Experimental study of the (n_{res}, γ) reaction on the ^{175}Lu

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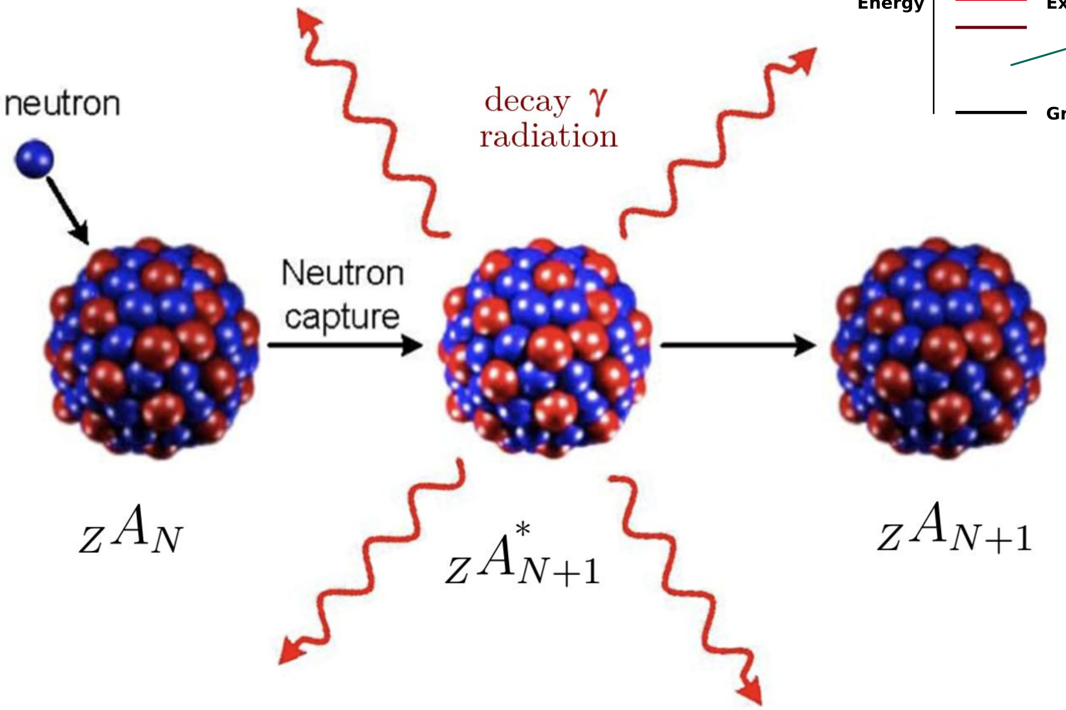
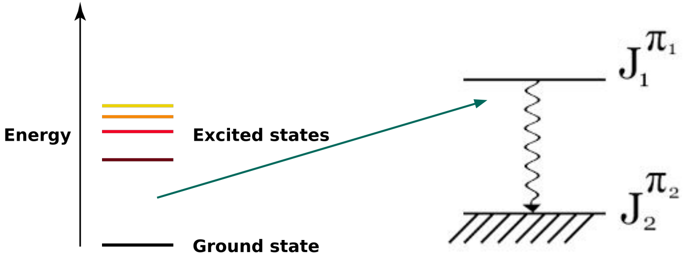
Outline

1. Introduction
2. Experimental setup (CSNS, Back-n)
3. Method: TOF + gamma-spectroscopy
4. Results:
   - Resonance identification - TOF spectrum
   - Primary gamma transitions - resonance spectra
   - Spin determination - the marker state method
   - Results on K-mixing
5. Conclusions and future plans

Radiative neutron capture





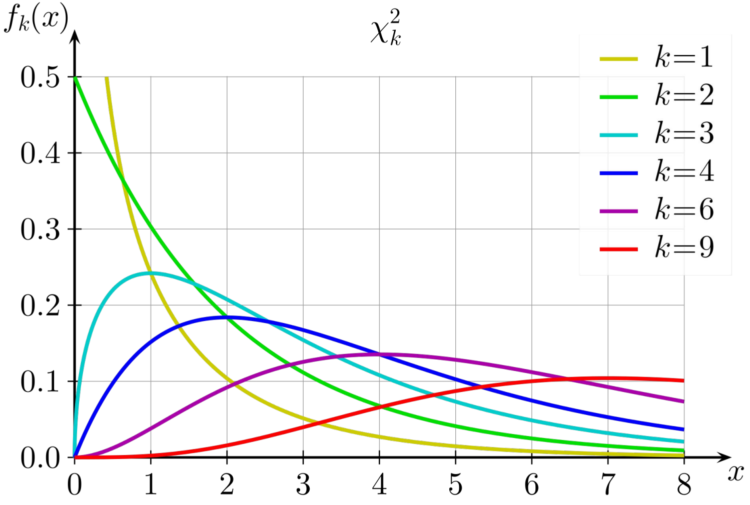
Each gamma-ray transition from an excited nuclear state is characterized by a partial radiative width $\Gamma_{\lambda j}^{(\gamma)}$. This width indicates the relative probability (or 'how easy' it is) for a nucleus in that state to emit a gamma-ray quantum of a specific energy via that transition.

