INVESTIGATION OF THE NATURE OF WEAK NEUTRON CAPTURE RESONANCES OF U-238

O.A. Shcherbakov

International Seminar ISINN-25, May 22-26, 2017, JINR, Dubna

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BRIEF HISTORY OF THE RESEARCH

1966 - 68 First observation of the intermediate structures in the neutron-induced fission cross sections of ^{237}**Np** (D. Paya, *et al*) and ^{240}**Pu** (E. Migneco and J.P. Theobald)

1968 - 69 Theoretical interpretation of the phenomenon (H. Weigmann and J.E. Lynn)

1971 First observation of the subthreshold fission in ^{238}**U** (M. Silbert, D. Bergen)

1974 - 76 Measurements of the capture gamma-ray spectra a predominantly class-II levels at **721** and **1211 eV** resonance clusters in ^{238}**U** (H. Weigmann et al, J. Browne)

1980 High-resolution measurements of the subthreshold neutron-induced fission cross section of ^{238}**U** in the energy range 3 eV - 3.5 MeV (F. Difilippo, *et al*.)

1986 High-resolution neutron capture gamma-ray measurements to resolve the nature of the subthreshold fission in ^{238}**U** (G. Auchampaugh, *et al*)

1991 Measurements of the capture gamma-ray spectra a predominantly class-II levels at **721** and **1211 eV** resonance clusters in ^{238}**U** (O.A. Shcherbakov, A.B. Laptev)

1991- 94 Study of the neutron capture near **721** and **1211 eV** resonance clusters in ^{238}**U** – search for unusual excited states of nuclei (G.V. Muradyan, *et al*.)

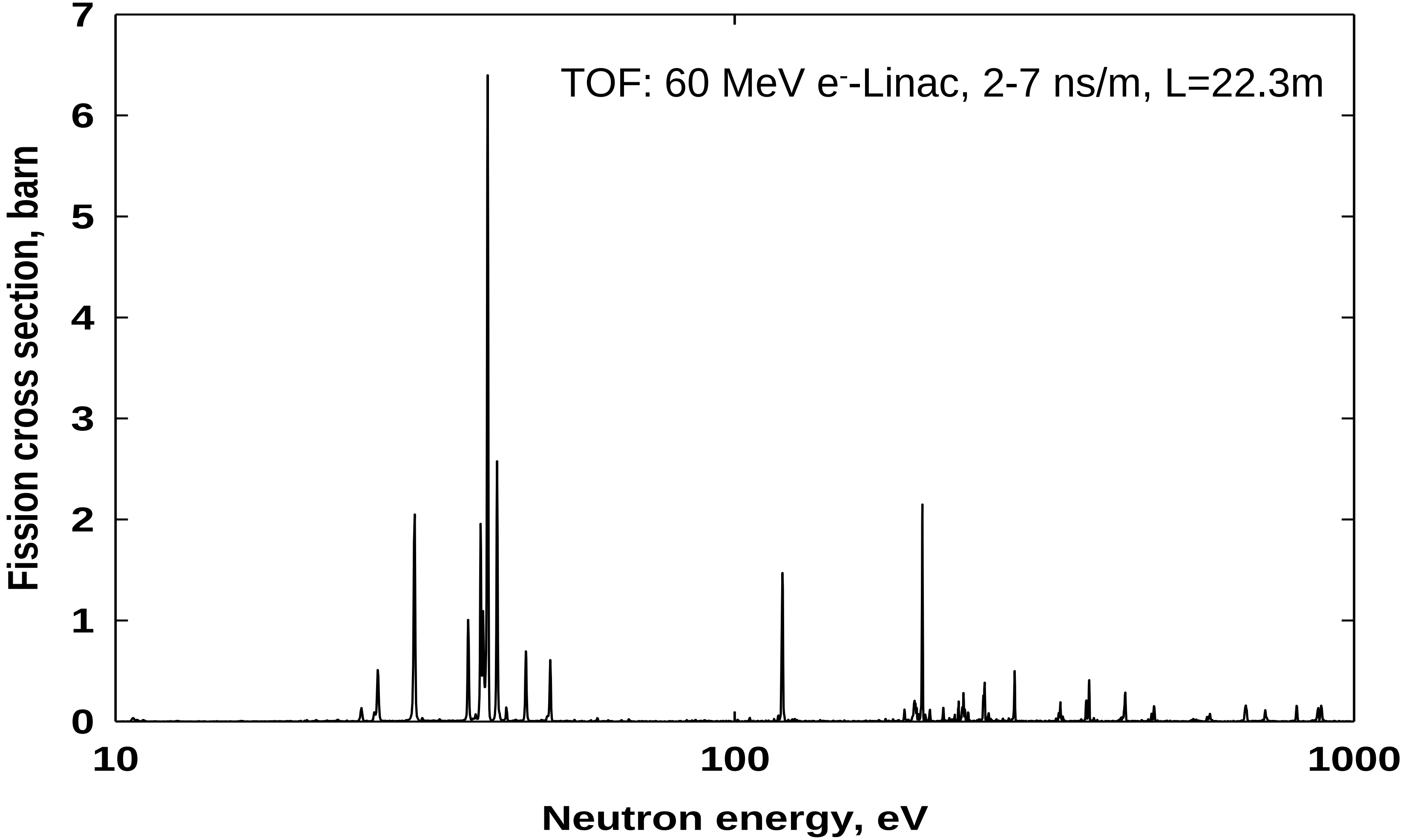
1994 - 98 Search for the gamma-decay towards the shape-isomeric ground state of ^{238}**U** (S. Oberstedt, F. Gunsing)

2014 -17 Neutron capture cross section and gamma-ray spectra measurements for ^{238}**U** in the resonance energy region (J. Ullmann, *et al*., F. Mingrone, *et al.,* H. Kim*, et al.)*

TOTAL AND FISSION CROSS SECTIONS OF ^{237}Np

D. Paya, H. Derrien, A. Fubini, A. Michaudon , P. Ribon
CEA, Saclay, France

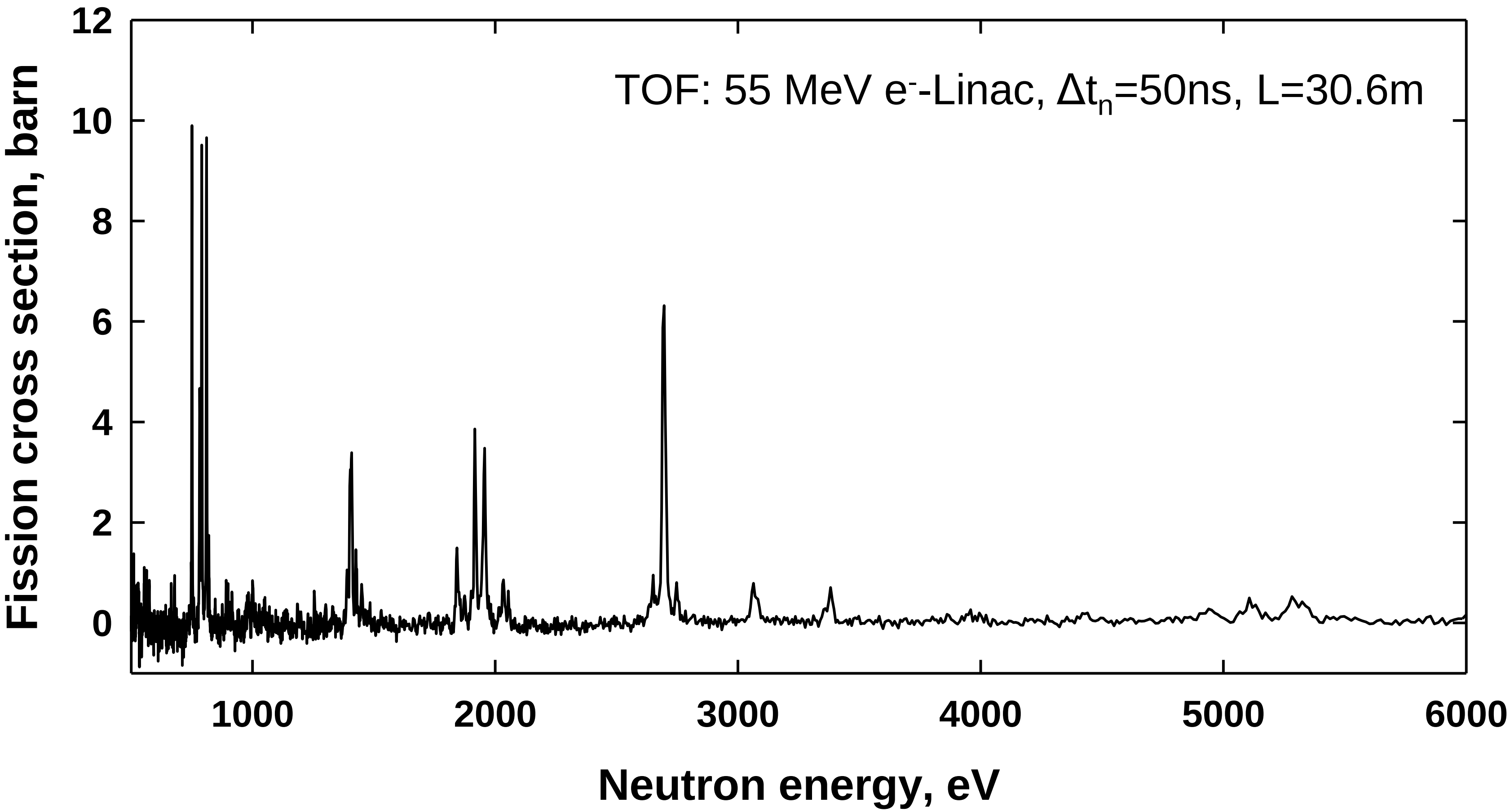
Proc. of the Conference on Nuclear Data, Microscopic Cross Sections and Other Data Basic to Reactors, Paris, 1966. IAEA, Vienna, Austria, 1967, Vol. II, p.128.



RESONANCE GROUPING STRUCTURE IN NEUTRON INDUCED SUBTHRESHOLD FISSION OF ^{240}Pu

E. MIGNECO and J. P. THEOBALD
Central Bureau for Nuclear Measurements
EURATOM, Geel, Belgium

Nuclear Physics **A112** (1968) 603—608.



An Interpretation of the Structure of Subthreshold Fission Cross Section of ^{240}Pu

H. WEIGMANN
Central Bureau for Nuclear Measurements, EURATOM, Geel — Belgium

Zeitschrift für Physik 214, 7—15 (1968)

STRUCTURE PHENOMENA IN NEAR-BARRIER FISSION REACTIONS

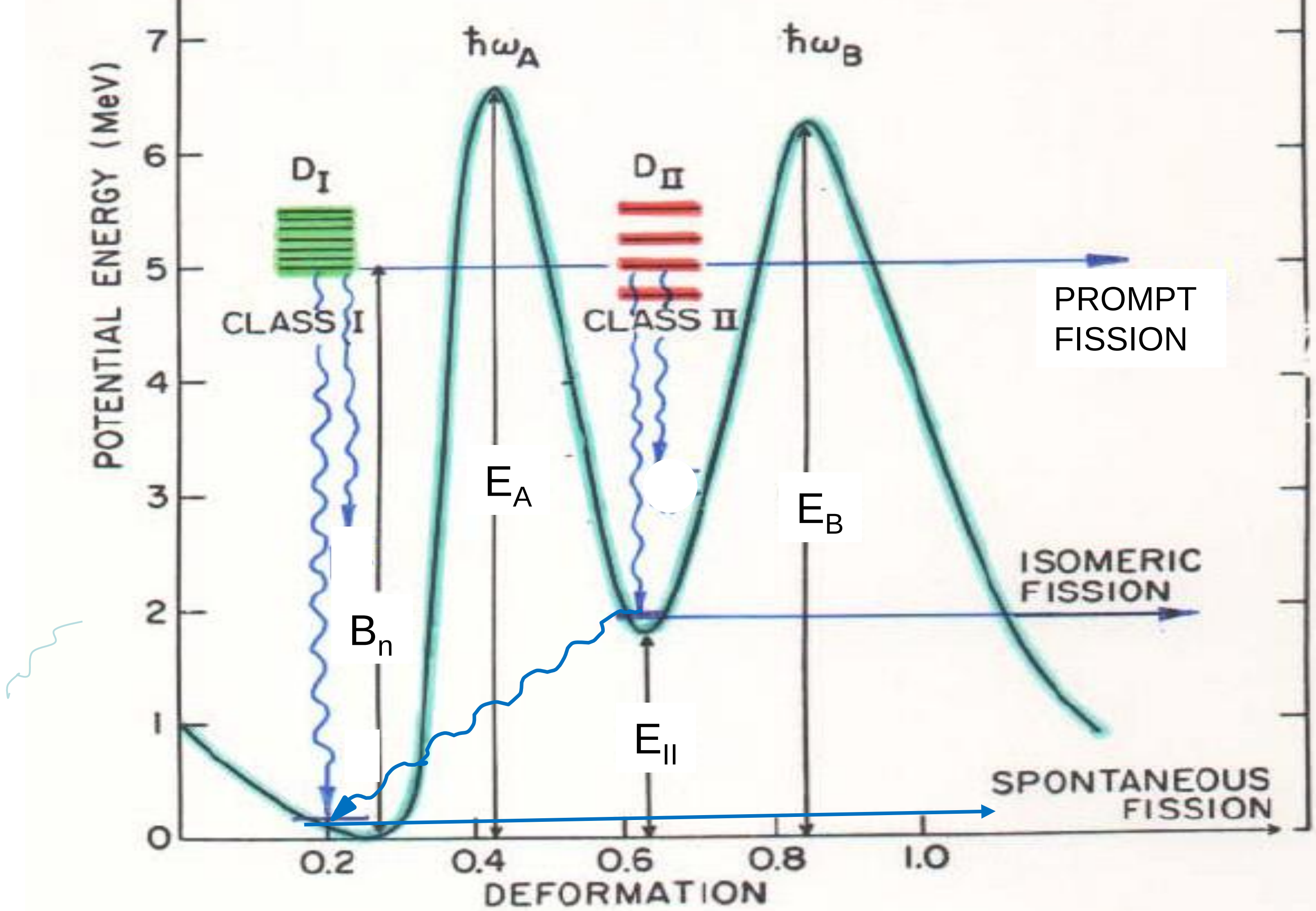
J.E. Lynn
UKAEA Research Group, AERE, Harwell, UK

Proc. of the 2-nd IAEA Symposium on Physics and Chemistry of Fission
IAEA, Vienna, Austria, 1969, p.249.

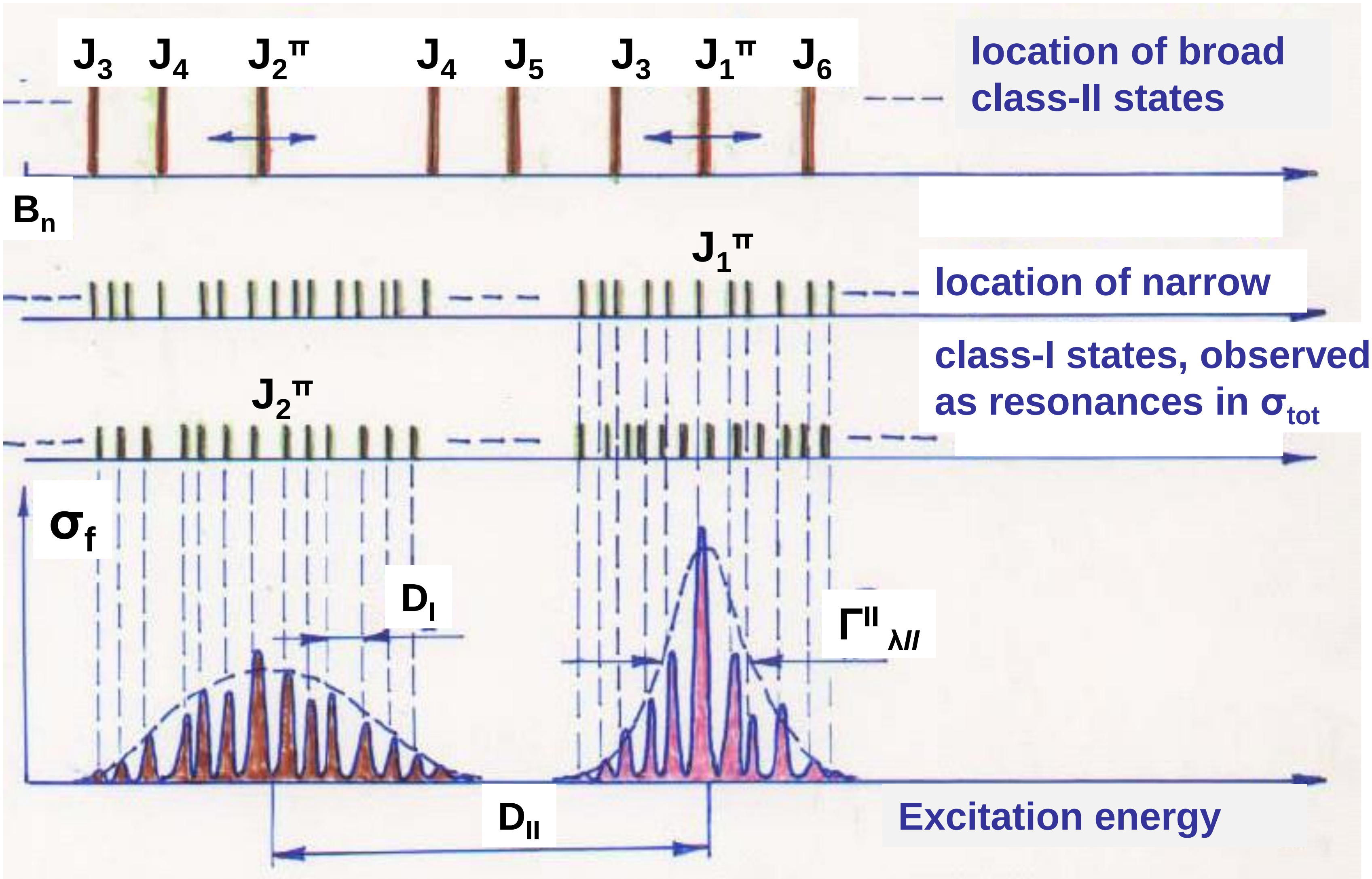
DOUBLE - HAMPED FISSION BARRIER

proposed by V.M. Strutinsky

Nuclear Physics A95 (1967) 429, A122 (1968) 1.



