sets

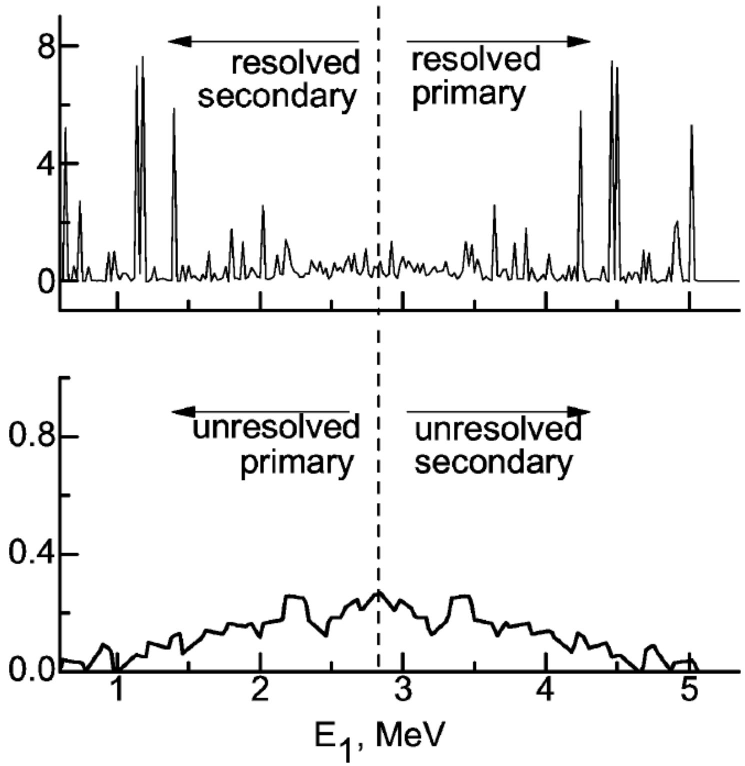
Matching datasets in ENSDF

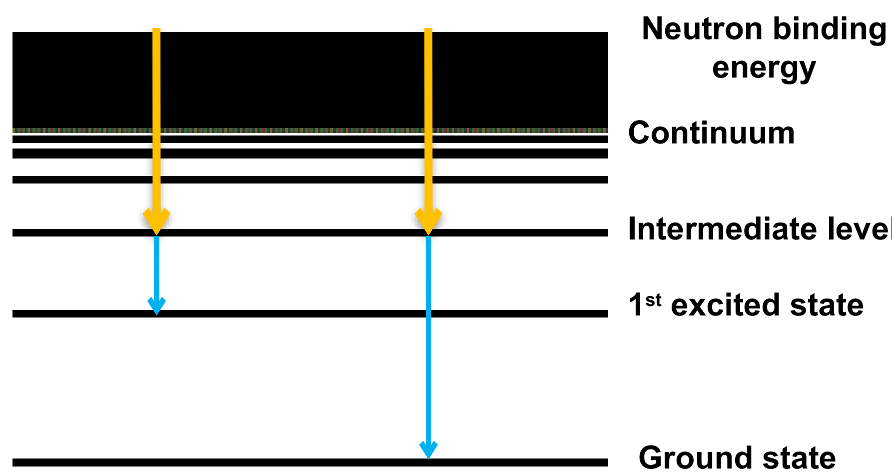
Retrieve selected ENSDF datasets:

PDF Version   ENSDF text format

Dataset
Select All
ADOPTED LEVELS, GAMMAS
94NB IT DECAY (6.263 M)
82SE(19F,A3NG)
92ZR(A,D)
93NB(N,G) E=THERMAL:PRIMARY
93NB(N,G) E=THERMAL:SECONDARY
93NB(N,G) E=RESONANCE
93NB(D,P)
93NB(16O,15O)
94ZR(P,NG)

Retrieve selected ENSDF datasets:





Spectroscopic results for ^{94}Nb

^{94}Nb

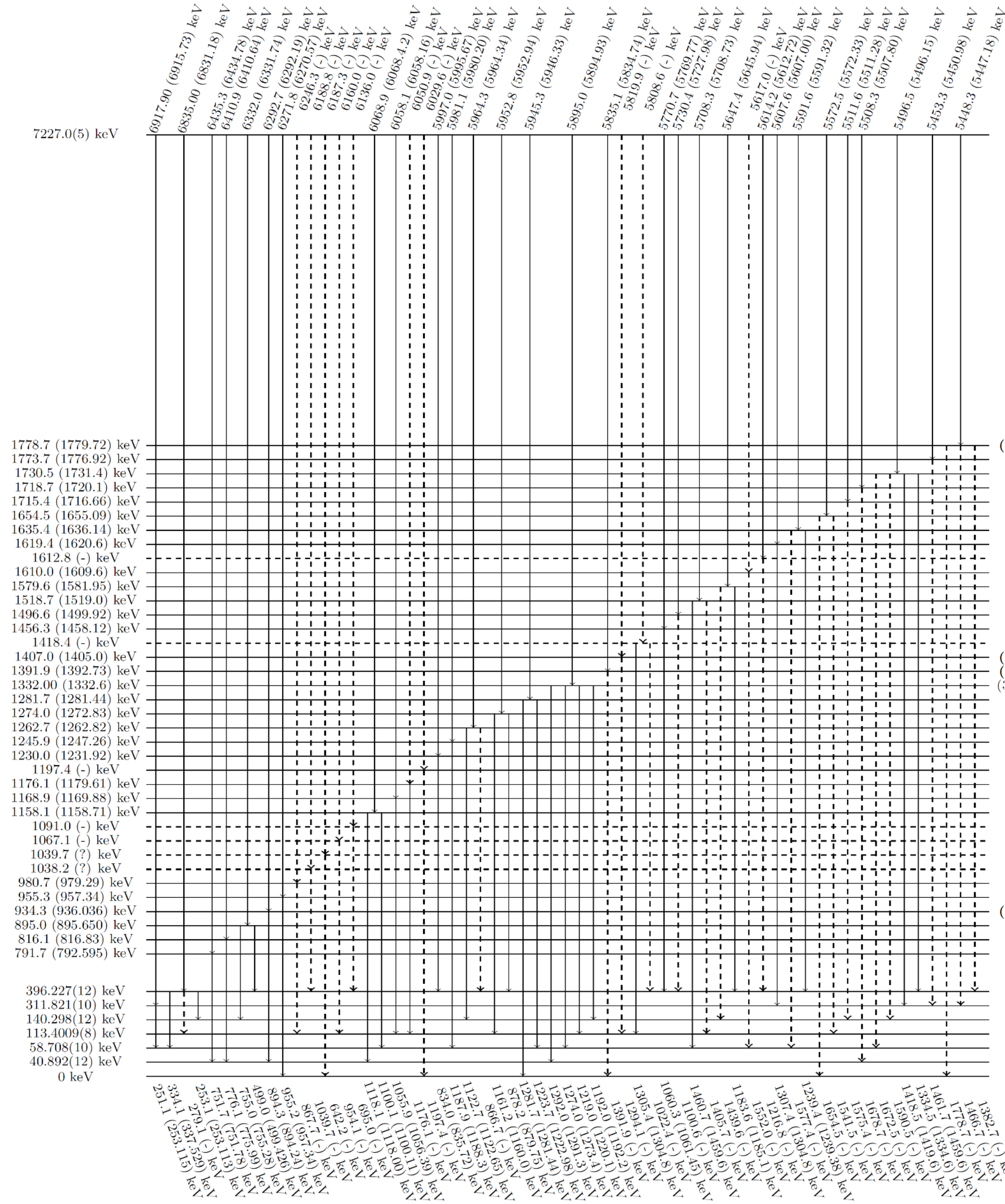
216 energy resolved cascades and, as a result of comparison with ENSDF library data:

27 recommendations for **new primary transitions**

29 recommendations for **new energy levels**

183 recommendations for **new secondary transitions.**

Knezevic et al. Nuclear Physics A, 993 (2020) 121645



Spectroscopic results for ^{56}Mn

^{56}Mn

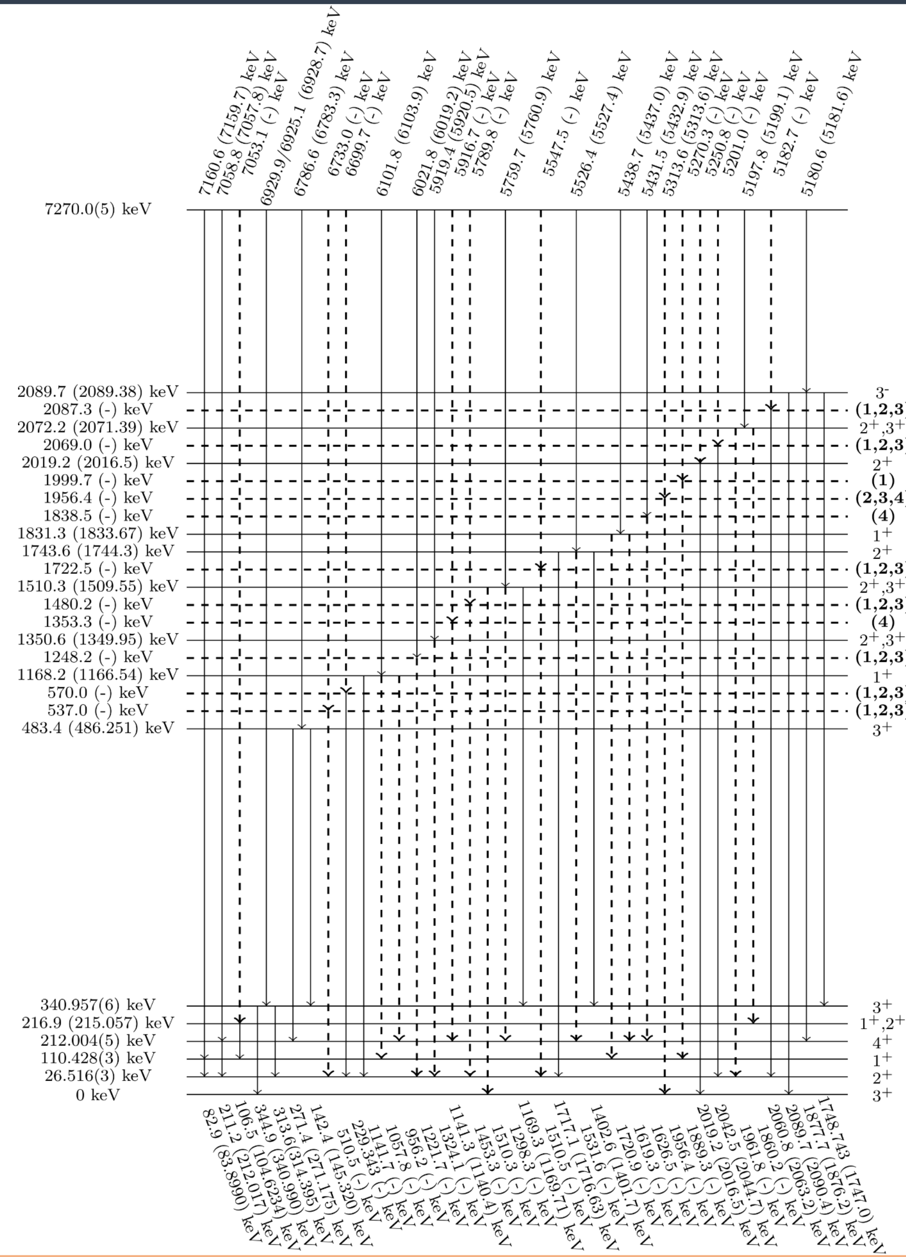
71 energy resolved cascades and, as a result of comparison with ENSDF library data:

23 recommendations for **new primary transitions**

24 recommendations for **new energy levels**

32 recommendations for **new secondary transitions.**

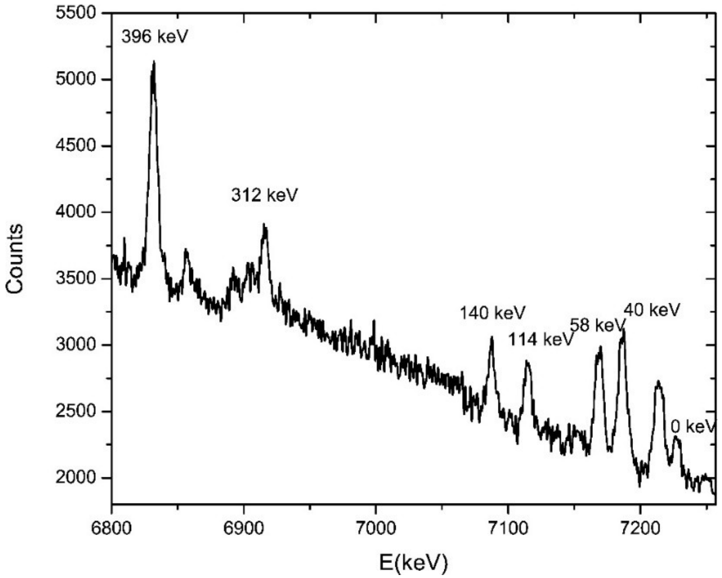
Knezevic et al. Nuclear Physics A, 992 (2019) 121628



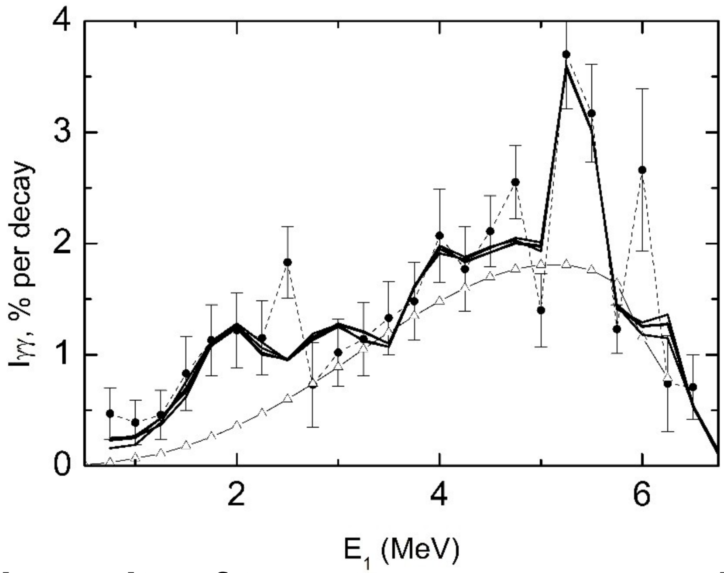
Intensity of two-step gamma cascades:

$$I_{\gamma\gamma}(E_1) = \sum_{\lambda,f} \sum_{i} \frac{\Gamma_{\lambda i}}{\Gamma_{\lambda}} \frac{\Gamma_{if}}{\Gamma_{i}} = \sum_{\lambda,f,j} \frac{\Gamma_{\lambda i}}{<\Gamma_{\lambda i}> m_{\lambda i}} n_j \frac{\Gamma_{if}}{<\Gamma_{if}> m_{if}}$$

Important: The intensity of the cascade as a function of the energy of primary quanta of the cascade depends on the number of available levels as well as the partial widths of γ transition.



SACP spectra



Total intensity of two-step gamma cascades, $I_{\gamma\gamma}$

Practical model of the cascade gamma-decay

Constructing a model to explain the experimental data: Phenomenological and theoretical representations are combined.

The model of level density

$$\rho = \rho_l \cdot C_{col}$$

$$\rho_l = \frac{(2J+1)\exp(-(J+1/2)^2/2\sigma^2)}{2\sqrt{(2\pi)}\sigma^3}\Omega_n(E_{ex})$$

$$\Omega_n(E_{ex}) = \frac{g^n(E_{ex}-U_l)^{n-1}}{((n/2)!)^2(n-1)!}.$$

The parametrized model of Strutinsky for density of n quasi-particle nuclear excitations.

$$C_{col} = A_l\exp(\sqrt{(E_{ex}-U_l)/E_v} - (E_{ex}-U_l)/E_\mu) + \beta$$

Increase of a density of collective levels – a phenomenological relation between entropies of phases of the nuclear matter with taking into account a cyclical breaking of Cooper pairs.

Practical model of the cascade gamma-decay

Constructing a model to explain the experimental data:
Phenomenological and theoretical representations are combined.

The model for *E*1- and *M*1-transition strength functions

$$k(E1,E_\gamma)=w_E\,\frac{\Gamma_{GE}^2(E_\gamma^2+\kappa_E 4\pi^2T_E^2)}{(E_\gamma^2-E_{GE}^2)^2+E_{GE}^2\Gamma_{GE}^2}+\sum_i W_{Ei}\,\frac{(E_\gamma^2+(\alpha_{Ei}(E_{Ei}-E_\gamma)/E_\gamma))\Gamma_{Ei}^2}{(E_\gamma^2-E_{Ei}^2)^2+E_\gamma^2\Gamma_{Ei}^2}$$

$$k(M1,E_\gamma)=w_M\,\frac{\Gamma_{GM}^2(E_\gamma^2+\kappa_M 4\pi^2T_M^2)}{(E_\gamma^2-E_{GM}^2)^2+E_{GM}^2\Gamma_{GM}^2}+\sum_i W_{Mi}\,\frac{(E_\gamma^2+(\alpha_{Mi}(E_{Mi}-E_\gamma)/E_\gamma))\Gamma_{Mi}^2}{(E_\gamma^2-E_{Mi}^2)^2+E_\gamma^2\Gamma_{Mi}^2}$$

KMF (Kadmenskij, Markushev, Furman) + peaks in the functions

Practical model of the cascade gamma-decay

Constructing a model to explain the experimental data: Phenomenological and theoretical representations are combined.