A question arises in statistical nuclear physics: how are these widths distributed for different resonances λ and different final states j?

Porter and Thomas's idea (1956):

the nuclear transition amplitude $A \sim \mathcal{N}(0, \sigma^2)$ - *a random Gaussian variable;*

the partial width - $\Gamma \propto A^2.$



$$P(\Gamma) = \frac{1}{\langle\Gamma\rangle} \exp\left(-\frac{\Gamma}{\langle\Gamma\rangle}\right)$$

Deformed nucleus ^{176}Lu

Previous data – work by Wasson & Chrien

PHYSICAL REVIEW C VOLUME 2, NUMBER 2 AUGUST 1970

Resonant Neutron Capture in ^{175}Lu†

O. A. Wasson and R. E. Chrien
Brookhaven National Laboratory, Upton, New York 11917
(Received 27 March 1970)

They analyzed 11 neutron resonances of ^{175}Lu in the range up to 40 eV, determined spins, measured primary gamma transition intensities, and discovered an anomaly: the partial width distribution does not follow a χ^2 distribution with one degree of freedom (ν = 1), yielding $\nu \approx 1.6$ instead.

Czech. J. Phys. B 28 [1978]

STATISTICAL PROPERTIES OF SECONDARY γ-TRANSITIONS IN THE ^{175,176}Lu(n_{res}, γ) ^{176,177}Lu REACTIONS

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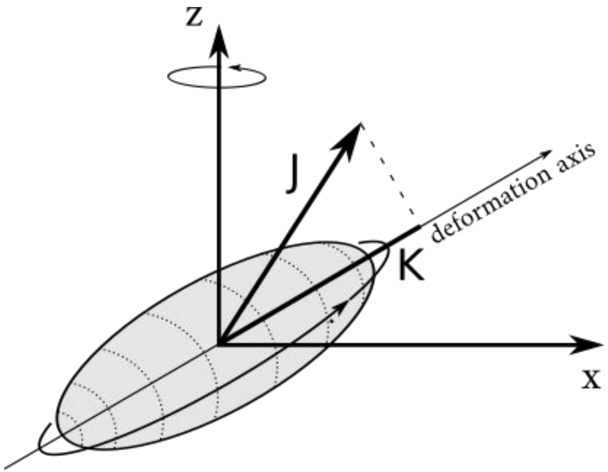
The data from Wasson & Chrien were refined in a series of measurements at the IBR-30 pulsed reactor in Dubna, both with respect to partial gamma widths and the analysis of possible non-statistical properties of the wave functions of neutron resonances.

Non-statistical effects: K-mixing



The selection rule for dipole transitions in deformed nuclei is $|\Delta K| \leq 1$ (assuming K is conserved).

$|K_{init} - K_{fin}| \geq 2$ is prohibited

Therefore, if a transition with $|\Delta K| > 1$ is observed, it indicates the presence of K-mixing.

K-mixing introduces correlations between partial widths, which manifest as an effective number of degrees of freedom $\nu > 1$ in the distribution of widths.

The main objectives of this work were:

— to obtain new experimental data on the energy and spin of neutron resonances of ^{175}Lu in the range up to 100 eV;