CLASS-I AND CLASS-II STATES



CLASS-I AND CLASS-II STATES

Fission width of the fine structure (class-I) resonances at energies $E_{\lambda'}$

$$\Gamma_{\lambda' f} = \frac{\langle H^2_{\lambda'\lambda''}\rangle \cdot \Gamma^{II}_{\lambda'' f}}{(E_{\lambda'} - E_{\lambda''})^2 + \frac{1}{4}(\Gamma^{II}_{\lambda''})^2}$$

where $\Gamma^{II}_{\lambda''} = \Gamma^{II}_{\lambda'' f} + \Gamma^{II}_{\lambda'' C} + \Gamma^{II}_{\lambda''\gamma} \approx \Gamma^{\uparrow} + \Gamma^{\downarrow}$ **<u>total width</u> of a class-II states are typically about 10-100 eV**

$$T_B = 2\pi \cdot \frac{\Gamma^{\uparrow}}{D_{II}} \qquad T_A = 2\pi \cdot \frac{\Gamma^{\downarrow}}{D_{II}} = \frac{2\pi}{D_{II}} \cdot \frac{2\pi}{D_I} \cdot \langle H^2_{\lambda'\lambda''}\rangle$$

T_B - **outer barrier transmission**

$\Gamma^{\uparrow}$ - **escape (fission) width**

D_{II} – **class-II average level spacing**

T_A - **inner barrier transmission**

$\Gamma^{\uparrow}$ - **spreading (coupling) width**

D_I – **class-I average level spacing**

$\langle H^2_{\lambda'\lambda''}\rangle$ **- average value of the square coupling matrix element between class-I level λ^{I} and class-II level λ^{II}**

CLASS-I AND CLASS-II STATES

$$D_{II} >> \Gamma^{II}_{\lambda''}$$ - very weak coupling

Two alternative coupling schemes are possible:

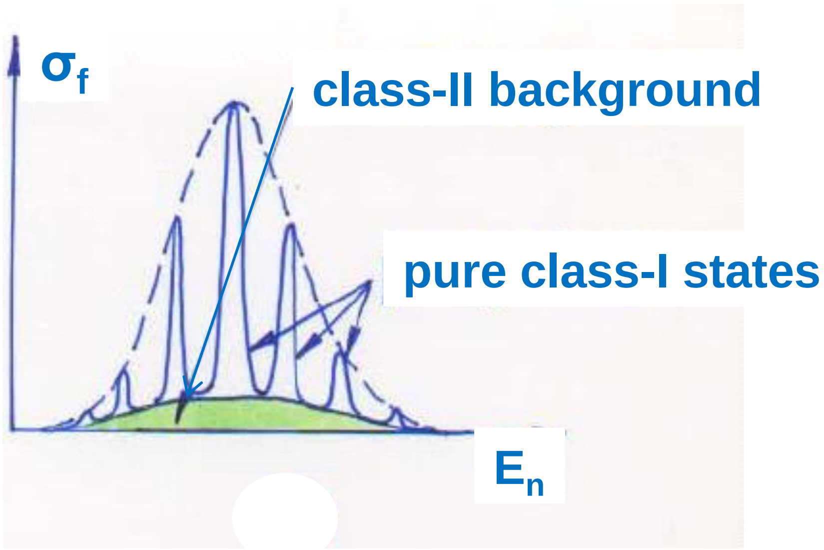
(a) $E_A > E_B \quad (\Gamma^{\downarrow} << \Gamma^{\uparrow})$ The sum rule in this case: $\sum_{\lambda'} \Gamma_{\lambda' f} = \Gamma^{\downarrow}$

One very broad state (the original class-II) taking 99% of the sum rule. This state is unobservable in neutron-induced reactions because of its small neutron width Γ_n . Fine structure resonances - pure class-I states.

Expected properties of the capture gamma-rays for the observed fine structure resonances in clusters:

(1) shape of the gamma-spectra is the same as for the other capture resonances;

(2) capture widths are of the same value as the ordinary resonances and distributed according to the Gaussian statistics.

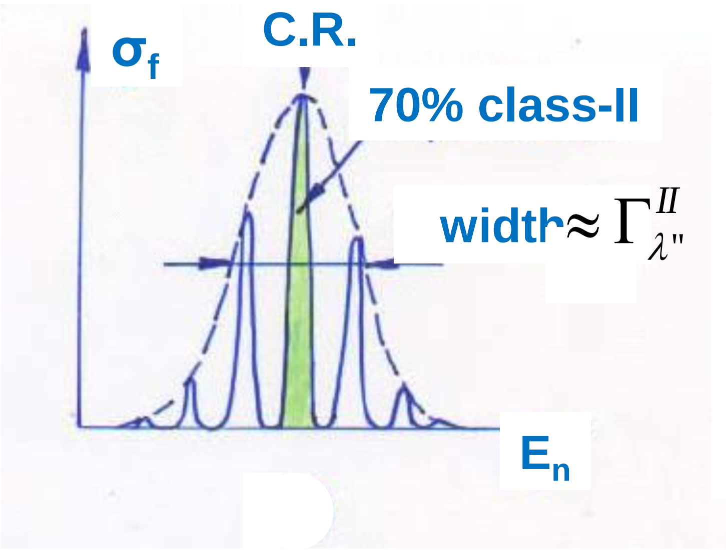


CLASS-I AND CLASS-II STATES

(b) $E_A < E_B \quad (\Gamma^{\downarrow} >> \Gamma^{\uparrow})$

$$\sum_{\lambda'} \Gamma_{\lambda' f} = \Gamma^{\uparrow}$$

The doorway (class-II) state is mixed into the fine structure resonances. The following sum rule is applied, the sum extends over all states including original doorway (class-II) state.



Central resonance (C.R.), which is predominantly class-II state, carries the largest fission width

$$\Gamma_{\lambda' f}(C.R.) \approx (0.6-0.8)\cdot(\Sigma\Gamma_{\lambda' f})$$

Expected properties of the capture gamma-rays for observed resonances in clusters:

(1) shape of the gamma-spectrum for C.R. should be softer than for the other resonances;

(2) capture width of the C.R. should be smaller than that for the other resonances

since the 2-nd well is ~ 2 MeV shallower than the 1-st well!

NEUTRON RESONANCE CAPTURE INVESTIGATIONS AS A MEANS OF STUDYING THE COUPLING CONDITIONS IN SUB-BARRIER FISSION

H. Weigmann, G. Rohr, T. van der Veen, G. Vanpraet

CBNM, Euratom, Geel, Belgium
RUCA, Antwerp, Belgium

Proceedings of the 2-nd International Symposium on Neutron Capture Gamma-Ray Spectroscopy and Related Topics, Petten, 1974. Reactor Centrum Nederland, Petten, 1975, p.673.

Experimental details:

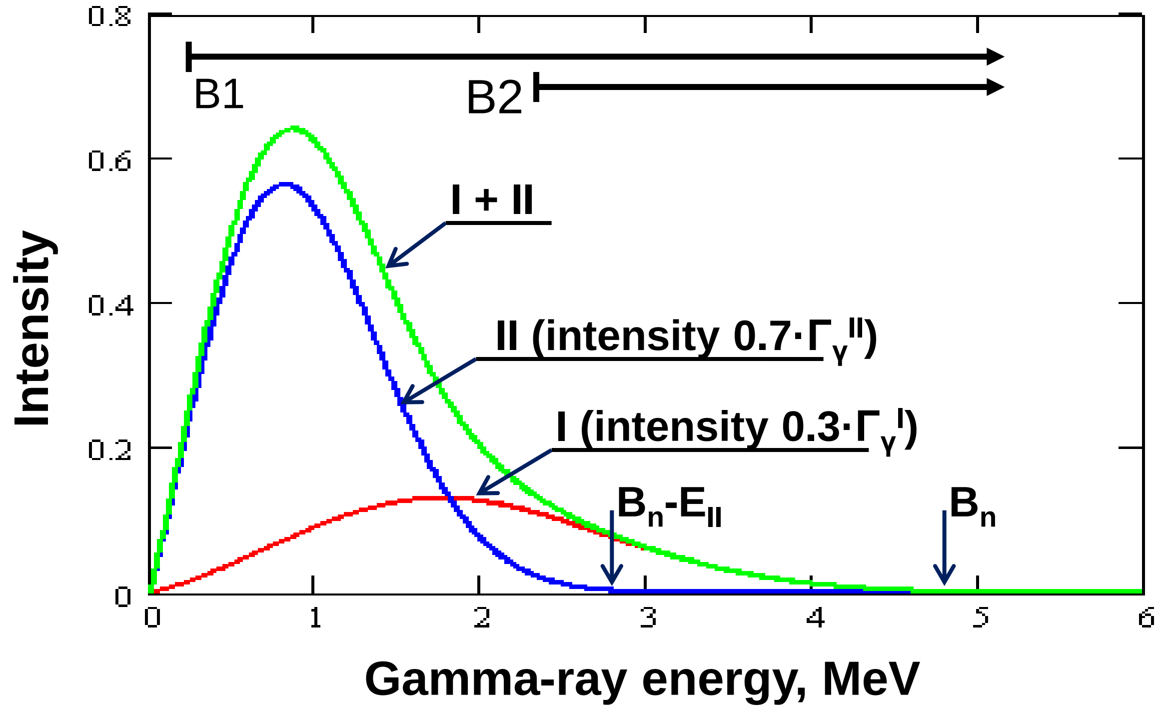
- **Neutron capture gamma-ray yield in resonances of ^{237}Np (40-120 eV) and ^{238}U (720 – 1211 eV)**
- **TOF: CBNM 55 MeV e^--Linac, L=30m, 1.5 – 5.5 n/s energy resolution**
- **$1.37 \cdot 10^{-3}$ at/barn (^{237}Np) and $6.3 \cdot 10^{-3}$ at/barn (^{238}U) samples**
- **4 C_6F_6 liquid scintillator gamma-ray detectors**

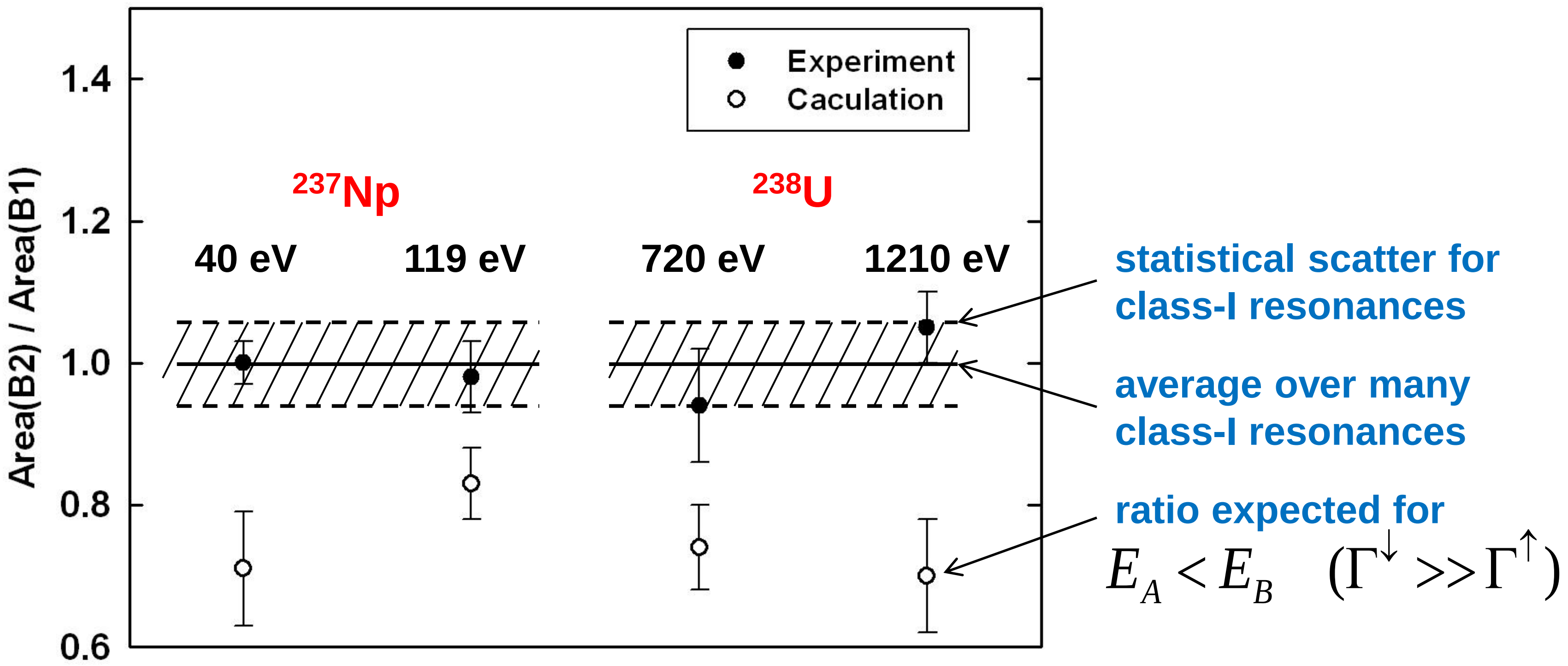
In the case of very weak coupling, since the 2-nd well is ~ 2 MeV shallower than the 1-st well,

1) **the capture width** of the C.R. would be **smaller**
2) **the capture gamma-ray spectrum** would be much **softer** than for the ordinary class-I resonances.

Using the experimentally observed capture gamma-rays, a ratio can be calculated

$$R = \frac{resonance\ area\ for\ Bias\ B2}{resonance\ area\ for\ Bias\ B1}$$





Results of data analysis and conclusion

For biases used B1=0.95 MeV, B2=3.7 MeV (^{237}Np) and B1=0.6 MeV, B2=2.4 MeV (^{238}U),

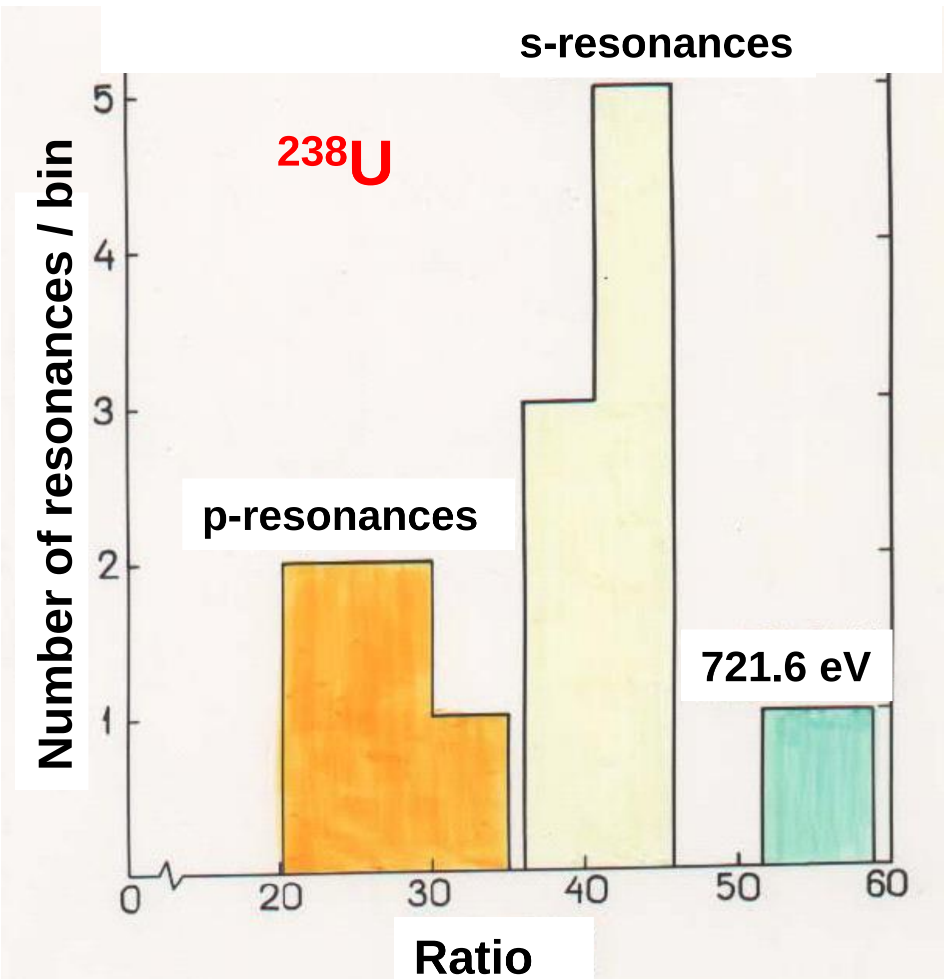
- shape of capture gamma-ray spectra of C.R.'s for both nuclei ^{237}Np and ^{238}U is the same (not softer!) as those for ordinary resonances (class-I states);
- experimentally observed ratios are in full agreement with the assumption that the C.R.'s are essentially pure class-I states, supporting the assumption

$$E_A > E_B \quad (\Gamma^{\downarrow} << \Gamma^{\uparrow})$$

Evidence for 2-nd well γ-decay of subthreshold fission resonances in ^{238}U

J.C. Browne, LLL, Livermore, USA

Proceedings of the International Conference on the Interaction of Neutrons with Nuclei, Univ. of Lowell, Mass. July 6-9, 1976, v. II, p. 1402.



The γ-ray spectra for capture resonances of ^{238}U between 600 eV and 900 eV measured with a Ge(Li)-detector. The ratio of γ-ray yields was determined:

$$Ratio = \sum_{0}^{2.9MeV} I\gamma \Big/ \sum_{2.9MeV}^{4.8MeV} I\gamma$$

Conclusion: the spectrum of **721.6 eV** resonance exhibits a **predominance of low-energy γ-rays,** according with the assumption that.

$$E_A < E_B \quad (\Gamma^{\downarrow} >> \Gamma^{\uparrow})$$

A class-II capture width Γ_{γ}^{II} = 3.9 meV was extracted from the experimental data.

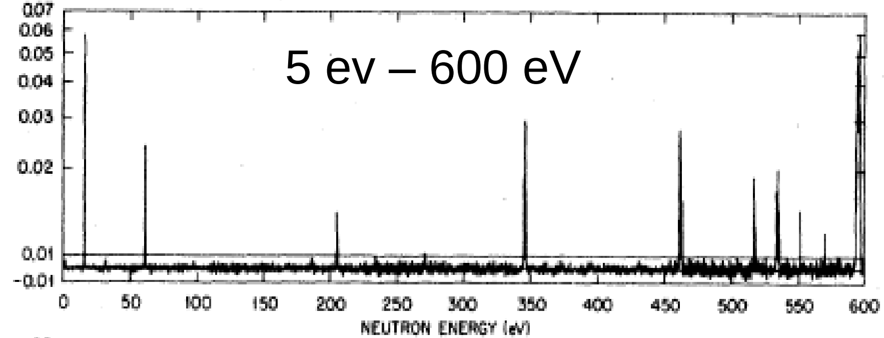
^{238}U neutron-induced fission cross section for incident neutron energies between 5 eV and 3.5 MeV

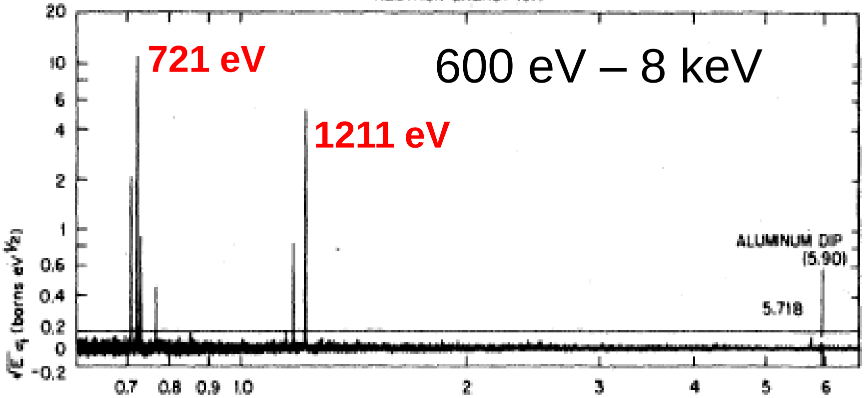
F. C. Difilippo,* R. B. Perez, G. de Saussure, D. K. Olsen, and R. W. Ingle

Oak Ridge National Laboratory, P.O. Box X, Oak Ridge, Tennessee 37830

Phys. Rev. C 21,1980, pp.1400 -1410.