Proposed fitted parameters for our model:

1) **the break up thresholds energies** U_l up to l=4,

2) **the** E_μ **and** E_v **parameters**, which are common for all Cooper pairs

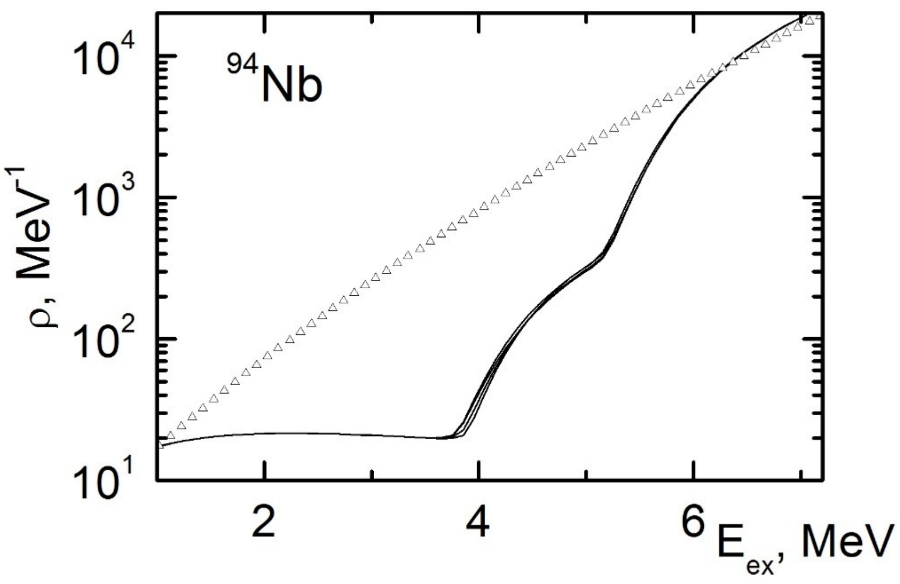
3) the mutually independent **parameters** A_l of the density of vibrational levels above the break up threshold U_l

4) the **coefficients** w, κ **and** β

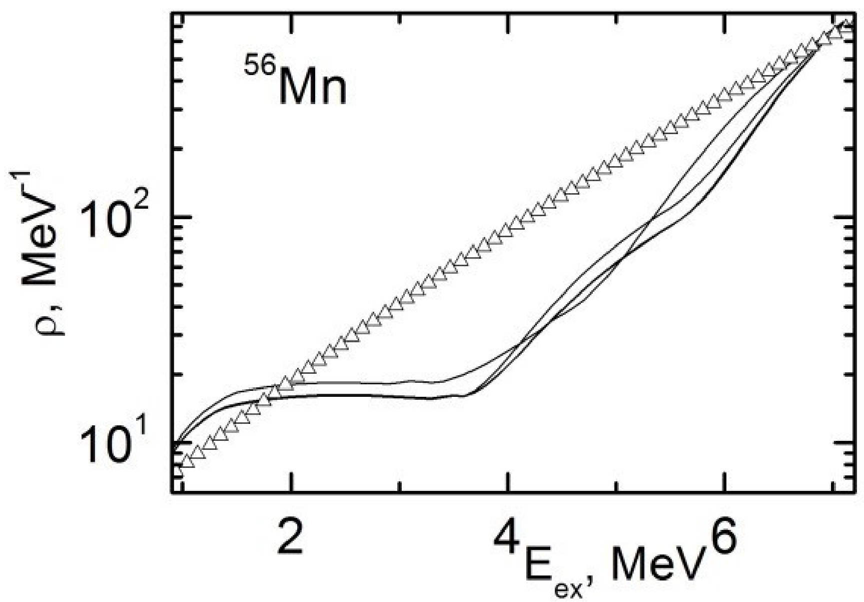
5) **the ratio** r **of negative parity and the total level density.**

LD results

^{94}Nb



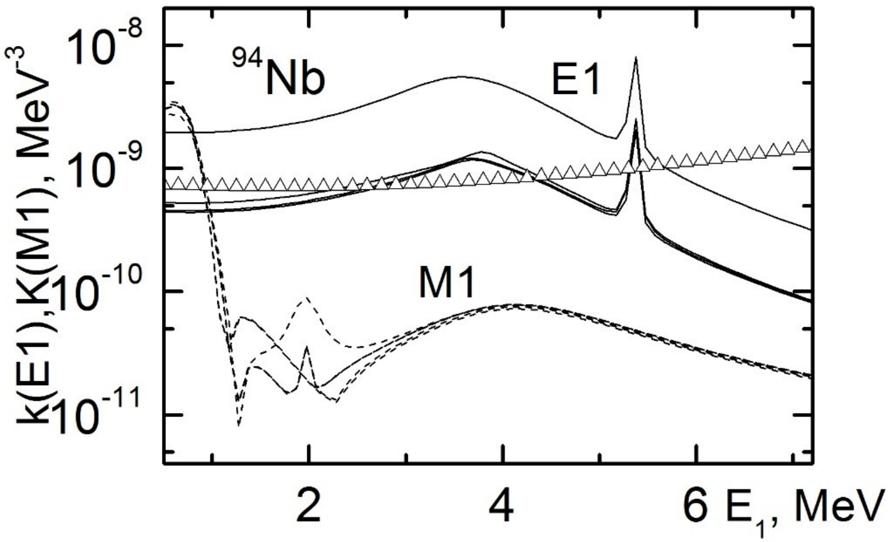
^{56}Mn



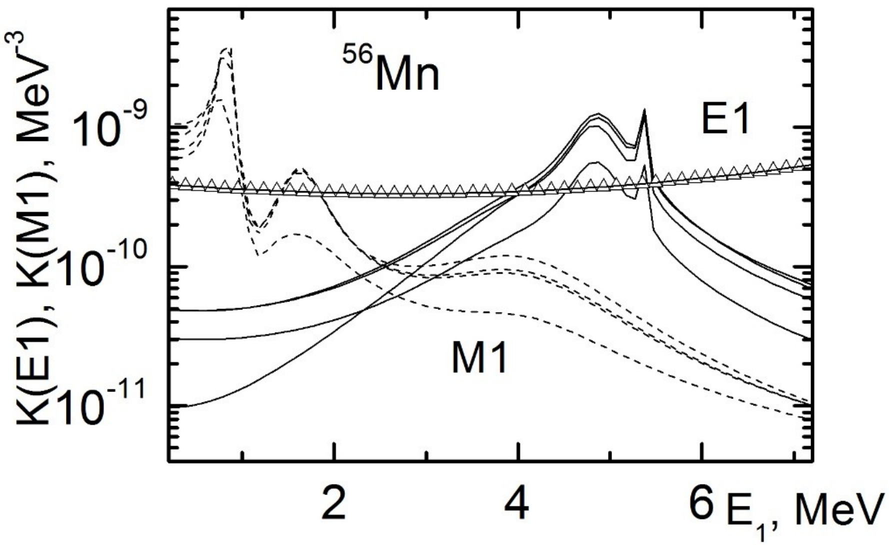
Multiple lines on every graph represent the fitting of data by varying fitting parameters.
LD data is compared to the BS Fermi gas model predictions.