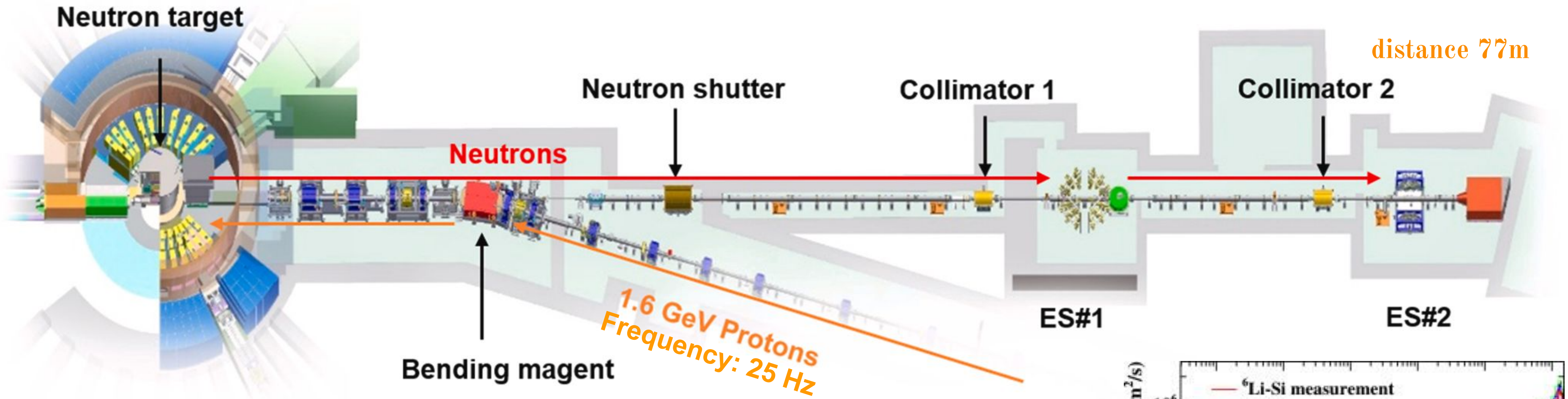
— measure the intensities of high-energy primary gamma transitions (E_γ > 5 MeV);

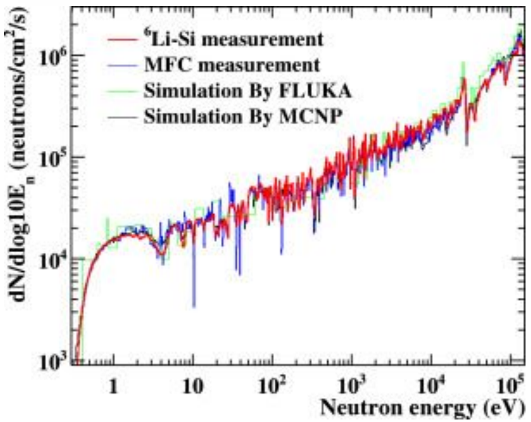
— compare the obtained results with the data of Wasson and Chrien to verify consistency and assess the feasibility of expanding the measurement statistics;

— create an experimental basis for future detailed analysis of the radiative strength function and the study of possible deviations from statistical behavior, including the search for correlations between partial radiative widths and neutron widths;

— study mixing effects in the wave functions of isolated excited states based on the projections of their total angular momentum J onto the deformation axis, using ^{176}Lu as an example.