A measurement of the ^{238}U neutron-induced fission cross section has been performed in the neutron energy range between 5 eV and 3.5 MeV. The favorable signal-to-background ratio and high resolution of this experiment resulted in the identification of 85 subthreshold fission resonances or clusters of resonances in the neutron energy region between 5 eV and 200 keV. The fission data below 100 keV are characteristic of a weak coupling situation between Class I and Class II levels. The structure of the fission levels at the 720- and 1210-eV fission clusters is discussed. There is an apparent enhancement of the fission cross section at the opening of the 2^+ neutron inelastic channel in ^{238}U at 45 keV. An enhancement of the subthreshold fission cross section between 100 and 200 keV has been tentatively interpreted in terms of the presence of a Class II, partially damped vibrational level. There is a marked structure in the fission cross section above 200 keV up to and including the plateau between 2 and 3.5 MeV.





TOF: ORELA 140MeV e^--Linac,

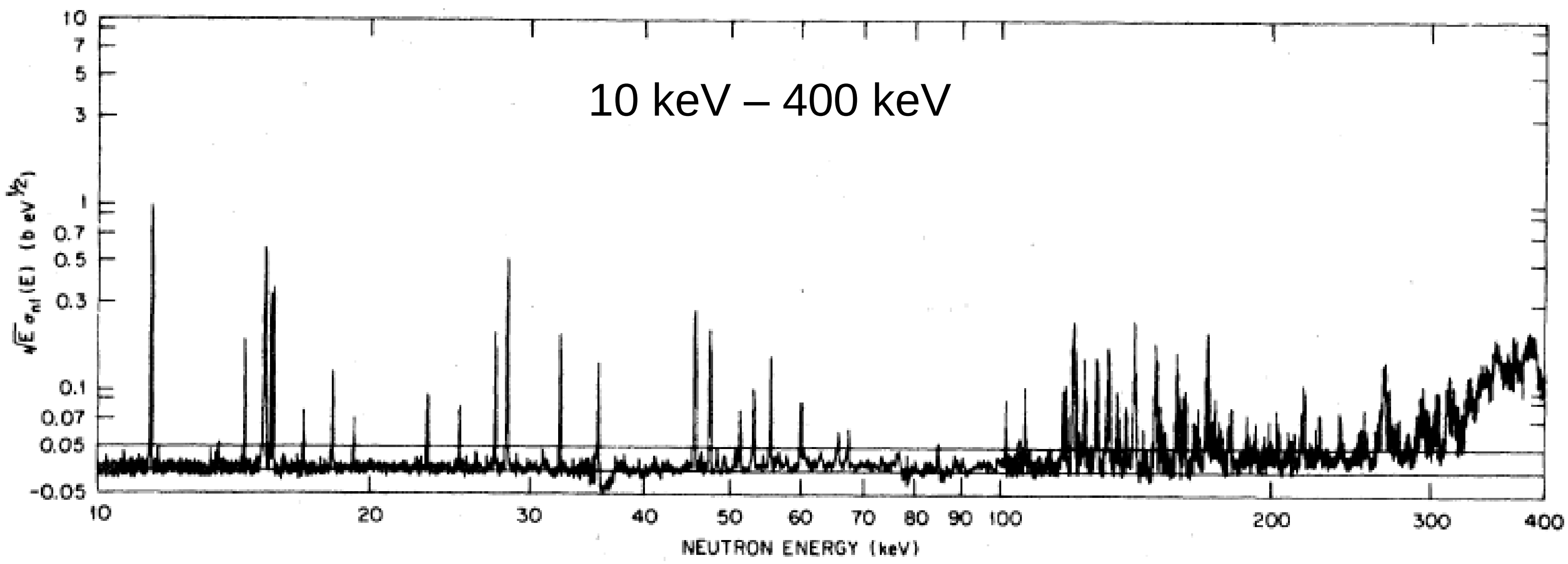
Δt_n = 30ns, L = 152m

^{238}U- high purity sample (2 ppm ^{235}U)

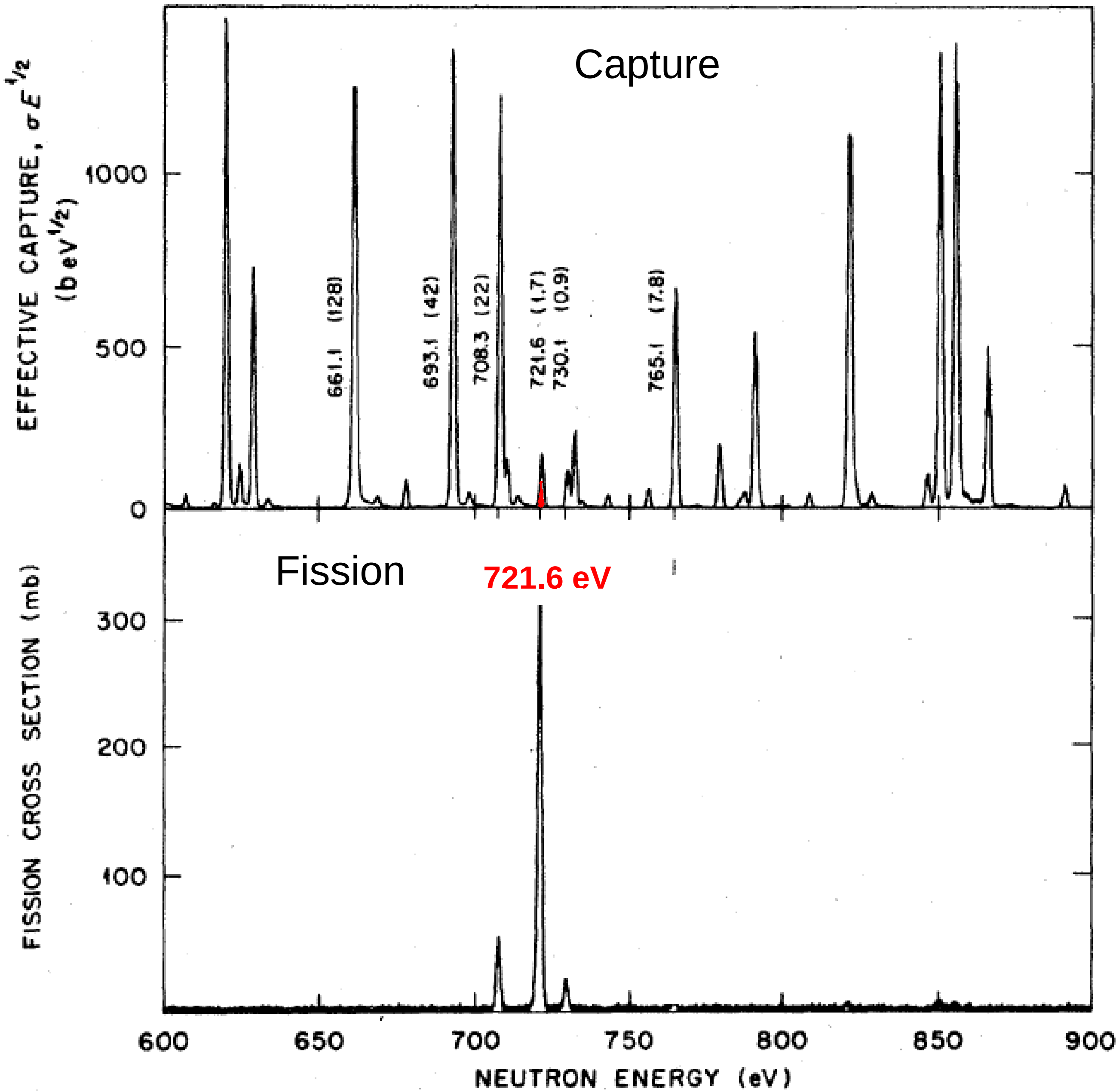
85 subthreshold fission resonances or resonance clusters have been identificated in the neutron energy range 5 eV – 200 keV.

Fission widths Γ_f of 27 resolved resonances have been obtained from the measured fission area

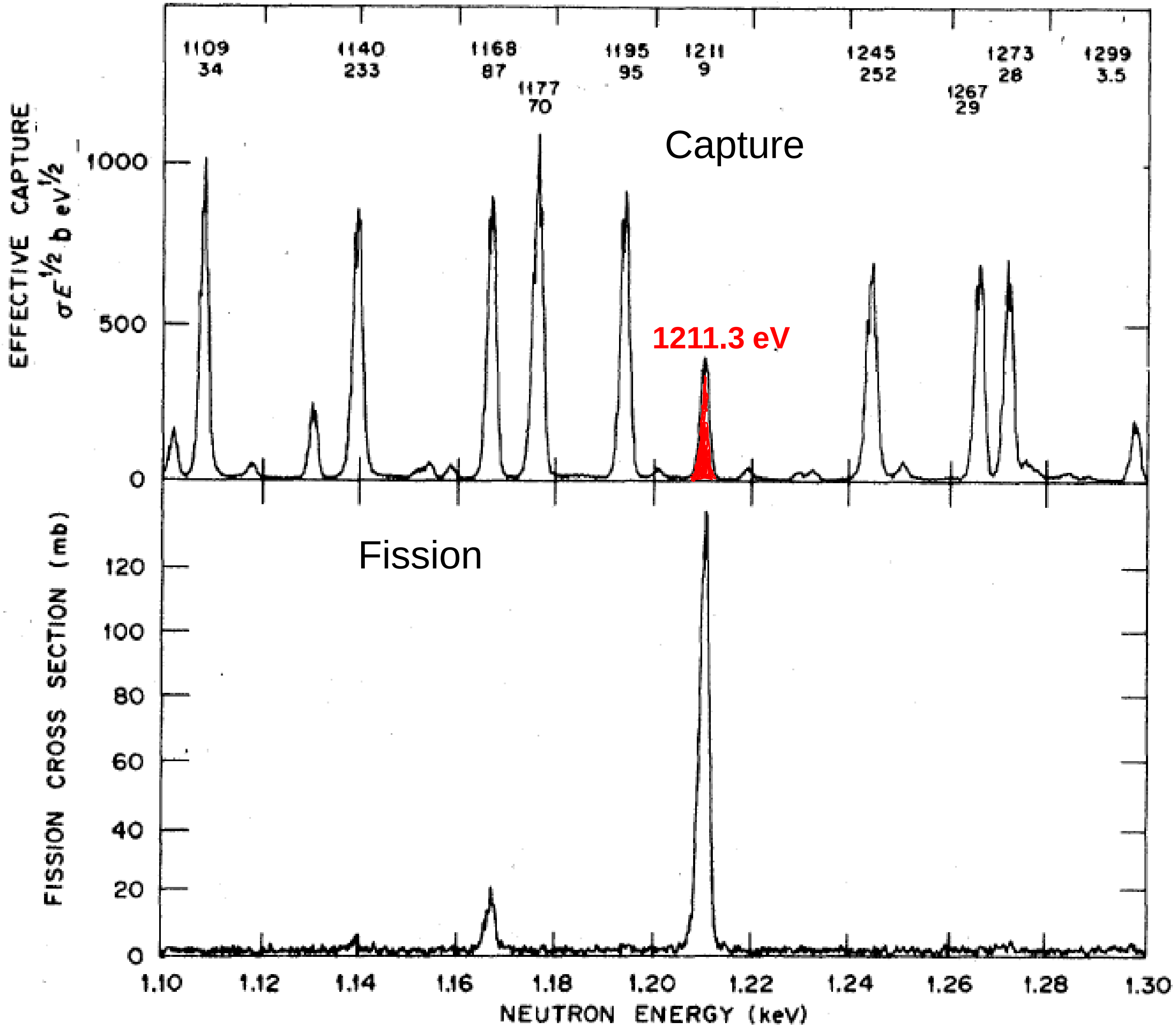
$$A_f = \int \sigma_f \cdot dE = \frac{2\pi^2}{k^2} g \frac{\Gamma_f \cdot \Gamma_n}{\Gamma}$$



de Saussure et al., Nucl. Sci. Eng. 51 (1975) 385.



de Saussure et al., Nucl. Sci. Eng. 51 (1975) 385



^{238}U class-II parameters for the intermediate resonance clusters 721.6 eV and 1211 eV

	721.6 eV (1)	721.6 eV (2)	1211 eV (1)	1211 eV (2)
$\Gamma^{II}_{\lambda'' f}(eV)$	$1.8\cdot10^{-3}$	0.89	$0.4\cdot10^{-3}$	4.61
$\Gamma^{II}_{\lambda'' C}(eV)$	0.89	$1.8\cdot10^{-3}$	4.61	$0.4\cdot10^{-3}$
$H^{2}_{\lambda'\lambda''}(eV)$	3.1	$6.3\cdot10^{-3}$	16	$1.4\cdot10^{-3}$

For analysis, two alternative interpretations have been used:
(1) $E_A < E_B$ or $T_A \approx 1.2\cdot10^{-2} >> T_B \approx 6\cdot10^{-6}$ (very weak coupling)
(2) $E_A > E_B$ or $T_A \approx 6\cdot10^{-6} << T_B \approx 1.2\cdot10^{-2}$ (moderately weak coupling)

Conclusion: **both interpretations give the same value of the total barrier transmission $T=T_A\cdot T_B$ and without additional information it is impossible to distinguish between them.**

Resolution of the nature of the coupling in subthreshold fission in $^{238}U + n$

George F. Auchampaugh
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

Gerard de Saussure, David K. Olsen, and Rex W. Ingle
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

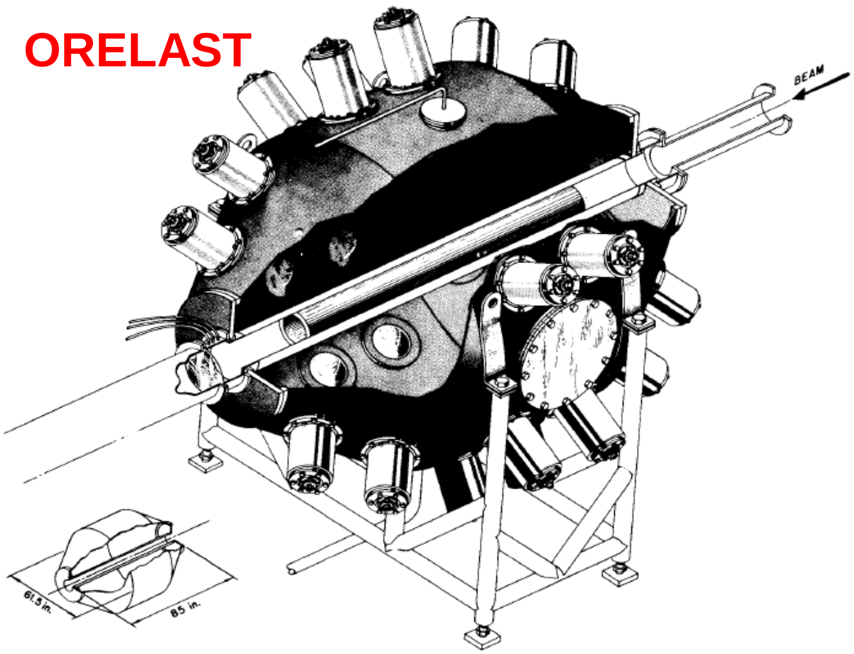
Rafael B. Perez and Roger L. Macklin
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830
and Department of Nuclear Engineering, University of Tennessee, Knoxville, Tennessee 37996

Phys. Rev. C 35,1986, pp.125-129.

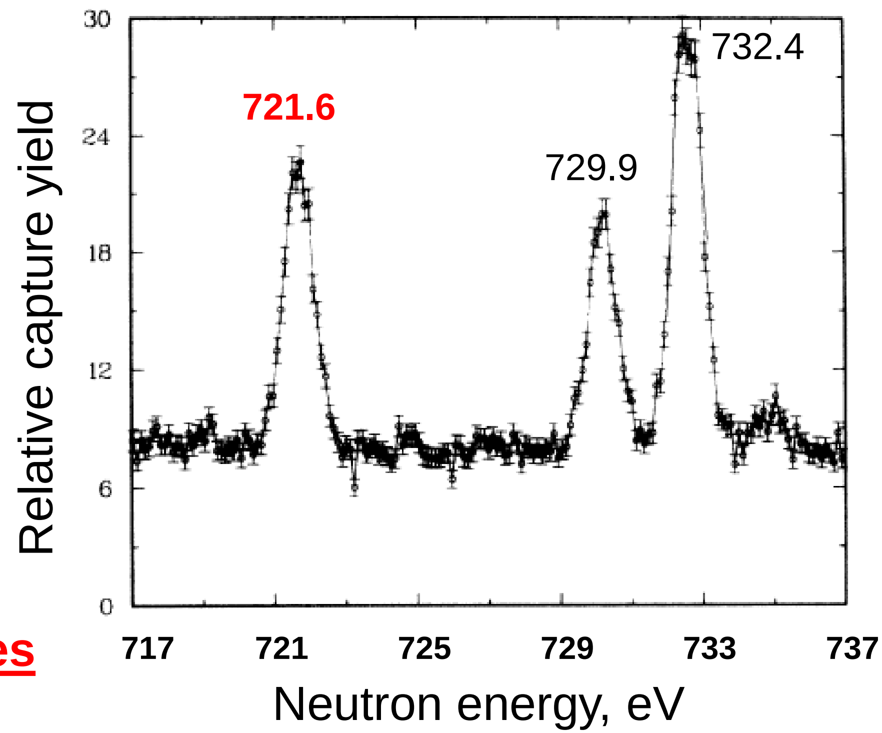
The analysis of a recent high-resolution neutron capture measurement at 152 m has provided the first evidence that the strong fission resonance at 721 eV is a class-II resonance. This conclusion is based on the measured capture width of 4.7 ± 0.6 meV, which is considerably smaller than the average capture width of 23.5 meV for the neighboring resonances. Furthermore, after analyzing the fission widths for the 721- and 1211-eV clusters, we conclude for the $J^{\pi} = \frac{1}{2}^{+}$ fission barrier in ^{239}U that the inner barrier is lower than the outer barrier by ~ 1.5 MeV.