RSF results

^{94}Nb



^{56}Mn

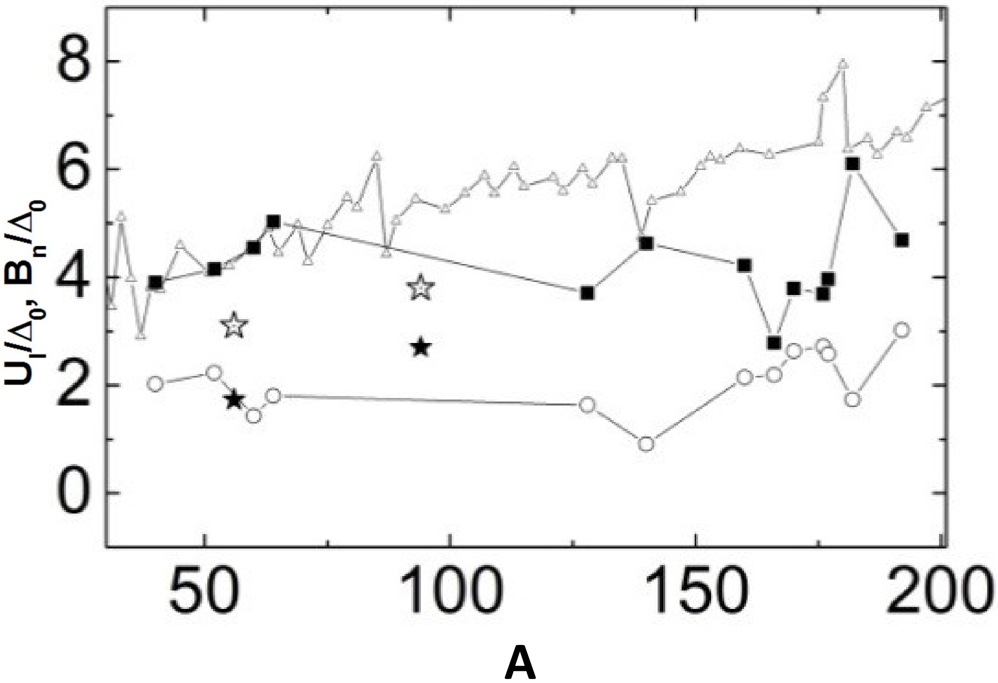


Multiple lines on every graph represent the fitting of data by varying fitting parameters.
RSF data is compared to the KMF model predictions.