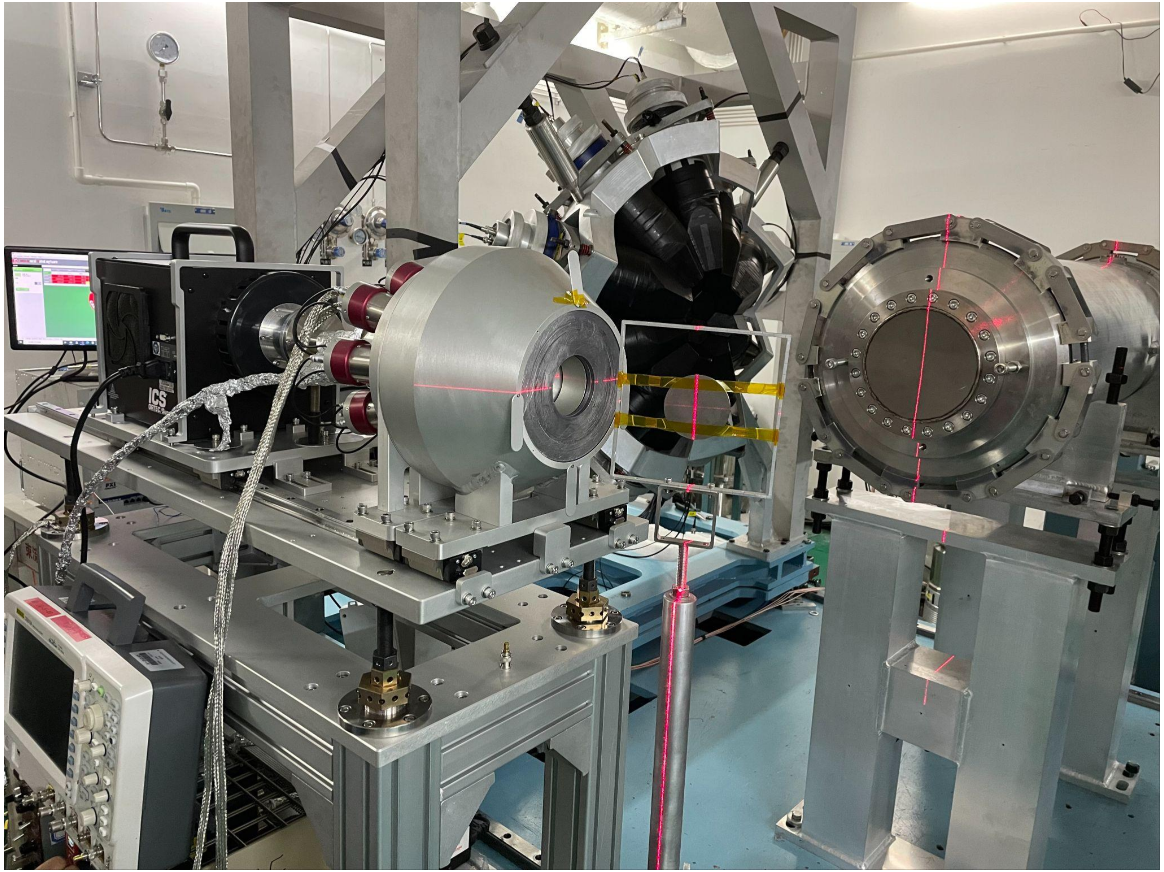
Experimental setup - CSNS Back-n

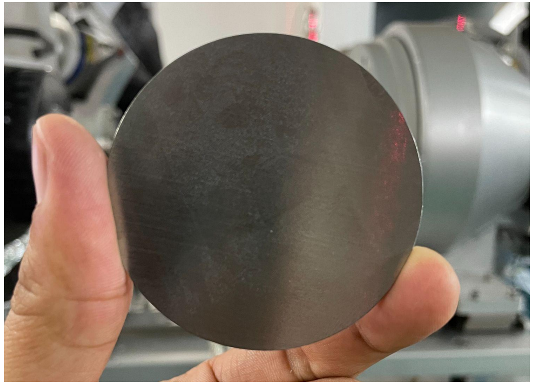




Neutron flux: 10^4 neutrons/cm²/s
(in the resonance region)

Detector system and sample





Naturally occurring metallic lutetium

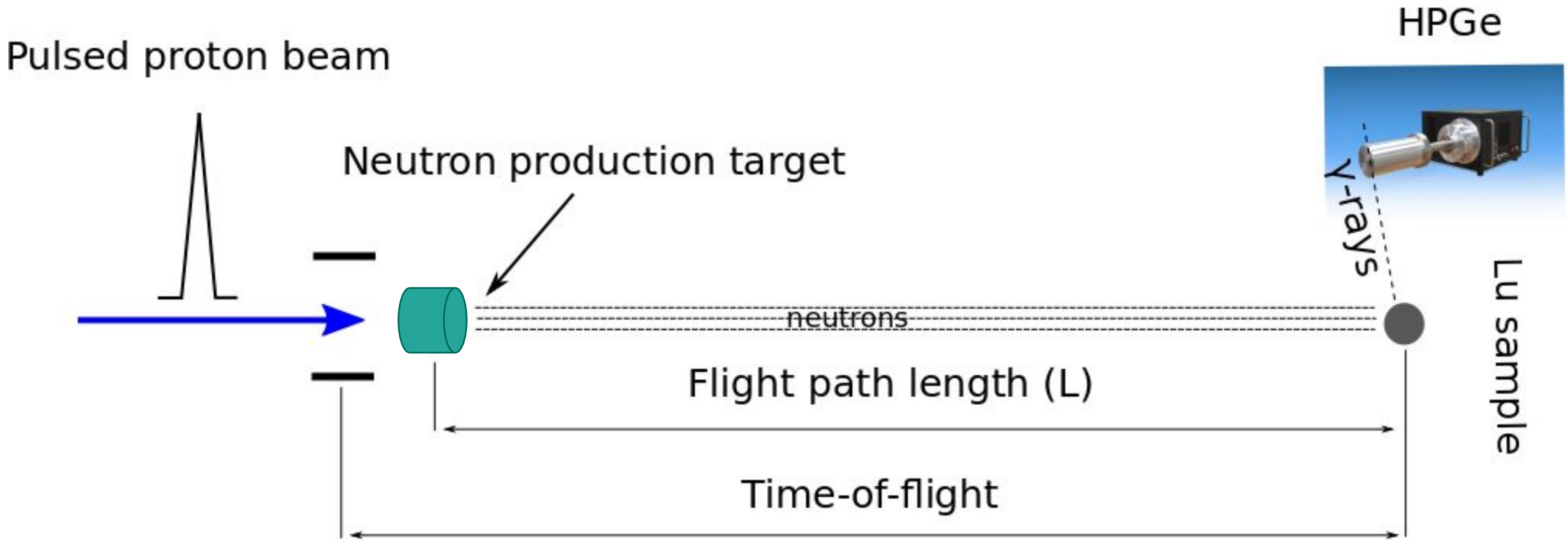
Sample parameters:
diameter – 60 mm,
thickness – 2.2 mm,
weight – 61.2 mg.