Neutron capture measurement on ^{238}U at the ORELA

ORELAST



TOF: 140MeV e$^-$-Linac, 40kW, 800Hz
Δt_n = 50ns, L = 152m
ORELAST, 3000-l large liquid scintillator capture gamma-ray detector
^{238}U- metal sample, 0.64mm, 99.99%



Problem:
due to poor (~70%) gamma-ray energy resolution and large gamma-ray background, high registration biases have been used, 4.0 to 8.6 MeV

Capture width was calculated from the expression

$$\Gamma_\gamma = \Gamma_n(a_\gamma - \varepsilon \cdot a_f)/(\Gamma_n - a_\gamma + a_f(\varepsilon - 1))$$

a_f, a_γ and Γ_n - fission, capture area and neutron width, respectively, measured in present (as a_γ) or some other (as a_f, Γ_n) experiments, ε- contribution to the capture a_γ area from fission gamma-rays. Exact value of ε is not known, for reasonable range of ε= 0-2 the capture width range is Γ_γ=(6.6 - 3.5) meV. Final data for resonances near 721eV are given in Table I for ε= 1.

TABLE I. Parameters for the resonances near 721 eV.

E_r (eV)	Γ_n (meV)	a_γ (meV)	a_f (meV)	Γ_γ (meV)
721.5	1.794 ± 0.034	1.328 ± 0.036	0.1070 ± 0.0013	4.7 ± 0.6[a]
729.9	1.020 ± 0.029	1.019 ± 0.033	0.0063 ± 0.0003	---
732.4	1.985 ± 0.036	1.956 ± 0.043	0	---

Probability to observe capture width of less than 4.7 meV from a normal distribution with average value 23.5 meV and σ=1.96 (exp.) for s-resonances (class-I) of ^{238}U is $P(4.7) \approx 10^{-22}$.

<u>Conclusion #1:</u> the 721 eV resonance is not a class-I resonance

If the 721 eV resonance is a class-II resonance, then is its capture width Γ_γ= 4.7 meV consistent with the theoretical estimates for the class-II width? Within a simple statistical theory approach, the relation between the capture widths for the secondary and primary wells is

$$\Gamma_{\lambda\gamma}^{II} = \left(\frac{E-\delta_{II}-E_{II}}{E-\delta_I}\right)^2 \cdot \frac{a_I}{a_{II}} \cdot \Gamma_{\lambda\gamma}^{I} \qquad \Gamma_{\lambda\gamma}^{II} = 6.9 \text{ meV}$$

where: E – excitation energy (for ^{238}U, E = B_n = 4.8 MeV), $\delta_I = \delta_{II}$ = 0.69 MeV - pairing energies, $a_I = a_{II}$ = 33.4 MeV – level density parameters, E_{II} – energy of the second minimum, $\Gamma^{I}_{\lambda\gamma}$ - average capture width of class-I resonances. If the gamma-ray strength is derived from GDR-model, then $\Gamma_{\lambda\gamma}^{II}$ = 3.7 meV.

Conclusion #2: the value of capture width 4.7 meV for 721 eV resonance of ^{238}U is consisted with that for the class-II state at neutron- binding energy.

For the 1211 eV resonance analogous calculations give capture width Γ_γ = 6.6 meV and the average class-II fission width for two resonances $\Gamma_{\lambda f}^{II}$ = 0.401 meV.

Conclusion #3: for fission barrier in compound-nucleus ^{239}U with J^π=1/2$^+$ the inner barrier is lower than the outer barrier by ~1.5 MeV.

ON THE NATURE OF THE 721.6 eV RESONANCE in ^{238}U

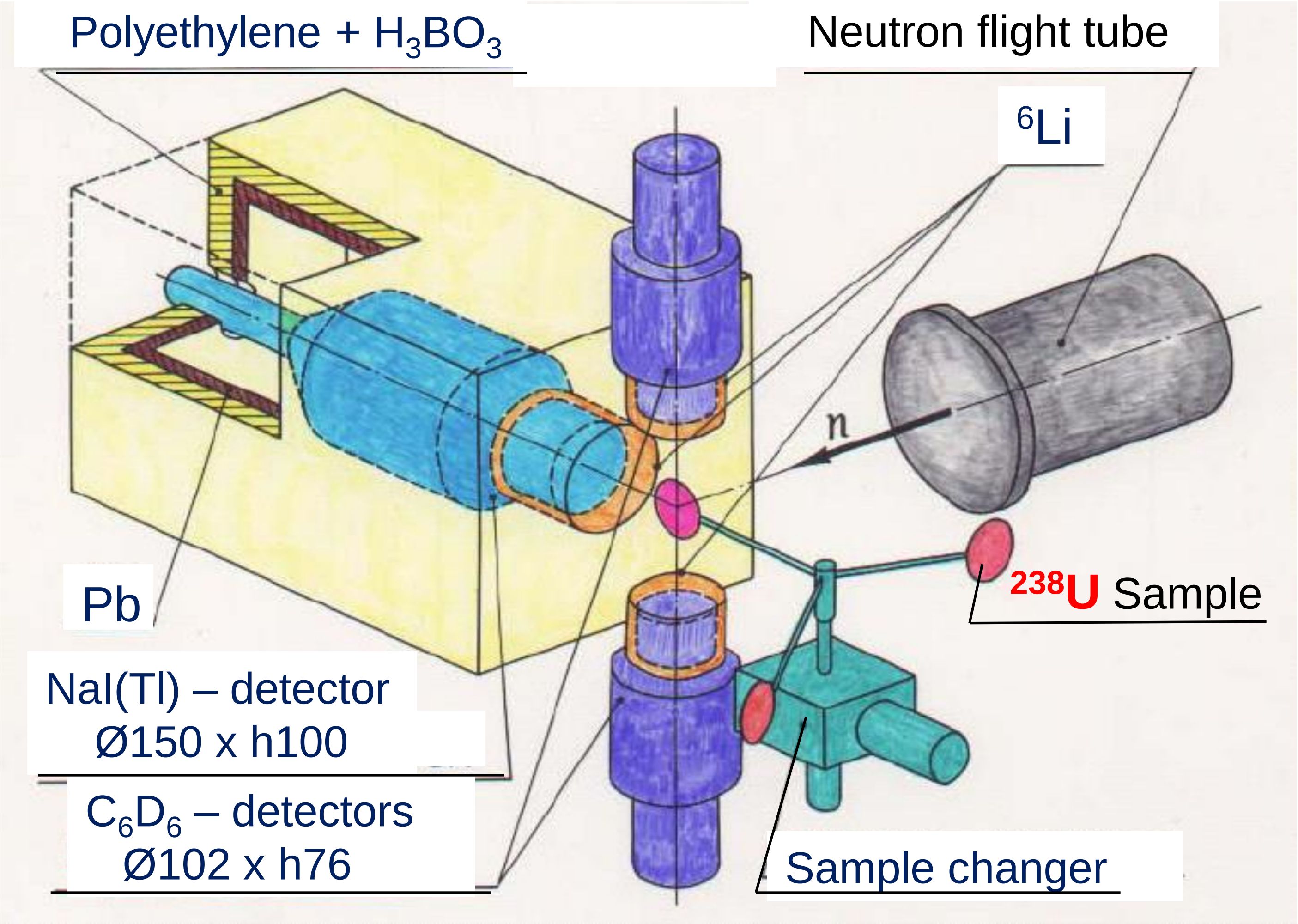
A.B Laptev, O.A. Shcherbakov
B.P. Konstantinov Leningrad Nuclear Physics Institute, Gatchina, Russia

Report at the International Workshop on Nuclear Fission
June 17-21, Smolenice, Czechoslovakia, 1991
LNPI Preprint -1712, July 1991

PREFISSION AND CAPTURE GAMMA-RAYS IN NEUTRON RESONANCES OF ^{235}U, ^{238}U AND ^{239}Pu

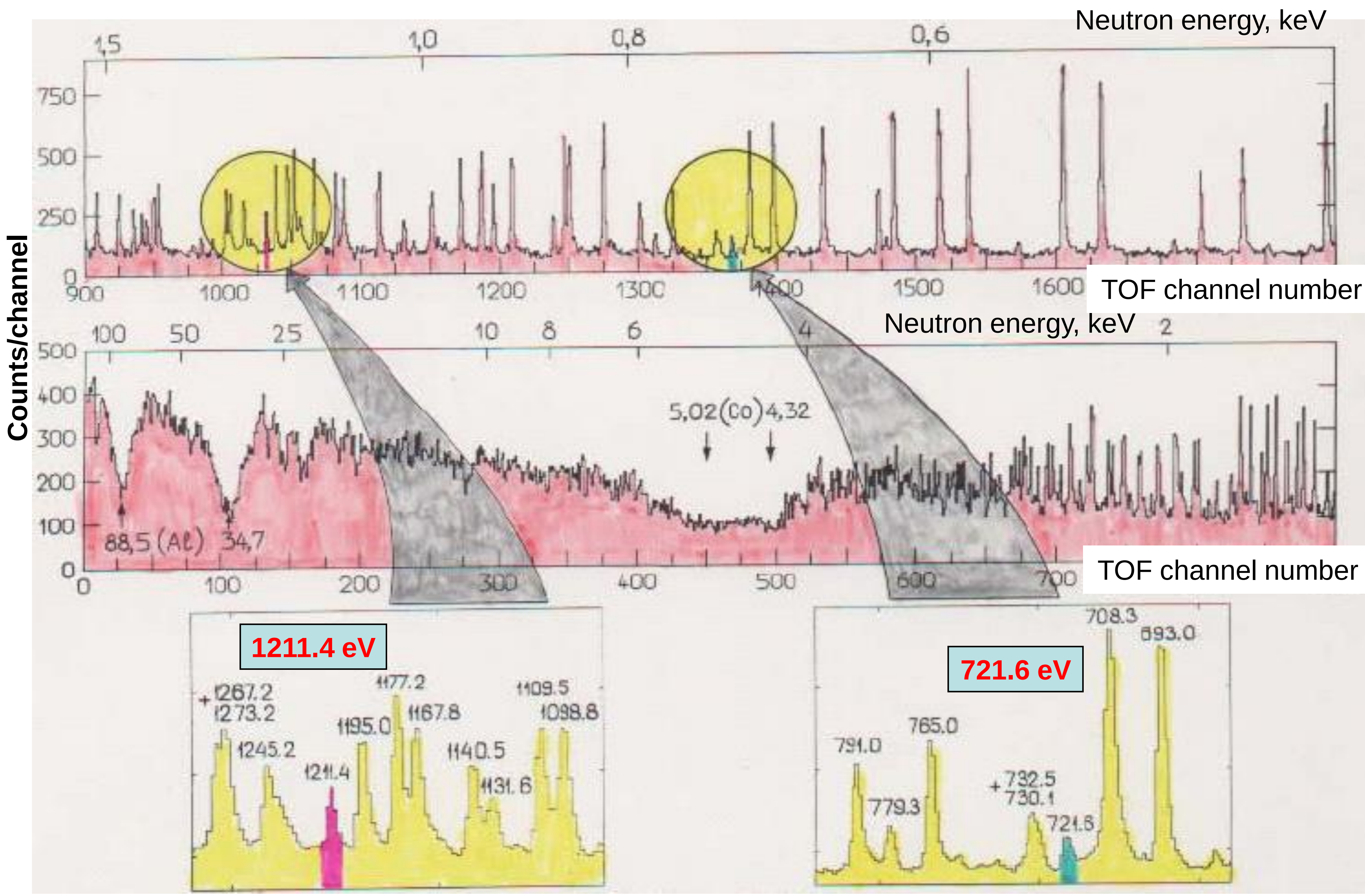
O.A. Shcherbakov, A.B Laptev
B.P. Konstantinov Petersburg Nuclear Physics Institute, Gatchina, Russia

Proceedings of the 10-th International Symposium
on Capture Gamma-Ray Spectroscopy and Related Topics,
Santa-Fe, N.M., 30 August-3 September, 1999.
AIP Conference Proceedings, vol. 529, N.Y., 2000, p.710.

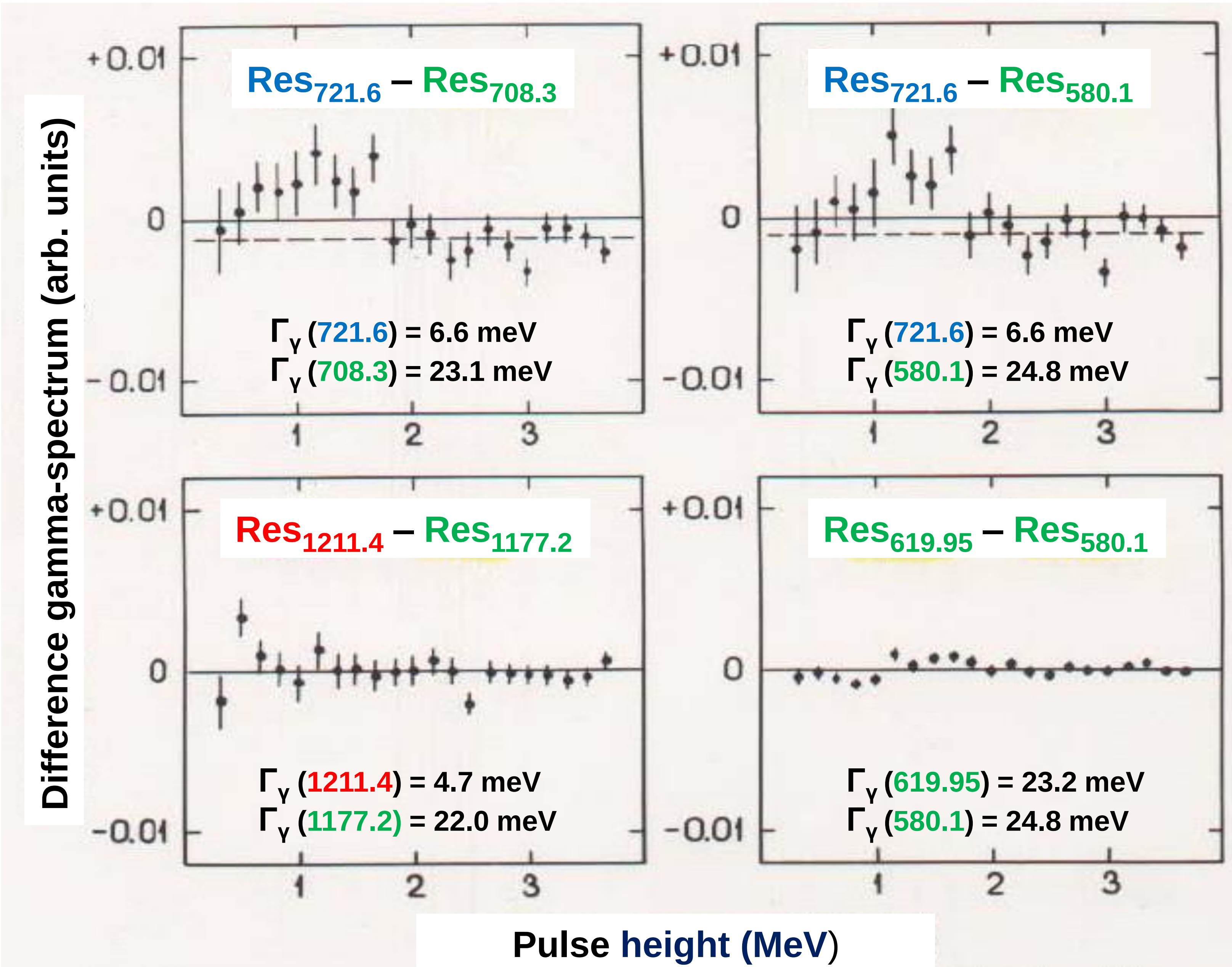


TOF: **1 GeV proton SC-1000, GNEIS, $3 \cdot 10^{14}$ n/s, Δt_n = 10ns, L = 45m,**
^{238}U highly enriched (99.996%) metal sample, $6.4 \cdot 10^{-3}$ at/barn thickness
1024 TOF ch x 64 PH ch, neutron energy range 400 eV – 1300 eV

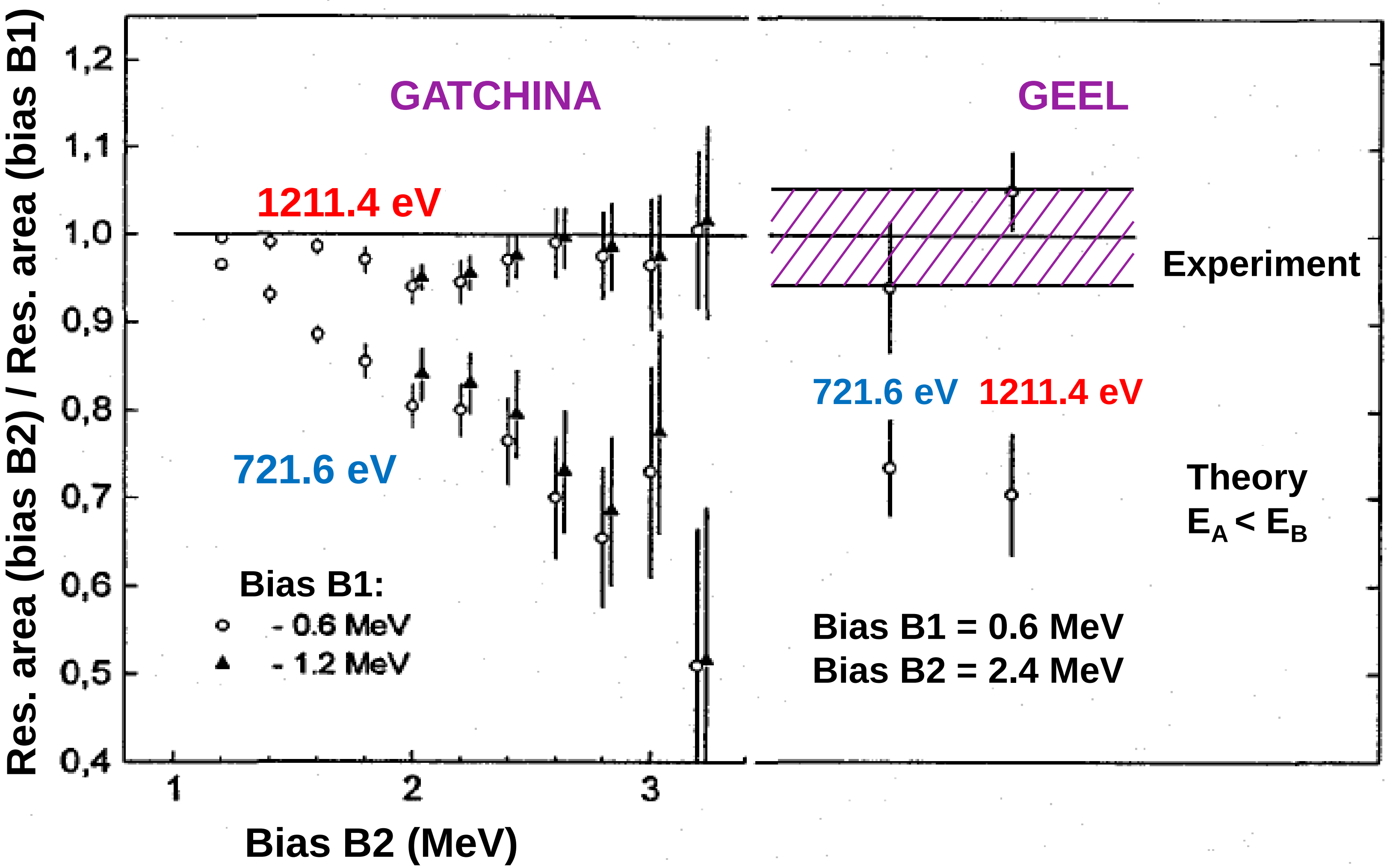
TOF-SPECTRUM OF CAPTURE YIELD FOR ^{238}U BETWEEN 0.2 AND 100 KeV



DIFFERENCE PULSE-HEIGHT SPECTRA FOR RESONANCES OF ^{238}U



EXPERIMENTAL RESULTS



Conclusion: 1) capture γ-ray spectrum of the 721.6 eV resonance shows that this resonance is predominantly class-II state

2) the 1211.4 eV resonance shows the properties of class-I state

STUDY OF NEUTRON RESONANCES AND SEARCH FOR UNUSUAL EXCITED STATES OF NUCLEI

G.V. Muradyan
I.V. Kurchatov Institute of Nuclear Energy, Moscow, Russia

Journal of Nuclear Physics, v.53, issue 4, 1991, p.883.