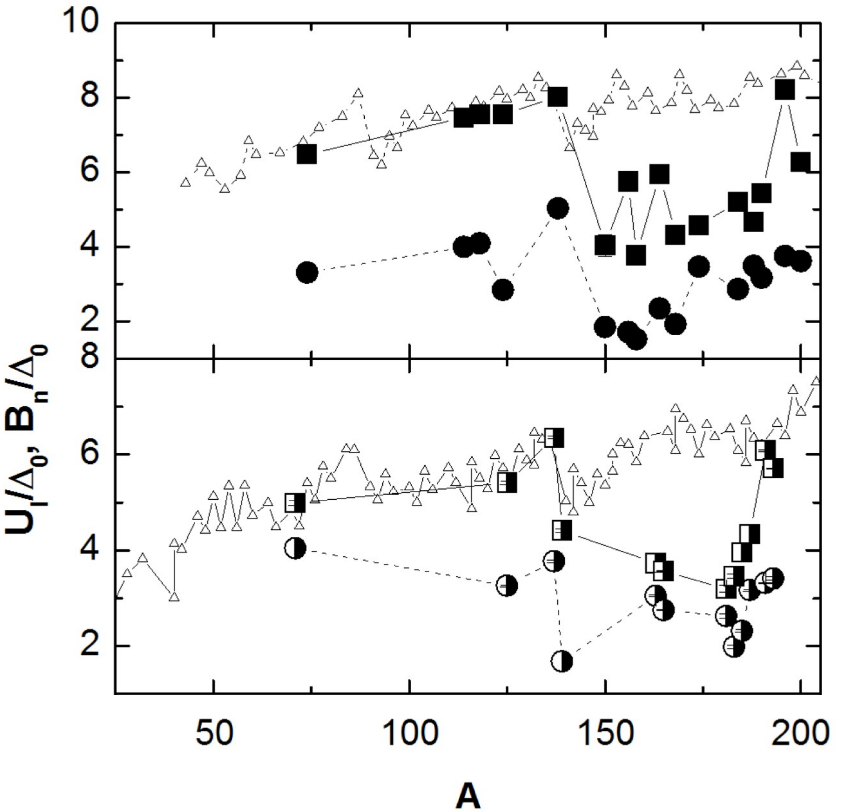
Cooper pairs braking points

Odd-odd nuclei

^{56}Mn and ^{94}Nb are both odd-odd

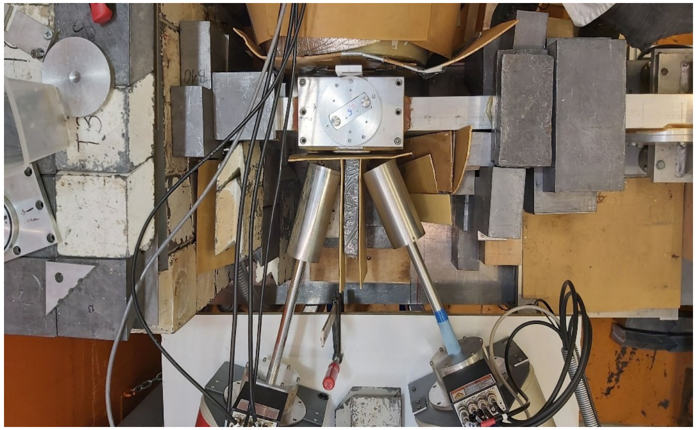


Even-even and even-odd nuclei

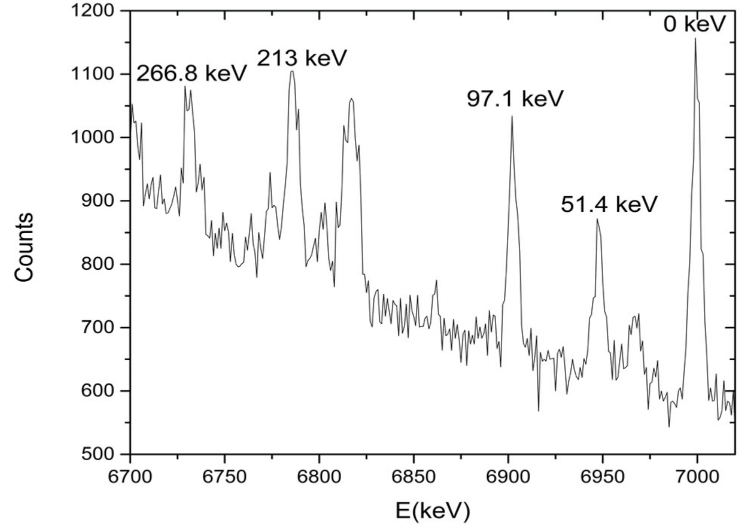


Experimentally derived breaking thresholds of Cooper pairs make it possible to study the dynamics of superfluid phase of nuclear matter (future plans: theoretical calculations).