HPGe detector

Calibration with sources: ^{22}Na, ^{60}Co, ^{137}Cs, ^{152}Eu, NaCl

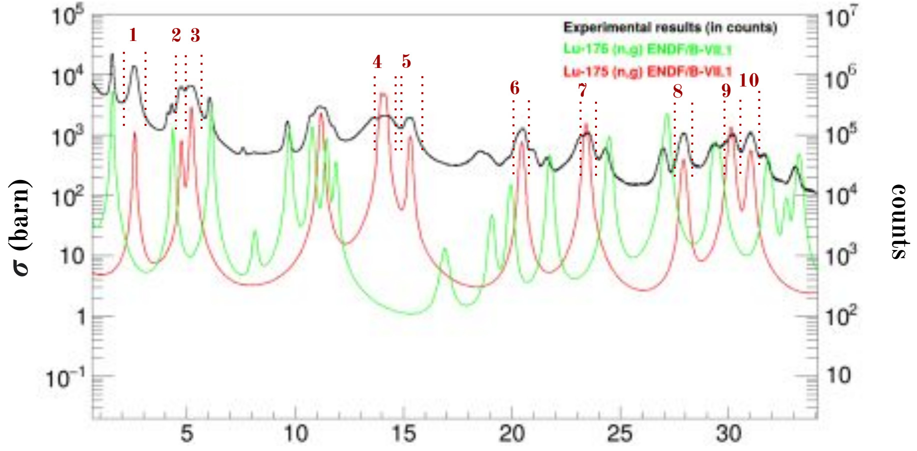
Resolution: 3.5 keV at 1173 keV

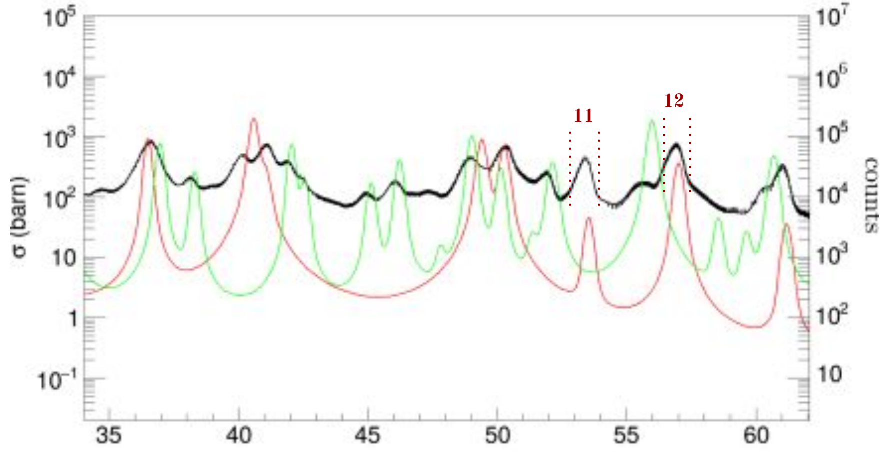
Method: time-of-flight γ-spectroscopy

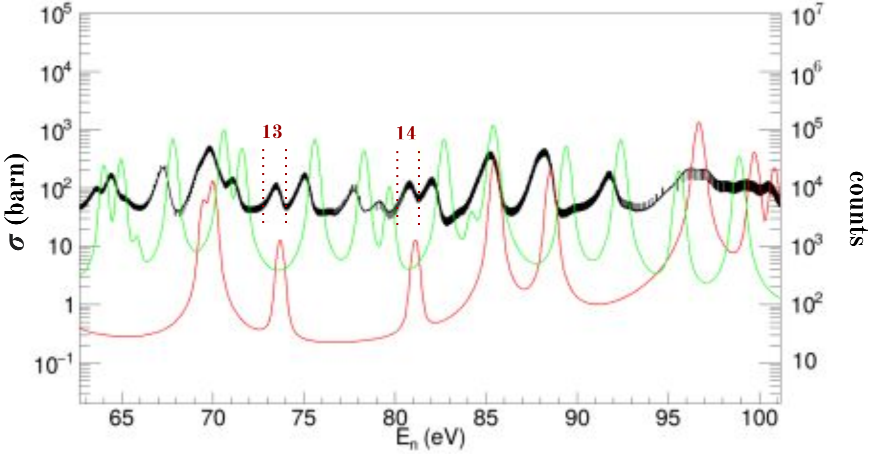


$$E_n = \left(\frac{72.3 \cdot L}{t_{\text{ToF}}}\right)^2$$