STUDY OF ^{238}U NEUTRON RESONANCES WITH ANOMALOUSLY LARGE FISSION WIDTHS

G.V. Muradyan, V.A. Stepanov, M.A. Voskanyan
I.V. Kurchatov Institute of Nuclear Energy, Moscow, Russia

Nuclear Physics A580, 1994, p.236.

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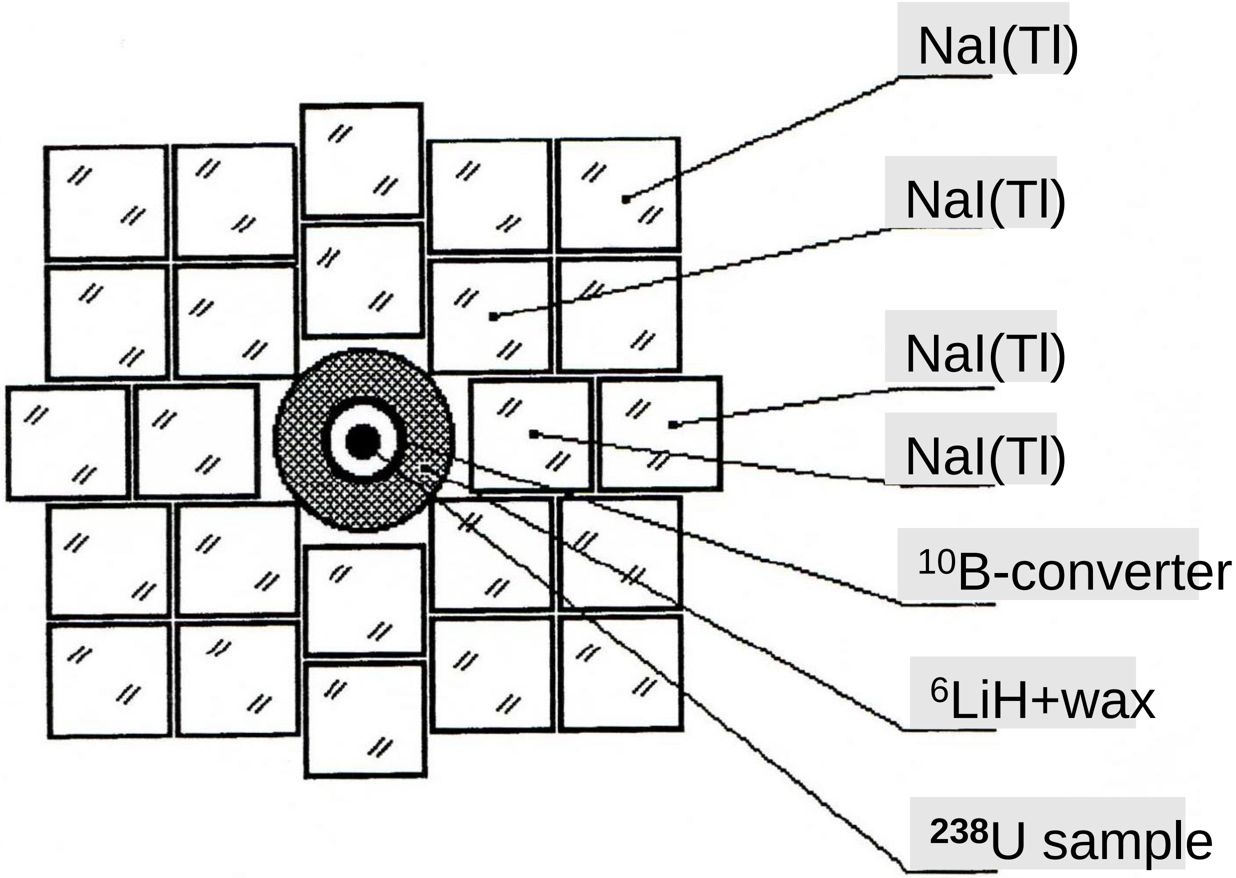
TOF: FAKEL e^- - Linac, 50 MeV, 3 kW, 10^{13} n/s, L = 25m, 3 ns/m

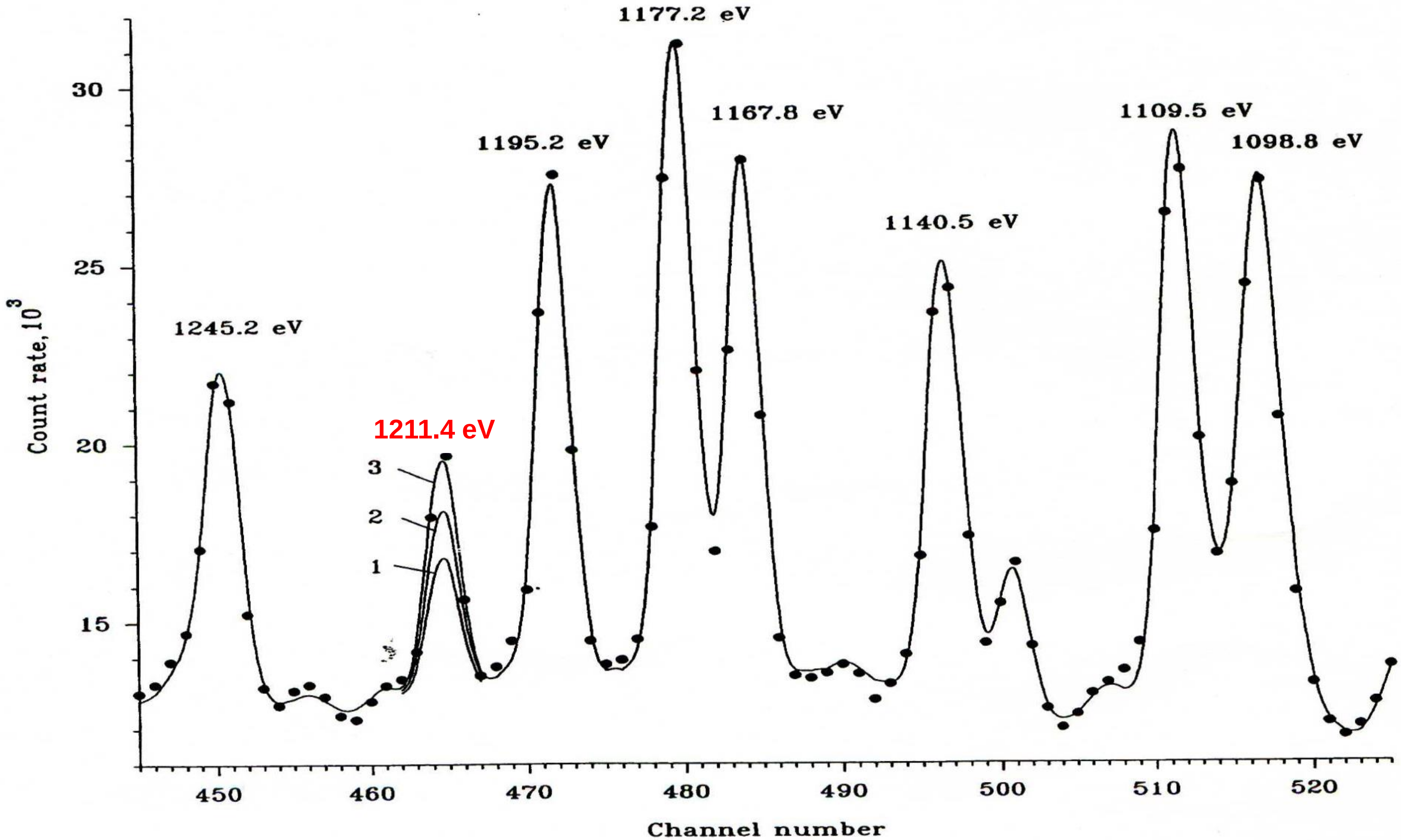
^{238}U highly enriched (99.996%) metal sample, $6.4 \cdot 10^{-3}$ at/barn

"Romashka" 48-sectional NaI(Tl) 4π-detector of γ-ray multiplicity



TOF-spectrum of capture events for U-238 in 1211.4 eV resonance region

G.V. Muradyan et al., Nucl. Phys. A580 (1994) 236

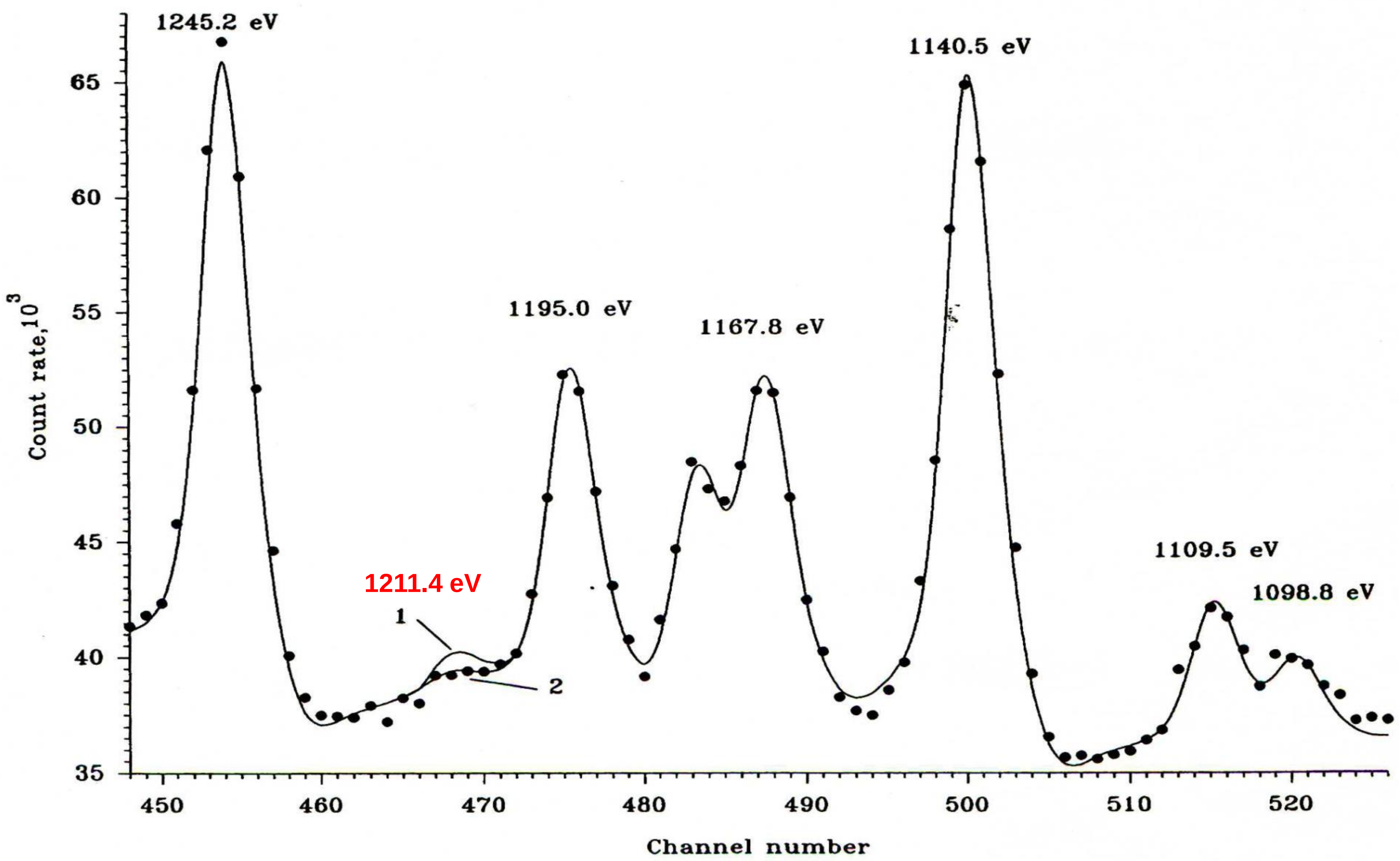


Points: experiment. Solid curve – calculation:

1) Γγ = 6.6 meV 2) Γγ = 12 meV 3) Γγ = 23 meV

TOF-spectrum of scattering events for U-238 in 1211.4 eV resonance region

G.V. Muradyan et al., Nucl. Phys. A580 (1994) 236

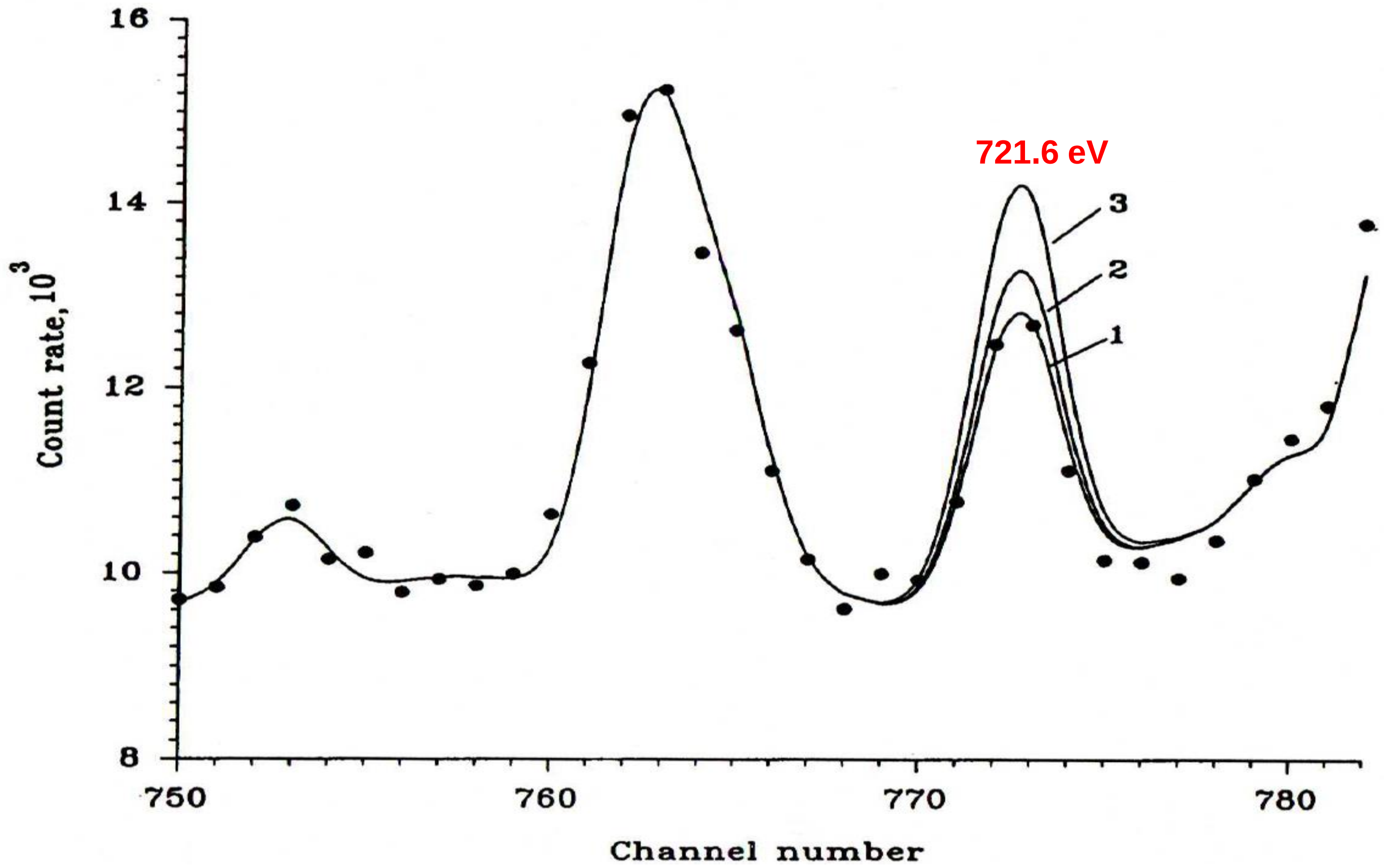


Points: experiment. Solid curve – calculation:

1) Γγ = 6.6 meV, 2) Γγ = 23 meV

TOF-spectrum of capture events for U-238 in 721.6 eV resonance region

G.V. Muradyan et al., Nucl. Phys. A580 (1994) 236

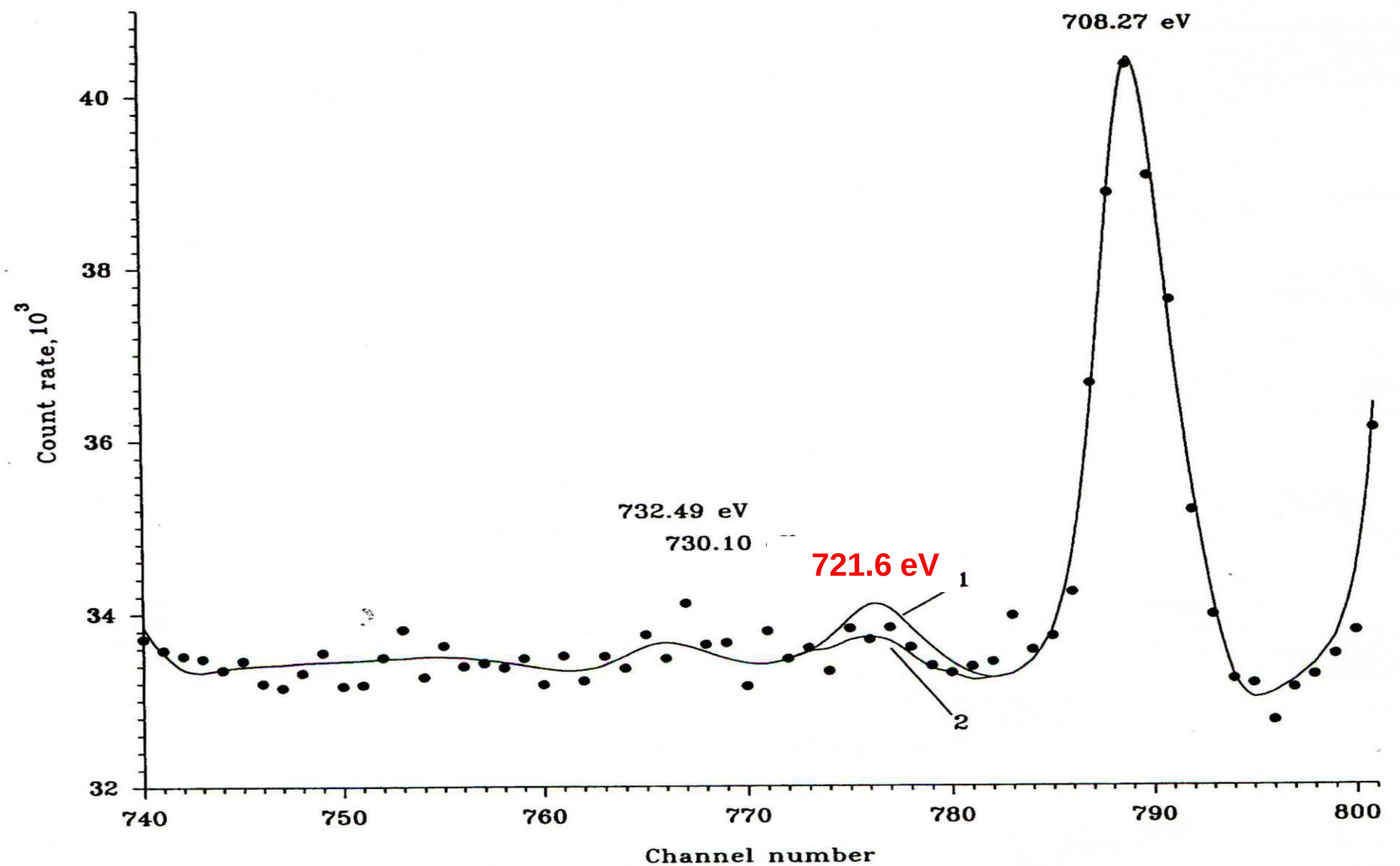


Points: experiment. Solid curve – calculation:

1) Γγ = 3.2 meV, 2) Γγ = 5.0 meV, 3) Γγ = 23.5 meV

TOF-spectrum of scattering events for U-238 in 721.6 eV resonance region

G.V. Muradyan et al., Nucl. Phys. A580 (1994) 236

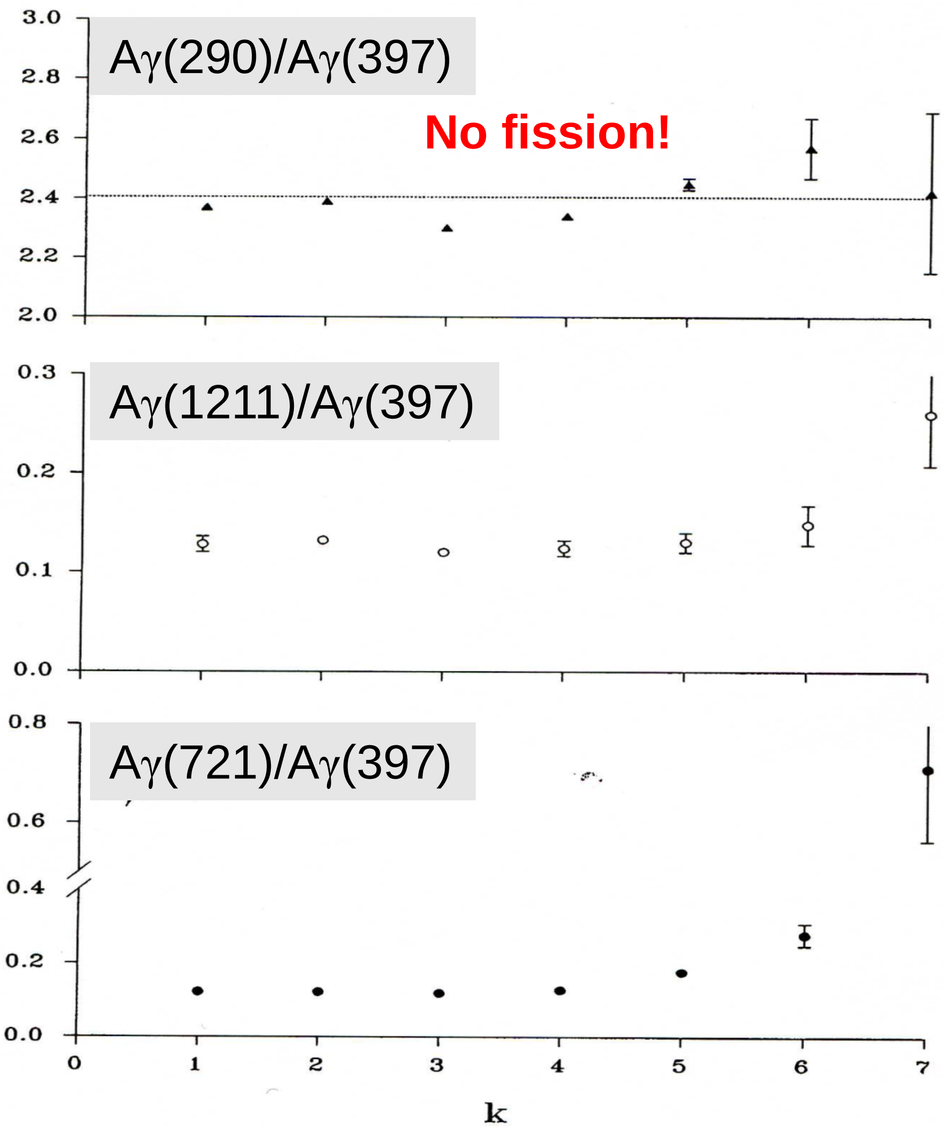


Points: experiment. Solid curve – calculation:

1) Γγ = 3.2 meV, 2) Γγ = 23.5 meV

Ratio of the resonance areas (A_γ) of 290 eV, 721.6 eV and 1211.4 eV to 397 eV

G.V. Muradyan et al., Nucl. Phys. A580 (1994) 236



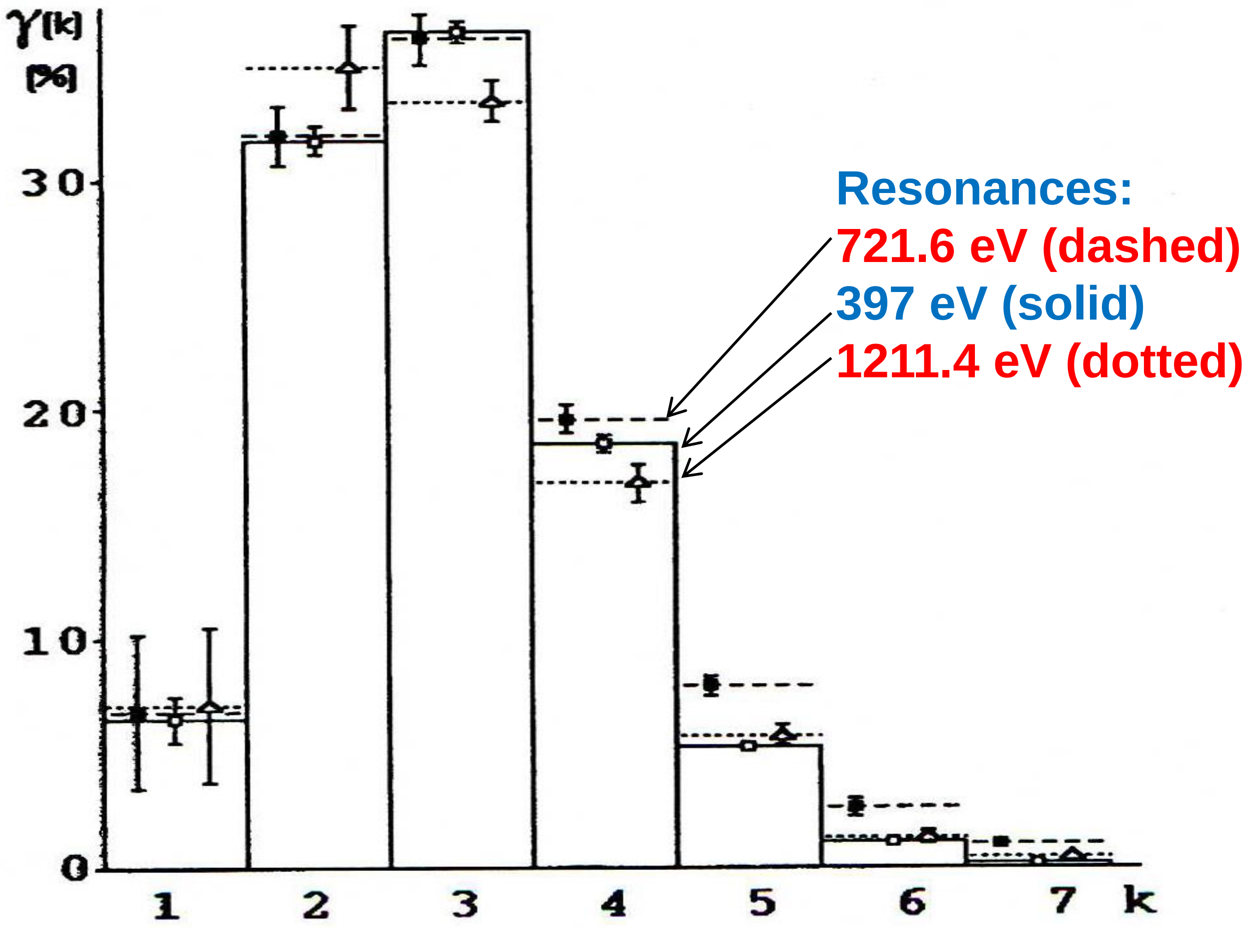
Ratio of resonance area

Important: fission is not observed for the 290 eV and 397 eV resonances. Ratio $A\gamma(290)/A\gamma(397)$ is constant for all K. Deviations from a constant are due to the fluctuations of multiplicity spectra.

Results: for the 1211 eV and 721 eV the constancy is observed only for k ≤ 4 and deviation is raised with k. It is caused by a fission contribution to the capture channel. Evidence: deviations for k≥4 is higher for 721 eV resonance than for 1211 eV because $\Gamma\gamma/\Gamma_f$ ratio for 721 eV is higher.

Capture gamma-ray multiplicity spectrum for resonances of U-238

G.V. Muradyan et al., Nucl. Phys. A580 (1994) 236



G.V. Muradyan et al., Nucl. Phys. A580 (1994) 236

Conclusions

1) capture width Γ_γ=23 ± 3 meV of the 1211eV resonance does not differ from $<\Gamma_\gamma>$ =23.5 meV of the s-resonances, as well as the multiplicity and energy spectra of capture gamma-rays. This indicates that **1211 eV resonance is unlikely the class-II state.**

2) anomalously small capture width Γ_γ=3.2 ± 0.5 meV of **the 721.6 eV resonance means that it is extraordinary.** Its multiplicity and energy spectra of capture gamma-rays are similar to those of other resonances. The extraordinary of the 721.6 eV resonance can be unlikely explained within the framework of the two-humped fission barrier model. **It can be related with isomeric state with anomalously large life time, which has never been observed before.**

Limits on the half life of the shape isomer in ^{239}U

S. Oberstedt [a,1], J.P. Theobald [a], H. Weigmann [b], J.A. Wartena [b], C. Bürkholz [b]

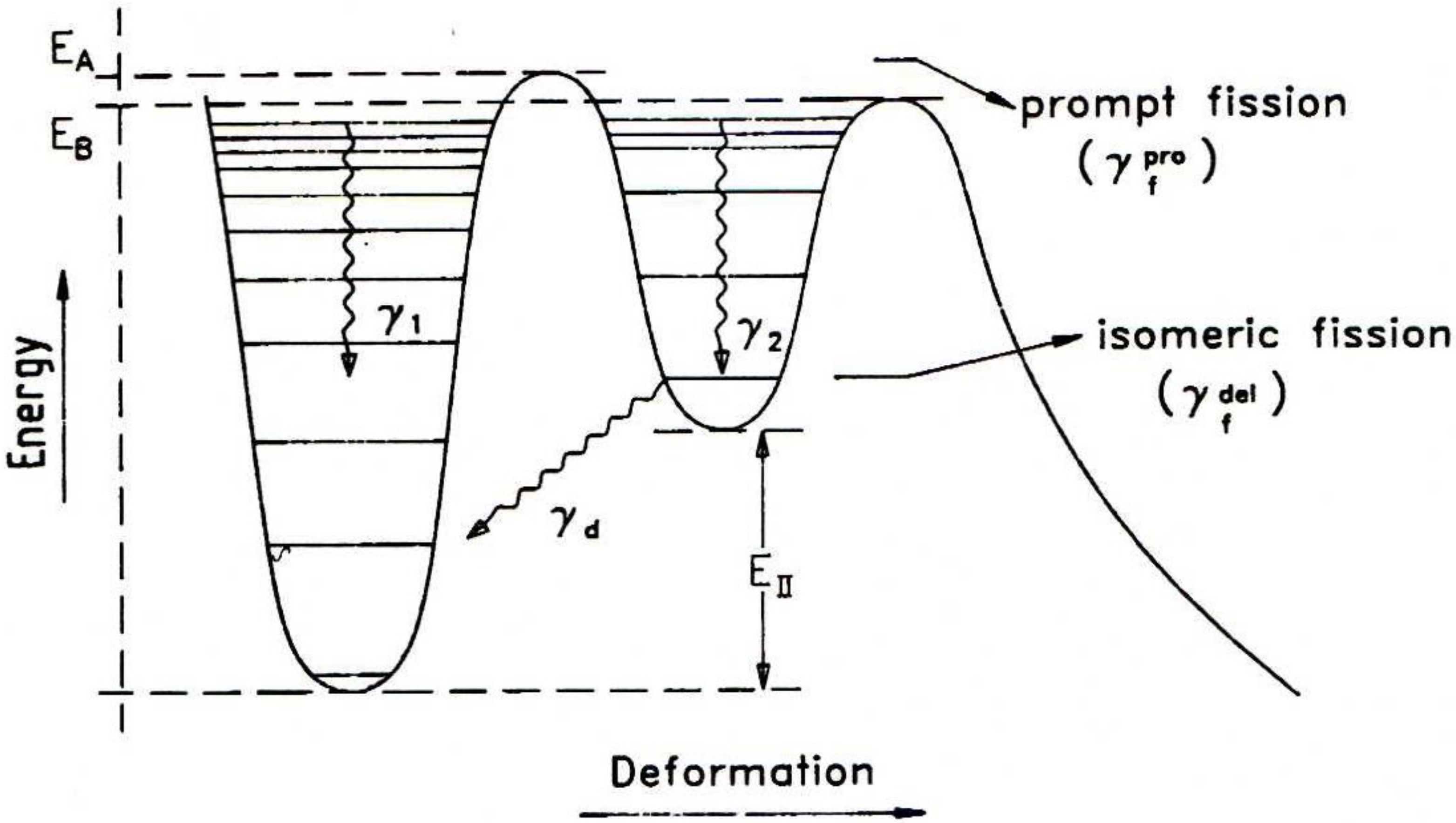
[a] *Institut für Kernphysik, Technische Hochschule, Schloß Gartenstraße 9, W-6100 Darmstadt, Germany*

[b] *Commission of the European Communities, Joint Research Center, Institute for Reference Materials and Measurements, B-2440 Geel, Belgium*

Nuclear Physics A 573 (1994) 467–485

Search of the shape isomer in U-239 at IRMM (Geel)

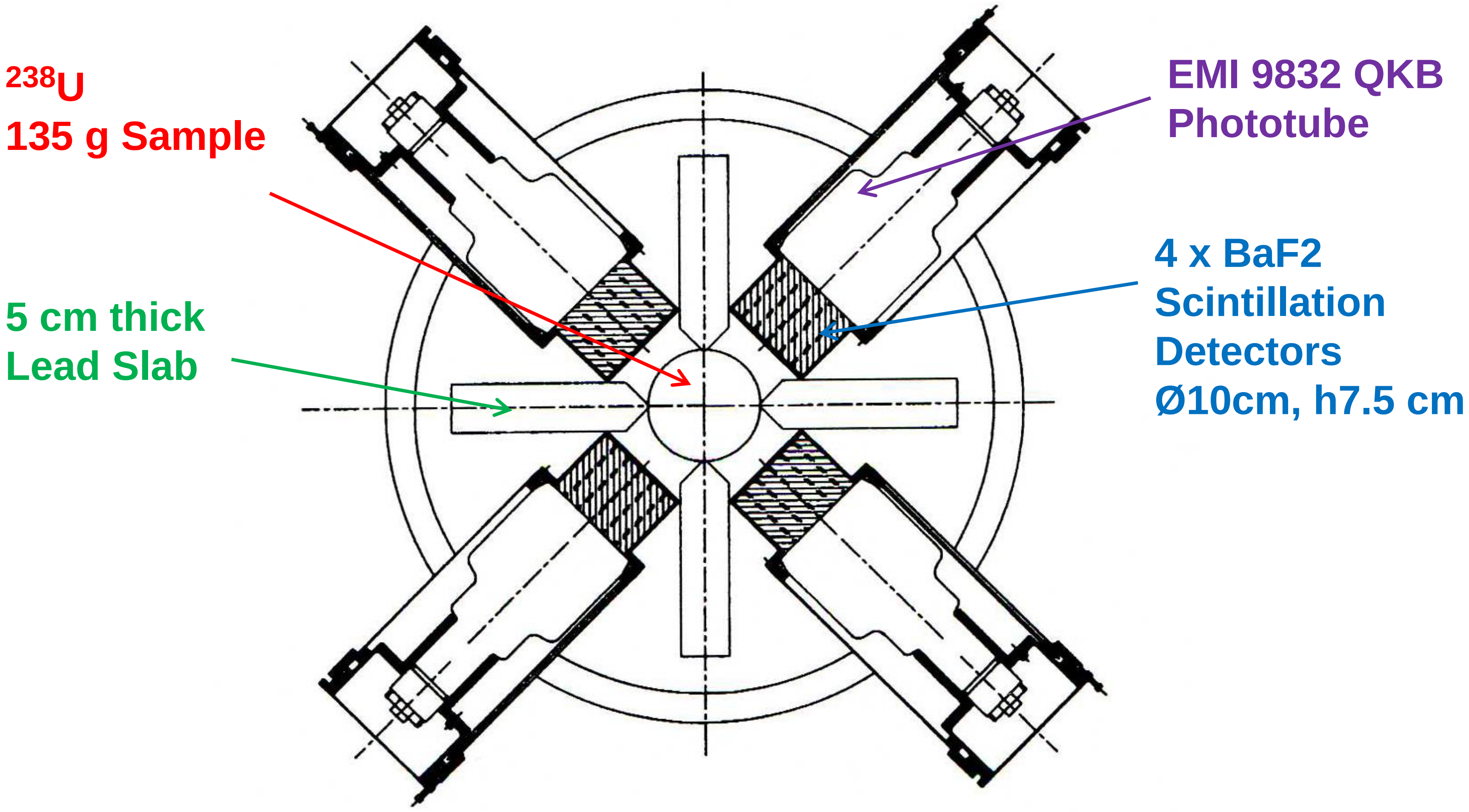
S. Oberstedt et al., Nucl. Phys. A573 (1994) 467