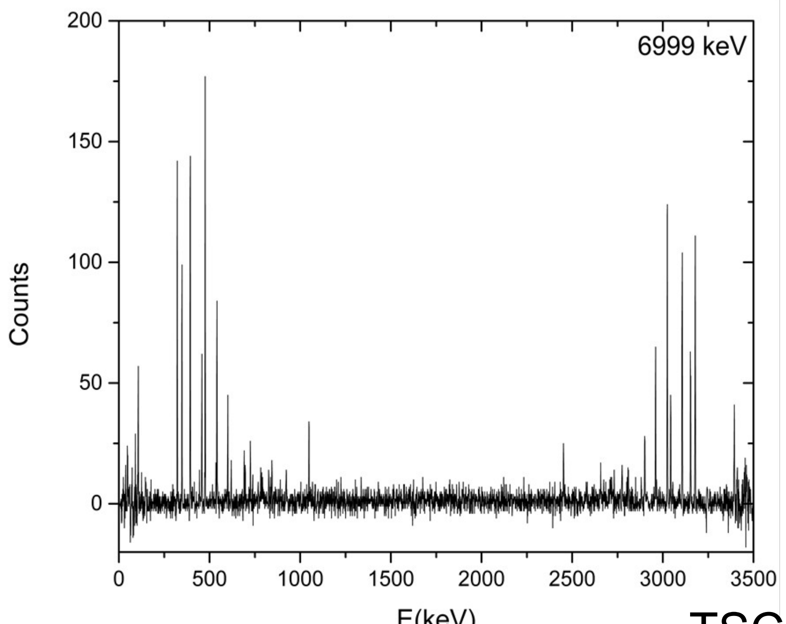
Measurement of ^{104}Rh

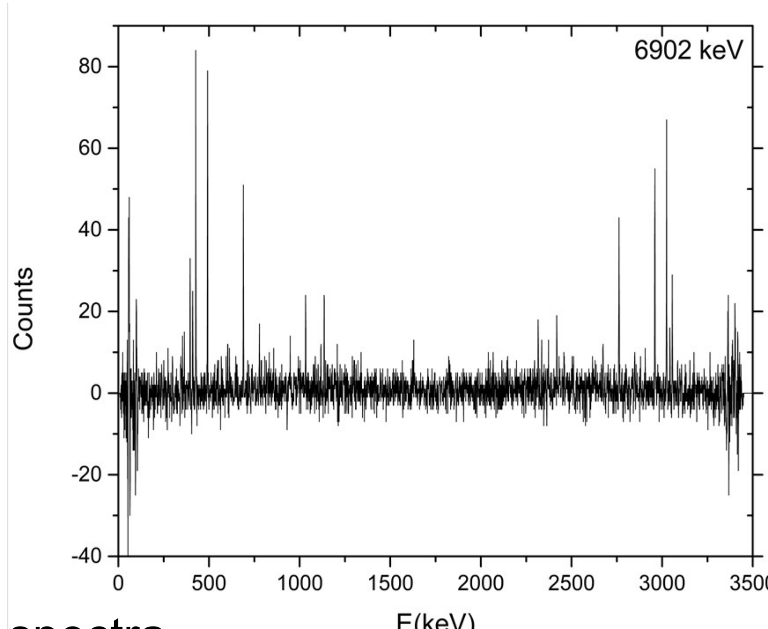


PGAA facility of Centre for Energy Research (MTA EK), Budapest, Hungary



SACP spectrum





TSC spectra

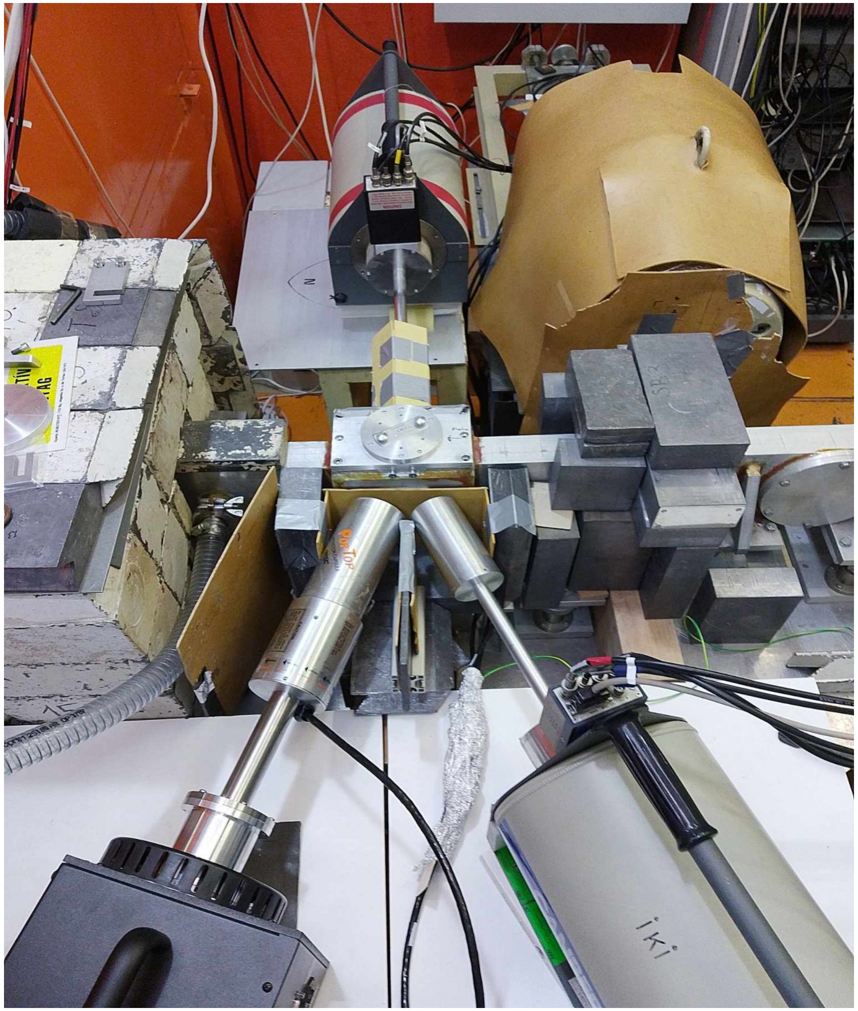
Measurement of ^{108}Ag

PGAA facility of Centre for Energy Research (MTA EK), Budapest, Hungary

3 HPGe detectors

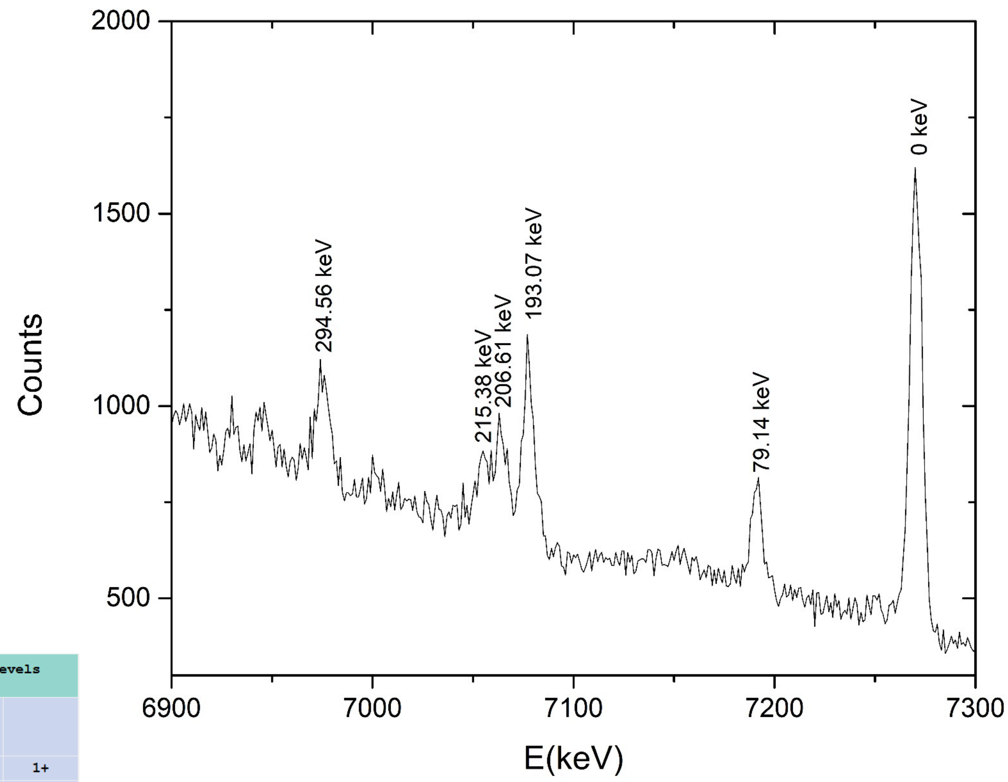
7 days of measurement

Enriched ^{107}Ag target (99.07%)



Measurement of ^{108}Ag

- It was detected gamma transition from neutron binding energy to ground and first 5 excited states