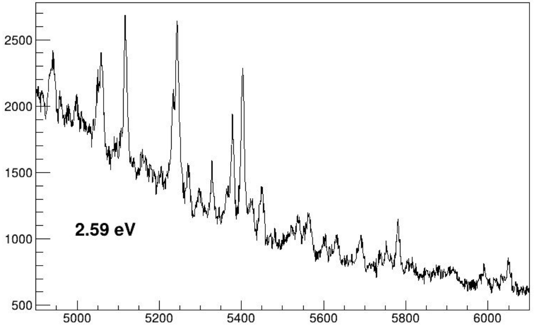
Resonance identification - ToF spectrum

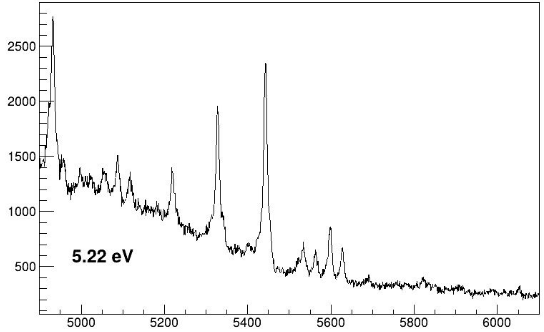


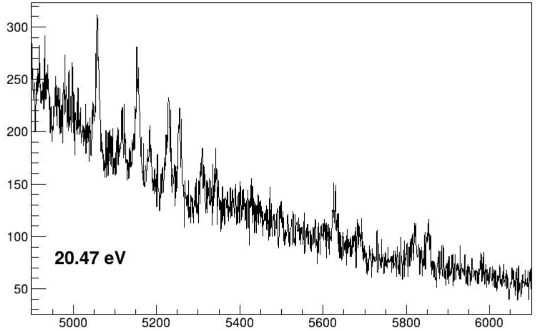


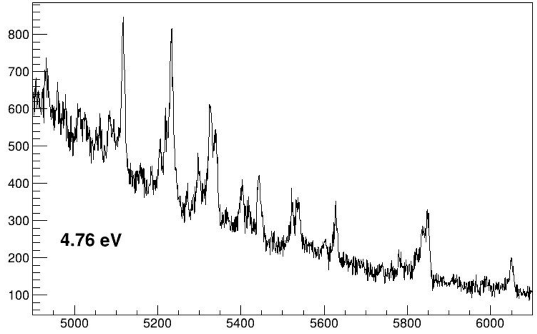


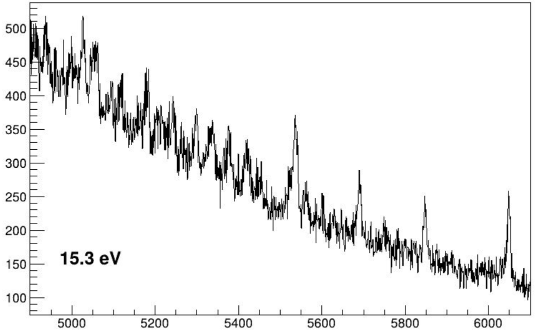
Primary γ-transitions - resonance spectra