In order to search for delayed reaction paths, the 721.6 eV resonance of U-238, a nearly pure class-II state, was investigated in a γγ – coincidence experiment at the IRMM Linac (GELINA)

Search of the shape isomer in U-239 at IRMM (Geel)

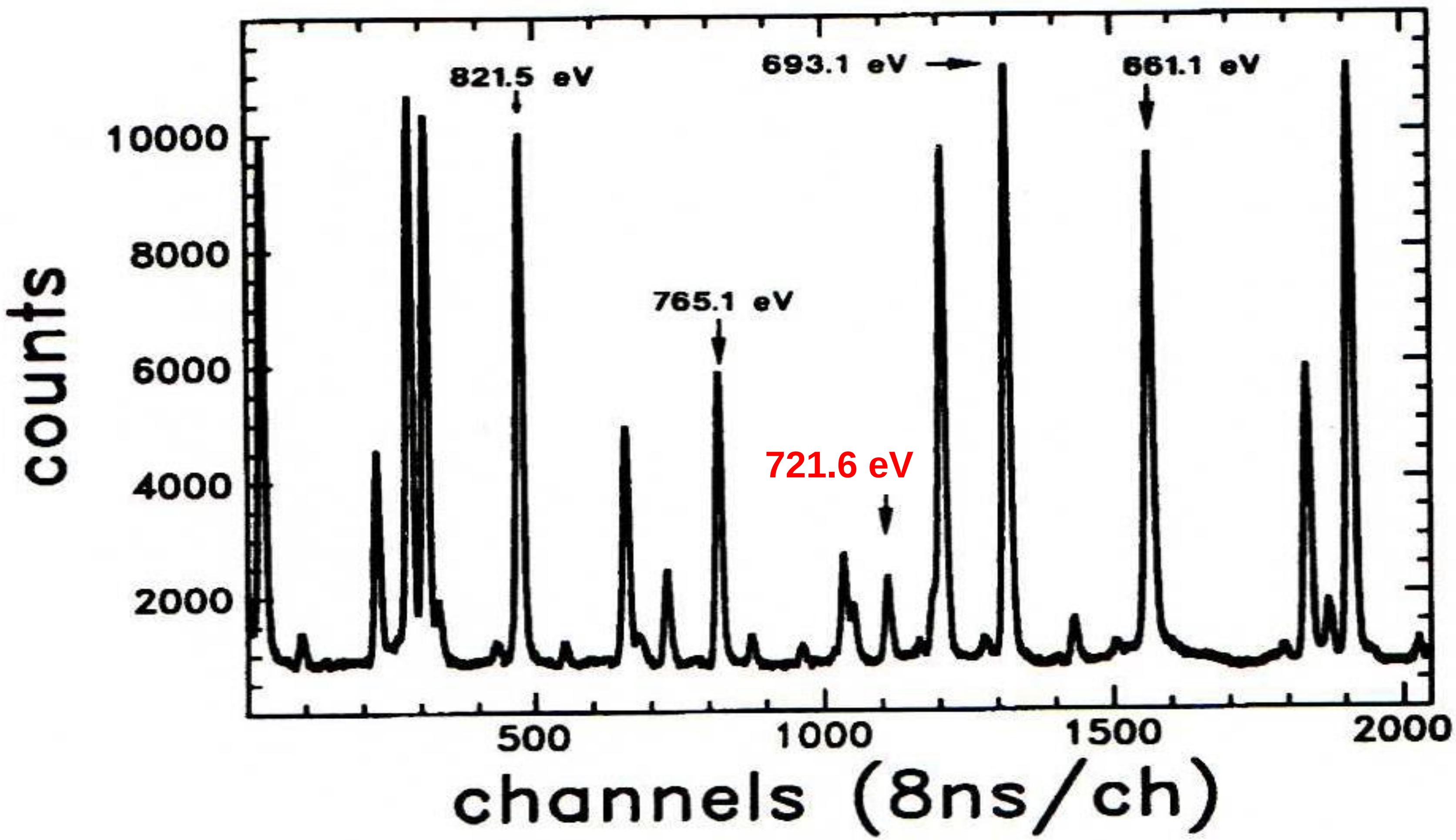
S. Oberstedt et al., Nucl. Phys. A573 (1994) 467



Experimental setup at the 30.1 m flight path of the GELINA

Search of the shape isomer in U-239 at IRMM (Geel)

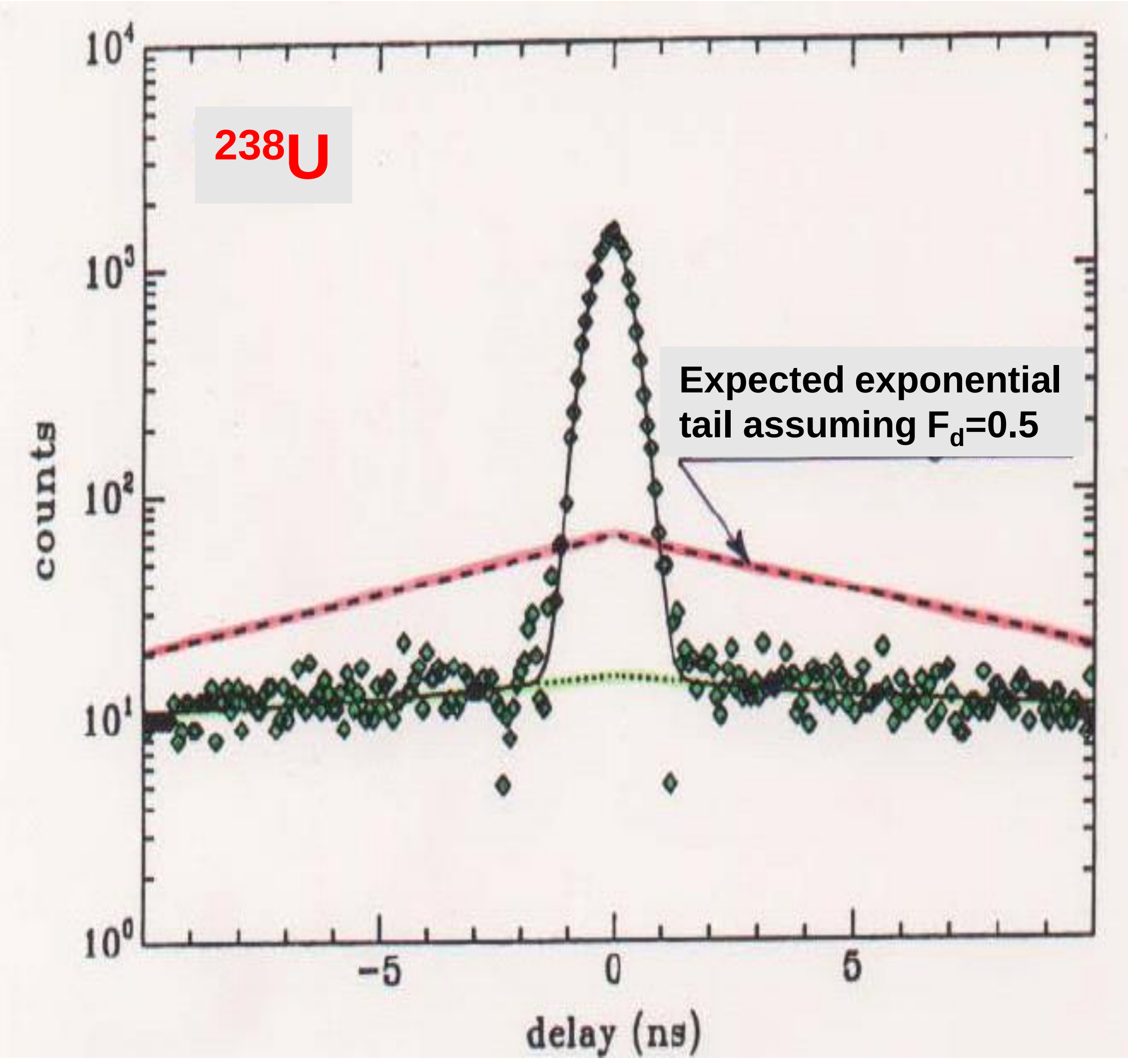
S. Oberstedt et al., Nucl. Phys. A573 (1994) 467



<u>Experimental neutron TOF spectrum</u>: for all resonances indicated by their energy the coincidence spectra were investigated

Search of the shape isomer in U-239 at IRMM (Geel)

S. Oberstedt et al., Nucl. Phys. A573 (1994) 467



The γ-γ coincidence spectrum for the 721.6 eV resonance was taken for all γ-ray energies greater that 160 keV.

Results: experimental decay can be fitted with parameters $T_{1/2}$ = 3.77 ± 0.61 ns and F_d = 0.039 ± 0.008, where F_d , the ratio between delayed and prompt coincidences, seems to be compatible with $F_{d,bad}$, the fraction of "bad" delayed coincidences (due to fission fragment isomeric decay)

Search of the shape isomer in U-239 at IRMM (Geel)

S. Oberstedt et al., Nucl. Phys. A573 (1994) 467

In a neutron capture experiment the shape isomer in ^{239}U was sought via delayed $\gamma\gamma$ – coincidences;

From the negative result it was concluded:

1) **isomeric half life is larger than 250 ns;**

2) **intermediate structure in the fission cross section of ^{238}U has to be interpreted as prompt fission (in contradiction to some theoretical expectations);**

3) **it could be assumed that the parametrization of the fission barrier of ^{238}U in terms of parabolic segments is not valid.**

γ-Decay towards the shape-isomeric ground state of ^{239}U

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[b] *Institute for Reference Materials and Measurements IRMM, Retieseweg, B-2440 Geel, Belgium*

Nuclear Physics A 589 (1995) 435--444

Evidence for low-energy γ-decay above the shape isomer in ^{239}U

S. Oberstedt [a], F. Gunsing [b]

[a] *Institute Laue-Langevin, Avenue des Martyrs, F-38042 Grenoble, France*

[b] *CEA Saclay, F-91191 Gif sur Yvette Cédex, France*

Nuclear Physics A 636 (1998) 129–138

Search of the shape isomer in U-239 at IRMM (Geel)

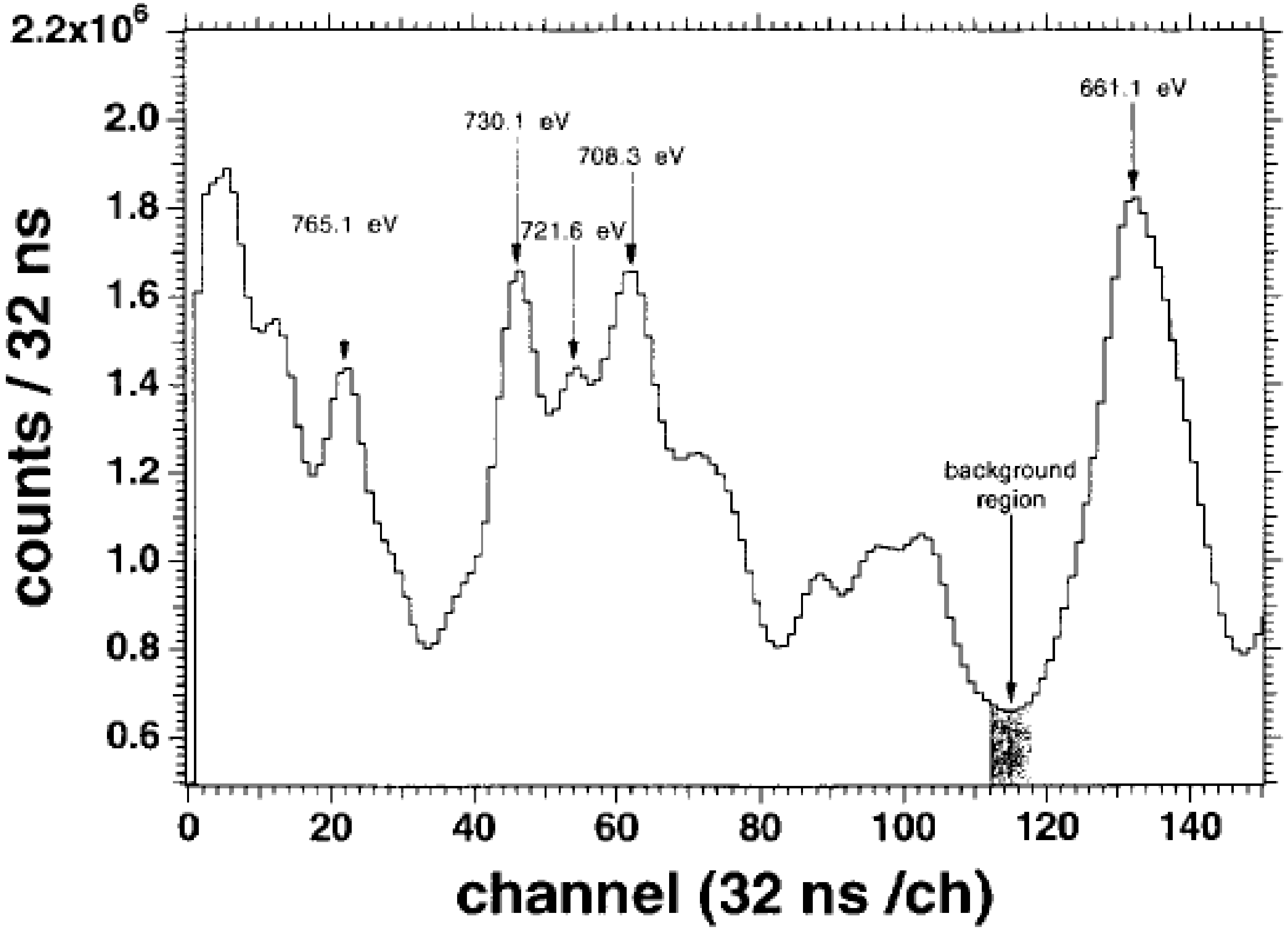
S. Oberstedt, F. Gunsing, Nucl. Phys. A589 (1995) 435, A636 (1998) 129

TOF: GELINA 140 MeV e^--Linac, Δt_n = 1ns, L = 12.85m

^{238}U- metal sample (9 ppm ^{235}U), 694 g, Ø111mm

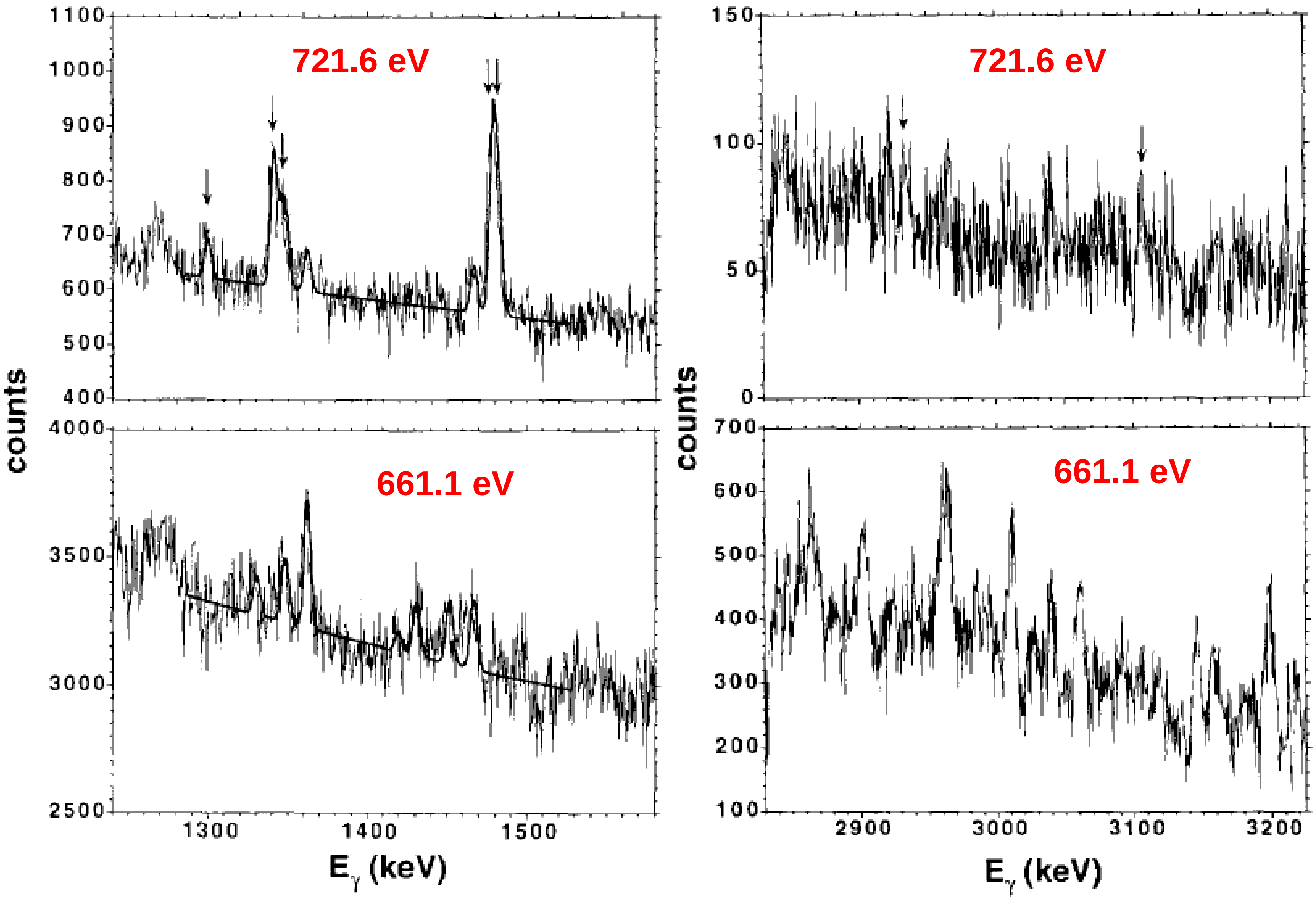
HPG-detector of capture gamma-rays

neutron energy range 600 – 800 eV



Search of the shape isomer in U-239 at IRMM (Geel)