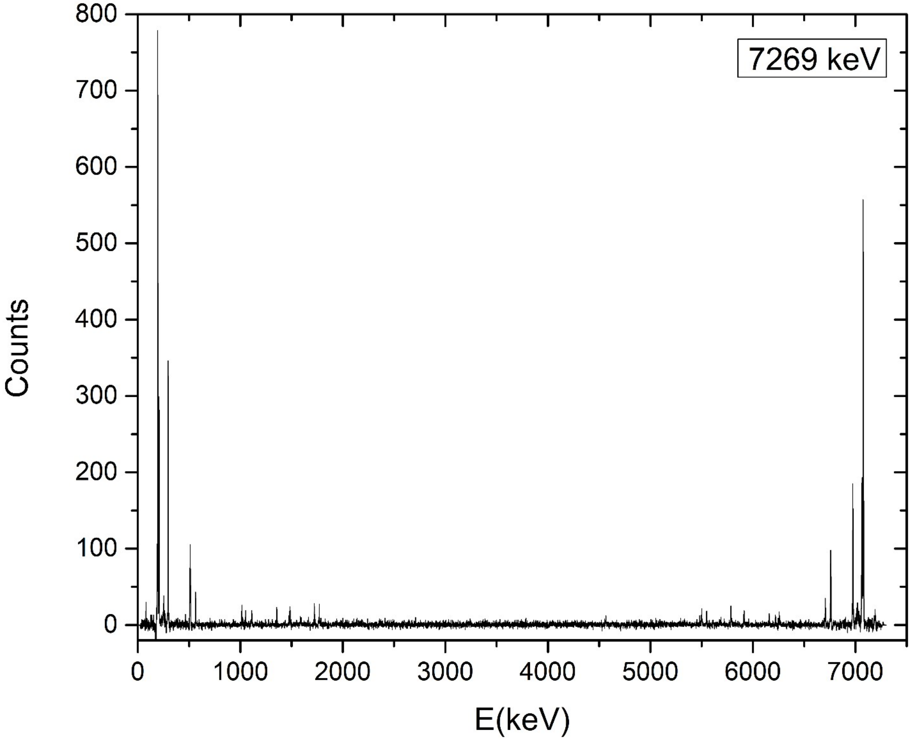


Spectrum of sums of amplitudes for coincident pulses

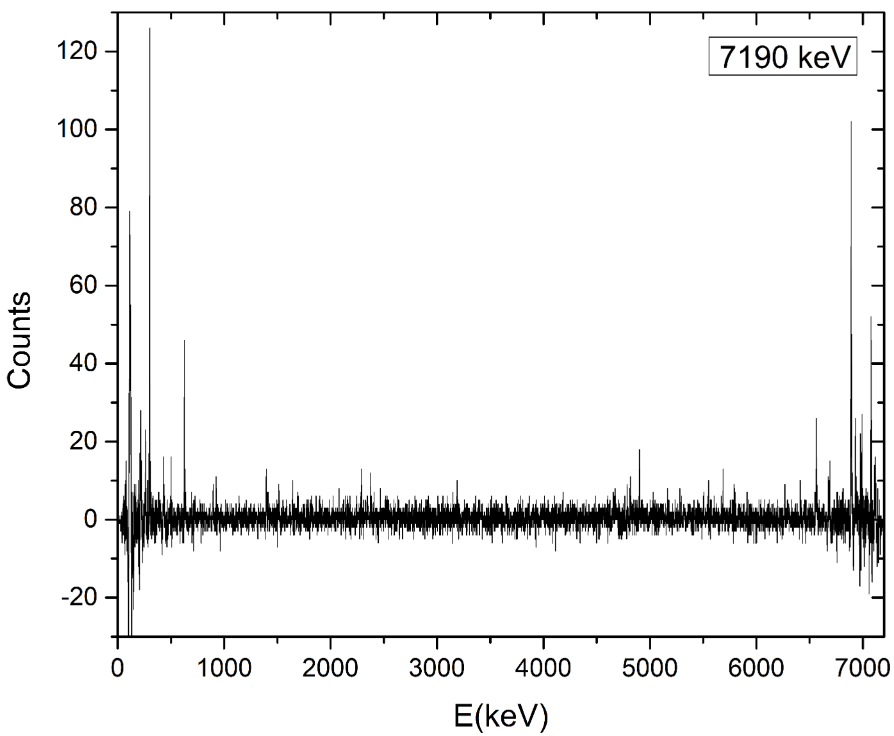
E(level) (keV)	XREF	J^{π}(level)	$T_{1/2}$(level)	E(γ) (keV)	I(γ)	M(γ)	Final Levels	
0.0	ABCDE G	1+	2.382 m *11* % β^- = 97.15 *20* % ε = 2.85 *20*					
79.1401 *23*	ABC EFG	2−	1.2 ns *4*	79.138 *3*	100	E1	0.0	1+
109.466 7	AB H	6+	438 y *9* % IT = 8.7 *9* % ε = 91.3 *9*	30.332 *8*	100	M4	79.1401	2−
155.900 7	B	5+,6+		46.435 *3*	100	M1+E2	109.466	6+
193.073 *3*	BCDE G	1+	< 0.5 ns	113.931 *2* 193.077 *6*	2.3 *2* 100 *5*	E1 M1+E2	79.1401 0.0	2− 1+
206.614 *3*	BC E G	2+	< 0.2 ns	127.474 *6* 206.612 7	0.20 *3* 100 *6*	[E1] M1	79.1401 0.0	2− 1+
215.382 *4*	B FGH	3+	45.8 ns 7	136.241 *6* 215.381 7	2.23 *17* 100 *6*	E1 E2	79.1401 0.0	2− 1+
286.7 *5* ?	G			286.7 *5*	100		0.0	1+
290.18 *23*	H			75.5 *3*	100		215.382	3+
294.560 *3*	BC E G	2+	< 0.14 ns	87.944 *4* 101.483 *3* 294.563 *9*	1.03 *9* 21.5 *12* 100 *8*	M1(+E2) M1 M1+E2	206.614 193.073 0.0	2+ 1+ 1+

Measurement of ^{108}Ag

It was obtained 6 two step gamma cascade (TSC) spectra.



TSC spectrum for summing energy of 7269 keV



TSC spectrum for summing energy of 7190 keV

Preliminary results: around 10 new levels and gamma transitions are observed

Conclusion

Two-step gamma cascade model can help improve the level scheme and gamma transition data.

Practical model of the cascade gamma-decay developed can go beyond the spectroscopic data and provide information about the LD and RSF (It was previously done for 44 nuclei).

Current and future work

Already measured: ^{94}Nb, ^{56}Mn, ^{104}Rh, ^{108}Ag.

Finished (spectroscopic part): ^{94}Nb, ^{56}Mn
In preparation (spectroscopic part): ^{104}Rh, ^{108}Ag.

Future plans:
- Level density studies for ^{94}Nb, ^{56}Mn, ^{104}Rh and ^{108}Ag.
- Application of ANN in data analysis

Thank you for your attention!