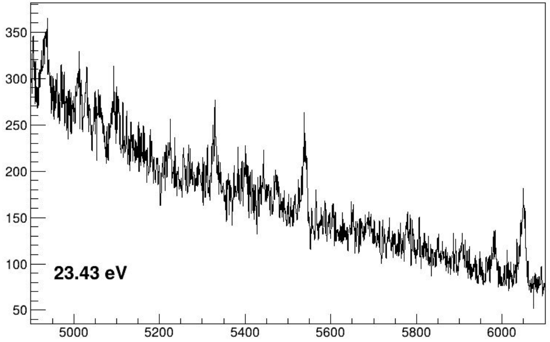




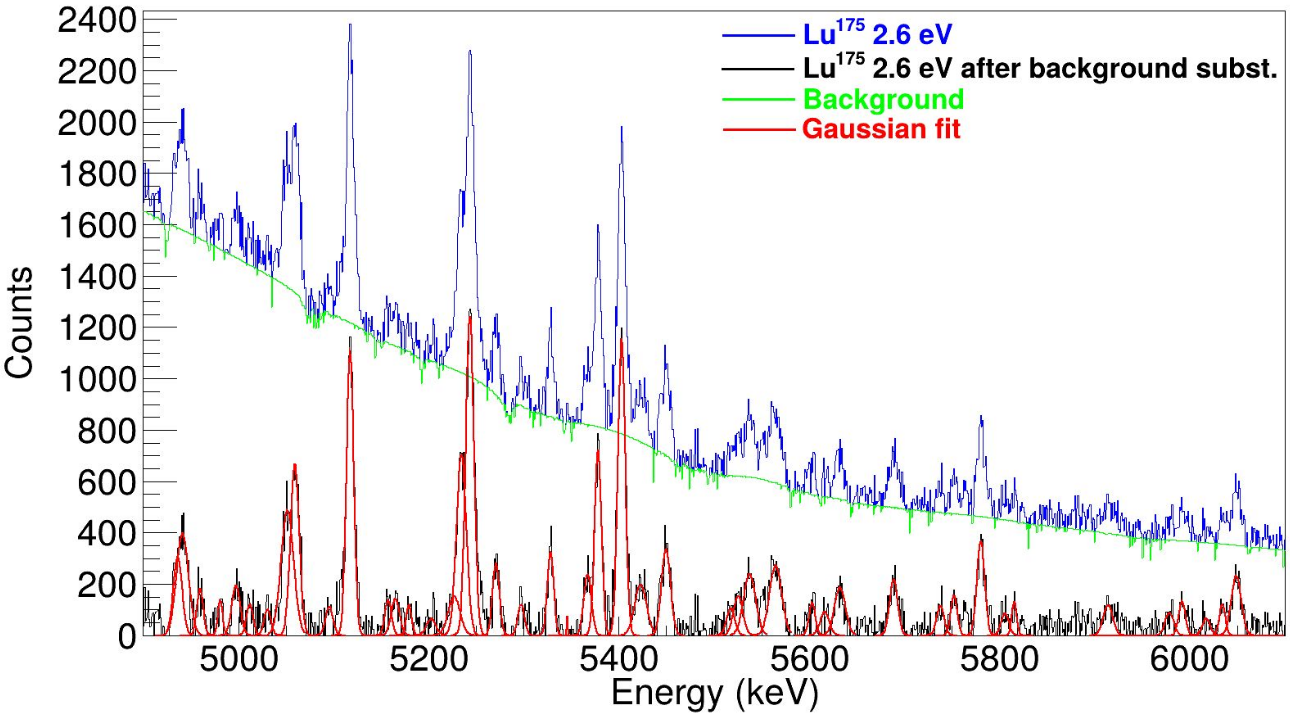








Primary γ-transitions - resonance spectra



Final-state excitation energy:

$E_x = B_n - E_\gamma$, *with* $B_n \approx 6293$ *keV.*

Intensities of primary gamma transitions

E_γ (keV)	I_j^{abs}(Wasson and Chrien)		I_j^{rel}(Our data)		I_j^{norm} (Normalized to Wasson)	
	4.76 eV	14.0 eV	4.76 eV	14.0 eV	4.76 eV	14.0 eV
6053.8	7.8(1.3)	6.5(1.0)	3.07(0.13)	2.34(0.05)	9.24(0.56)	8.82(0.83)
5984.8	1.6(0.8)	9.2(0.8)	-	2.41(0.12)	-	9.09(0.91)
5856.3	-	5.5(0.7)	-	1.63(0.06)	-	6.15(0.58)
5852.0	19.6(1.6)	-	6.15(0.21)	-	18.51(0.93)	-
5840.6	13.0(1.2)	1.3(0.8)	4.09(0.3)	-	12.31(1.0)	-
5825.1	4.3(0.6)	1.0(0.8)	2.4(0.15)	-	7.22(0.51)	-
5784.2	3.7(1.2)	9.1(1.0)	2.2(0.09)	1.4(0.08)	6.62(0.36)	5.28(0.51)
5693.3	-0.2(1.0)	6.4(0.9)	-	1.76(0.04)	-	6.64(0.62)
5631.2	12.4(1.2)	5.1(0.8)	3.75(0.17)	-	11.29(0.69)	-
5601.4	2.8(1.2)	10.8(1.0)	0.96(0.08)	3.38(0.16)	2.89(0.26)	12.74(1.22)
5574.3	0.5(1.0)	5.5(1.0)	-	0.73(0.07)	-	2.75(0.28)
5537.3	4.5(1.6)	2.2(0.8)	2.85(0.27)	-	8.58(0.9)	-
5525.7	8.4(2.0)	4.5(0.9)	3.1(0.23)	1.05(0.11)	9.33(0.85)	3.96(0.43)
5456.2	1.2(1.0)	9.0(0.9)	-	1.7(0.2)	-	6.41(0.79)
5446.1	8.5(1.0)	7.8(0.8)	3.12(0.24)	1.6(0.11)	9.39(0.85)	6.03(0.6)
5429.3	2.8(1.2)	8.0(1.2)	-	1.76(0.07)	-	6.64(0.63)
5420.2	4.9(1.3)	4.0(1.2)	1.6(0.15)	-	4.82(0.51)	-
5405.7	13.6(0.8)	-0.2(1.0)	4.11(0.18)	-	12.37(0.74)	-
5367.8	3.4(1.2)	1.6(0.8)	1.12(0.1)	-	3.37(0.34)	-