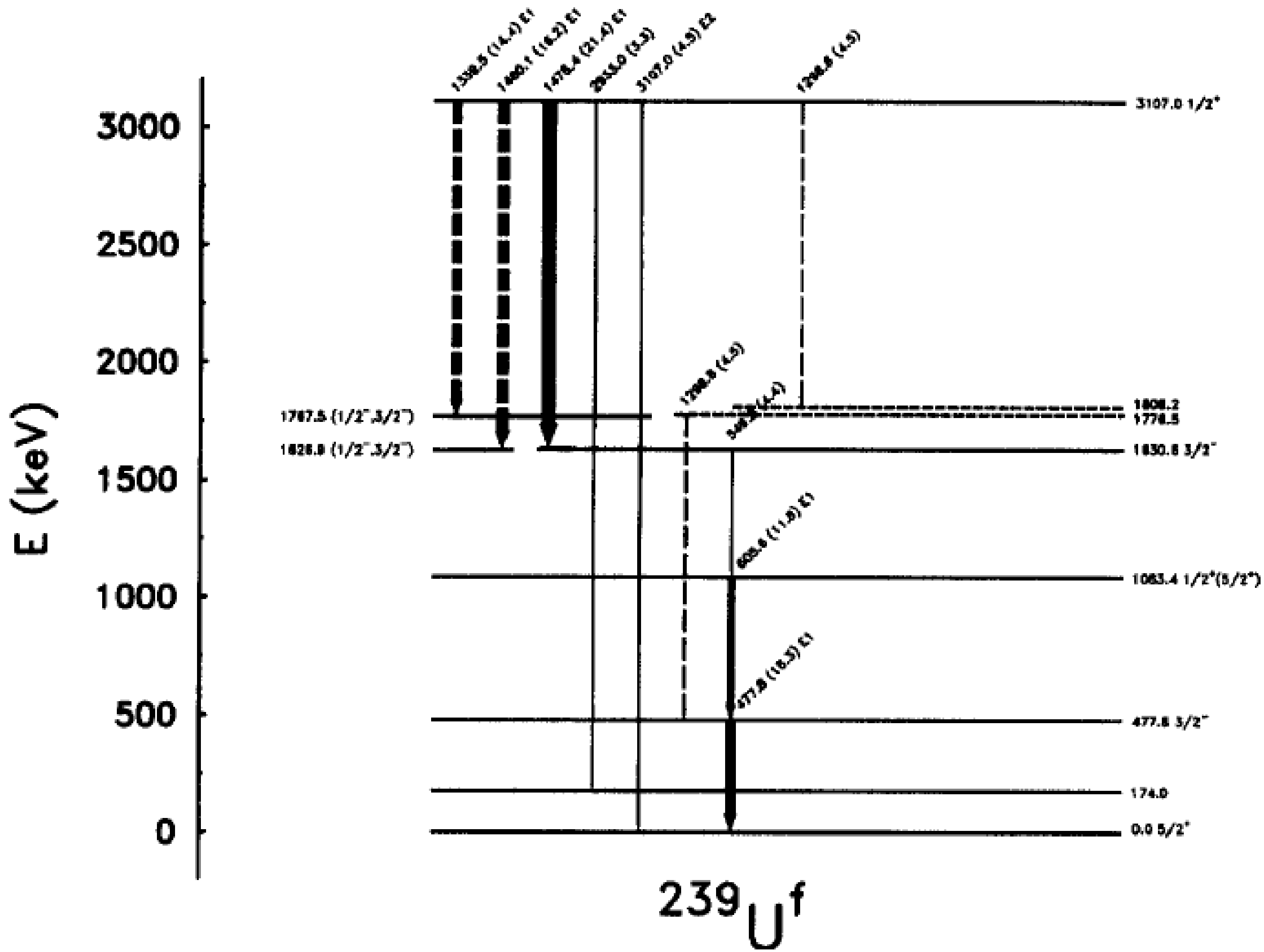
S. Oberstedt, F. Gunsing, Nucl. Phys. A589 (1995) 435, A636 (1998) 129



Measured gamma-ray spectra for 721.6 eV and 661.1 eV neutron resonances

Search of the shape isomer in U-239 at IRMM (Geel)

S. Oberstedt, F. Gunsing, Nucl. Phys. A589 (1995) 435, A636 (1998) 129



Proposed level scheme above the shape-isomeric ground state in ^{239}U.

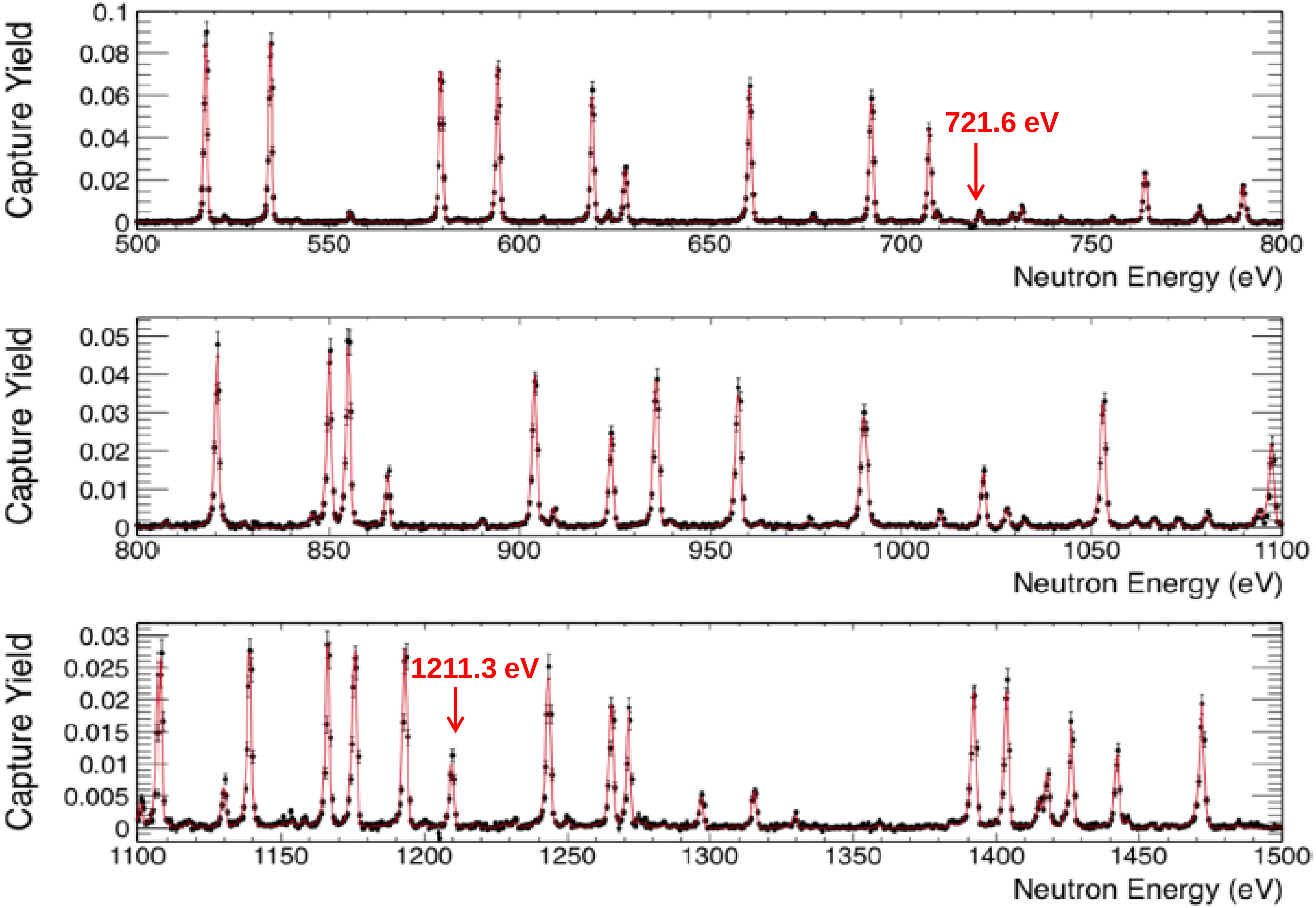
PHYSICAL REVIEW C 95, 034604 (2017)

Neutron capture cross section measurement of ^{238}U at the CERN n_TOF facility in the energy region from 1 eV to 700 keV

F. Mingrone,[1,2,3,*] C. Massimi,[2,3] G. Vannini,[2,3] N. Colonna,[4] F. Gunsing,[5] P. Žugec,[6] S. Altstadt,[7] J. Andrzejewski,[8] L. Audouin,[9] M. Barbagallo,[4] V. Bécares,[10] F. Bečvář,[11] F. Belloni,[5] E. Berthoumieux,[5,1] J. Billowes,[12] D. Bosnar,[6] M. Brugger,[1] M. Calviani,[1] F. Calviño,[13] D. Cano-Ott,[10] C. Carrapiço,[14] F. Cerutti,[1] E. Chiaveri,[1,12] M. Chin,[1] G. Cortés,[13] M. A. Cortés-Giraldo,[15] M. Diakaki,[16] C. Domingo-Pardo,[17] I. Duran,[18] R. Dressler,[19] C. Eleftheriadis,[20] A. Ferrari,[1] K. Fraval,[5] S. Ganesan,[21] A. R. García,[10] G. Giubrone,[17] I. F. Gonçalves,[14] E. González-Romero,[10] E. Griesmayer,[22] C. Guerrero,[1] A. Hernández-Prieto,[1,13] D. G. Jenkins,[23] E. Jericha,[22] Y. Kadi,[1] F. Käppeler,[24] D. Karadimos,[16] N. Kivel,[19] P. Koehler,[25] M. Kokkoris,[16] M. Krtička,[11] J. Kroll,[11] C. Lampoudis,[5] C. Langer,[7] E. Leal-Cidoncha,[18] C. Lederer,[26] H. Leeb,[22] L. S. Leong,[9] S. Lo Meo,[27,3] R. Losito,[1] A. Mallick,[21] A. Manousos,[20] J. Marganiec,[8] T. Martínez,[10] P. F. Mastinu,[28] M. Mastromarco,[4] E. Mendoza,[10] A. Mengoni,[27] P. M. Milazzo,[29] M. Mirea,[30] W. Mondalaers,[31] C. Paradela,[18] A. Pavlik,[26] J. Perkowski,[8] A. Plompen,[31] J. Praena,[15] J. M. Quesada,[15] T. Rauscher,[32] R. Reifarth,[7] A. Riego,[13] M. S. Robles,[18] C. Rubbia,[1,33] M. Sabaté-Gilarte,[15] R. Sarmento,[14] A. Saxena,[21] P. Schillebeeckx,[31] S. Schmidt,[7] D. Schumann,[19] G. Tagliente,[4] J. L. Tain,[17] D. Tarrío,[18] L. Tassan-Got,[9] A. Tsinganis,[1] S. Valenta,[11] V. Variale,[4] P. Vaz,[14] A. Ventura,[3] M. J. Vermeulen,[23] V. Vlachoudis,[1] R. Vlastou,[16] A. Wallner,[26] T. Ware,[12] M. Weigand,[7] C. Weiß,[22] and T. Wright[12]
(n_TOF Collaboration)
[1]*European Organization for Nuclear Research (CERN), Geneva, Switzerland*

n_TOF: 20 GeV proton synchrotron , ~2·10^{15} n/pulse, Δt_n = 10ns, L = 182.3m
^{238}U- metal sample (1 ppm ^{234}U ,11 ppm ^{235}U, 1 ppm ^{236}U), 6.125 g
2 C_6D_6- liquid scintillator detectors of capture gamma-rays
FLASH-ADCs, pulse-weighting technique

Experimental capture yield for $^{238}U(n,\gamma)$ and SAMMY code fit
F. Mingrone et al., Phys. Rev. C 95, 034604 (2017)



Experimental capture yield for $^{238}U(n,\gamma)$ and SAMMY code fit
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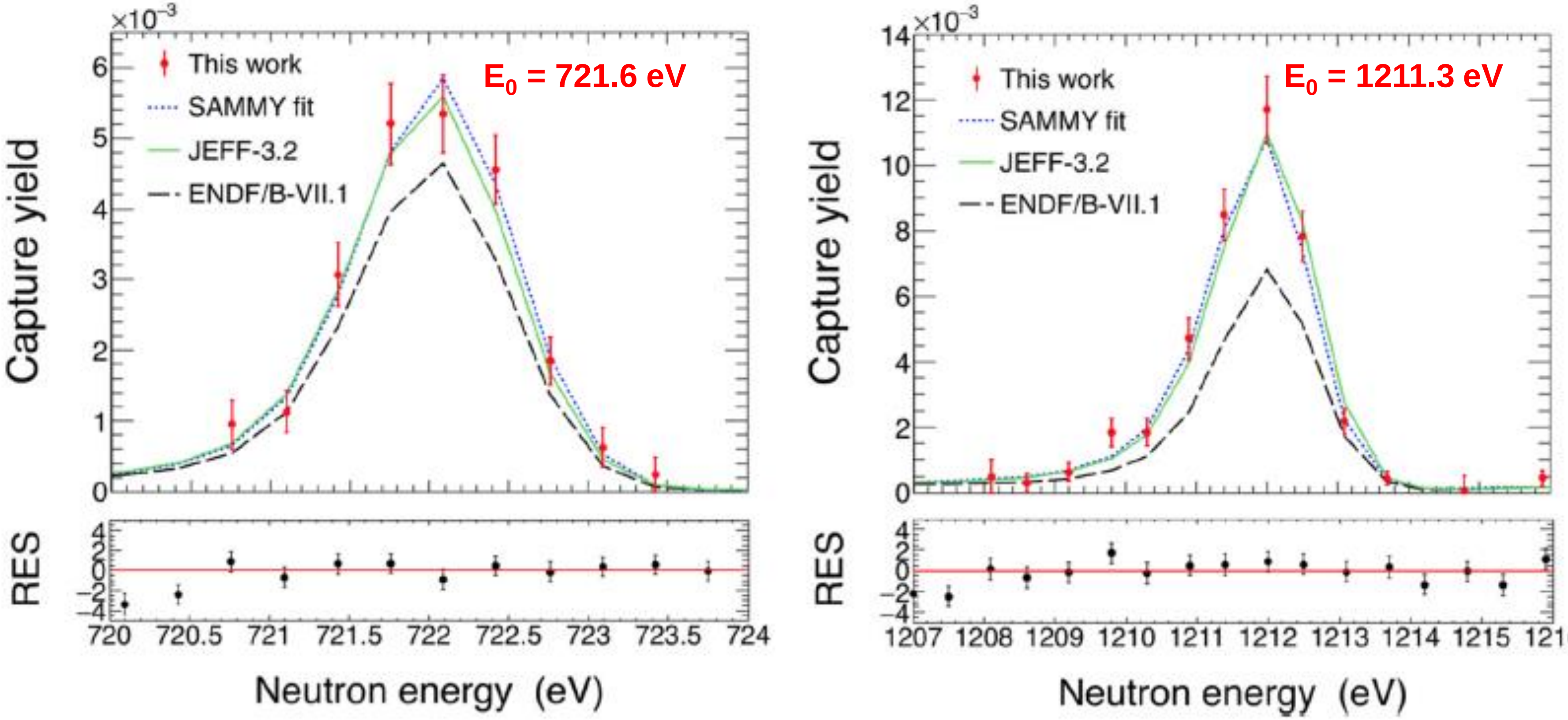

Resonance kernel (capture area) = $g\Gamma_n\Gamma_\gamma/(\Gamma_n + \Gamma_\gamma + \Gamma_f)$, meV

Resonance	This work	ENDF/B-VII.1	JEFF-3.2
721.68 eV	1.45 ± 0.09	1.12 (Γ_γ = 3.15 meV Γ_n = 1.965 meV	1.36 (Γ_γ = 23 meV Γ_n = 1.475 meV)
1211.32 eV	6.5 ± 4	4.01(Γ_γ = 6.6 meV Γ_n = 10.57 meV)	6.54 (Γ_γ =17.56 meV Γ_n = 10.57 meV)

EVALUATED DATA LIBRARIES

"Old" evaluations

Resonance **721.68 eV**

Capture width Γ_γ (meV)

4.7	ENDF/B-VI, USA (2001)
4.7	JENDL-3.3, Japan (2002)
23.0	JEFF-3.1, Europe (2005)
3.15	ENDF/B-VII, USA (2006)
3.15	ROSFOND, Russia (2008)

Evaluations currently in use (http://www.nndc.bnl.gov)

J(L)	Γ_γ (meV)	Γ_n (meV)	Γ_f (meV)	Library
0.5(0)	3.15	1.965	0.411	ENDF/B-VII.1, USA (2011)
0.5(0)	3.15	1.965	0.411	JENDL-4.0, Japan (2016)
0.5(0)	3.15	1.965	0.411	ROSFOND, Russia (2010)
0.5(0)	23.0	1.475	0.411	JEFF-3.2, Europe (2014)
0.5(0)	4.7	1.794	0.411	CENDL-3.1, China (2009)
0.5(1)	22.5	1.494	1.854	ENDF/B-VIII.b4, IAEA (2017)

EVALUATED DATA LIBRARIES

"Old" evaluations

Resonance **1211.32 eV**

Capture width Γ_γ (meV)

14.13	ENDF/B-VI, USA (2001)
14.13	JENDL-3.3, Japan (2002)
17.56	JEFF-3.1, Europe (2005)
6.6	ENDF/B-VII, USA (2006)
6.6	ROSFOND, Russia (2008)

Evaluations currently in use (http://www.nndc.bnl.gov)

J(L)	Γ_γ (meV)	Γ_n (meV)	Γ_f (meV)	Library
0.5(0)	6.6	10.569	0.236	ENDF/B-VII.1, USA (2011)
0.5(0)	6.6	10.569	0.236	JENDL-4.0, Japan (2016)
0.5(0)	6.6	10.569	0.236	ROSFOND, Russia (2010)
0.5(0)	17.56	10.569	0.236	JEFF-3.2, Europe (2014)
0.5(0)	14.13	10.569	0.236	CENDL-3.1, China (2009)
0.5(0)	19.9	10.512	0.301	ENDF/B-VIII.b4, USA(2017)

Instead of conclusion.

WHAT SHOULD WE DO?

WHAT SHOULD WE DO?

WHAT SHOULD WE DO?


We have to continue high-quality experimental data production!


We have to generate new theoretical ideas!
Let the best win!
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