Determination of spins of neutron resonances — the marker state method

- $E_x = 308.4$ keV, $J_f = 2$ ($\gamma = 5984.8$ keV)
- $E_x = 436.9$ keV, $J_f = 2$ ($\gamma = 5856.3$ keV)
- $E_x = 441.2$ keV, $J_f = 5$ ($\gamma = 5852.0$ keV)
- $E_x = 992.0$ keV, $J_f = 5$ ($\gamma = 5301.2$ keV)

Selection rule for dipole transitions: $|J_{res} - J_f| \leqslant 1$.

Consequently:

— If a transition to $J_f = 2$ is observed, J_{res} cannot be 4 (since $|4-2| = 2 > 1$).

— If a transition to $J_f = 5$ is observed, J_{res} cannot be 3 (since $|3-5| = 2 > 1$).

Results - spins of 10 resonances

Resonance energy E_{res}(eV)	Marker lines E_γ(keV)				Final spin J_{res}
	5984.8	5856.3	5852.0	5301.2	
4.76	no	no	yes	yes	4
5.22	no	yes	no	no	3
14.0	no	yes	no	no	3
15.3	no	no	yes	yes	4
20.47	no	yes	no	no	3
23.43	yes	yes	no	no	3
31.0	no	yes	no	no	3
53.61	no	no	yes	yes	4
57.0	yes	yes	no	no	3
73.6	yes	yes	no	no	3

K-mixing

$^{176}_{71}Lu_{105}$–1 NUCLEAR DATA SHEETS $^{176}_{71}Lu_{105}$–1

Adopted Levels, Gammas

$Q(\beta^-)$=1190.2 *8*; S(n)=6287.98 *15*; S(p)=5975.7 *13*; $Q(\alpha)$=1568 *6* 2003Au03.

^{176}Lu Levels

Cross Reference (XREF) Flags

A ^{175}Lu(n,γ) E=thermal
B ^{175}Lu(n,γ) E=2,24 keV Res: Av
C ^{175}Lu(n,γ) E=res
D ^{176}Yb(p,nγ)
E Coulomb Excitation
F ^{175}Lu(d,p)
G ^{177}Hf(t,α)
H ^{176}Lu(d,d')
I ^{176}Yb(^{7}Li,Xγ)

E(level)†	Jπ‡	XREF	$T_{1/2}$§	Comments
0.0@	7−	A DE GHI	3.76×10^{10} y *7*	Jπ: J=7, atomic beam (1962Sp03); π=−, L=4 in (t,α). %β^-=100. No ε (<0.36% (2004No09). Other value: <0.9% (2005Am04) and <10%

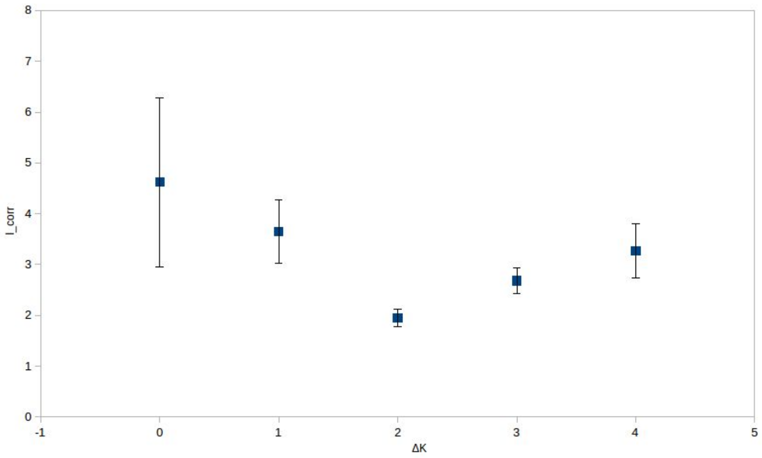
E_x and K_f were determined

⇩

For each line, $\Delta K = |K_f - K_{res}|$ was calculated.

⇩

Transitions were grouped by ΔK. The average intensity ⟨I⟩ for the group was calculated.



Conclusion and future plans

What we have done:

- Measured 14 neutron resonances of ^{175}Lu up to 81 eV;
- Determined spins for 10 of them;
- Measured primary gamma intensities for all;
- First indications of K-mixing: transitions with $\Delta K > 1$ observed above the statistical noise

Future plans:

- Build the radiative strength function.
- Compare with theoretical models of K-mixing in deformed nuclei.

Thank you for your attention!