Application of Oslo Method on Heavy Nd Isotopes

Kursad Osman Ay

6th workshop on Level Density and Gamma Strength,
8-12th May 2017, Oslo.

Department of Physics, Eskisehir Osmangazi University, 26480 Eskisehir, Turkey
(kursadosmanay@gmail.com)

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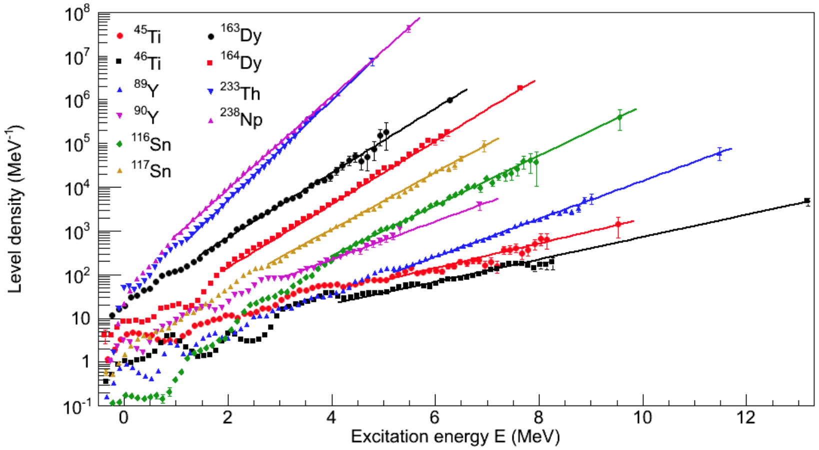
A. Schiller et al., Nucl. Instrum. Methods in Phys. Res. A 447, 494 (2000)

Nuclear Level Densities

- The number of quantum energy levels accessible at a specific excitation energy, within a given energy bin.
- Some examples of level densities calculated by the Oslo Method[1]:
- More data can be found at:
- http://www.mn.uio.no/fysikk/english/research/about/infrastructure/OCL/nuclear-physics-research/compilation/



Application Areas

- Reactor Physics (design, transmutation of wastes).
- Important inputs in statistical Hauser-Feshbach reaction-rate calculations.
- Calculations for heavy ion collisions.
- Important ingredients for statistical models of the nuclear reactions.

[1] M. Guttormsen et al., The European Physical Journal A, 51:170, (2015).

The Oslo Method

- The Oslo Cyclotron Group has developed a method to extract the Nuclear Level Density and Gamma Strength Function simultaneously[2,3]. The main steps are:

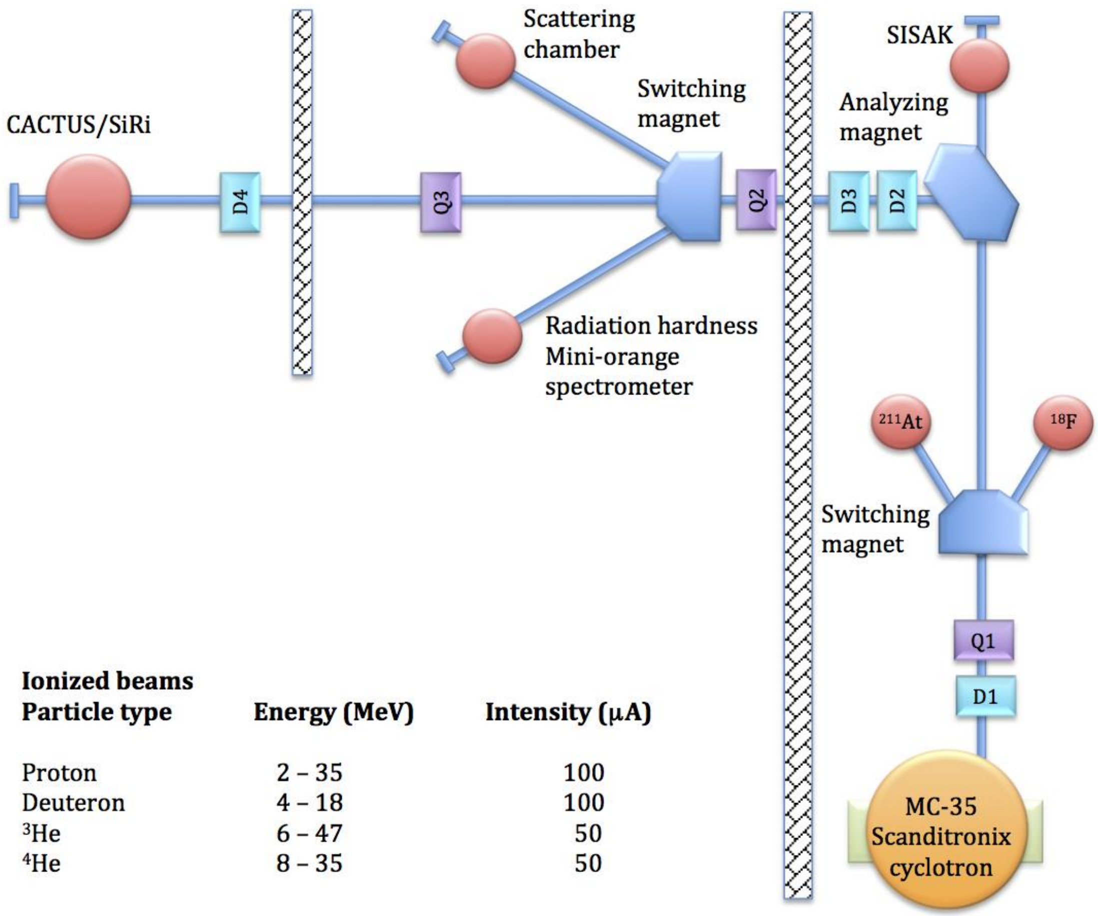
1- Measuring particle-g coincidences.
2- Unfolding γ spectra at each E.
3- Extraction of first-generation matrix.
4- Ansatz: First-generation matrix.

$$P\left(E_i, E_\gamma\right) \propto \rho\left(E_f\right) \mathcal{T}(E_\gamma)$$

5- Obtain level density, transmission coeffient and thus gama strength function.

[2] A. Schiller et al., *Nucl. Instrum. Methods in Phys. Res. A* 447, 494 (2000)
[3] A.C. Larsen et al., *Phys. Rev. C* 83, 034315 (2011)

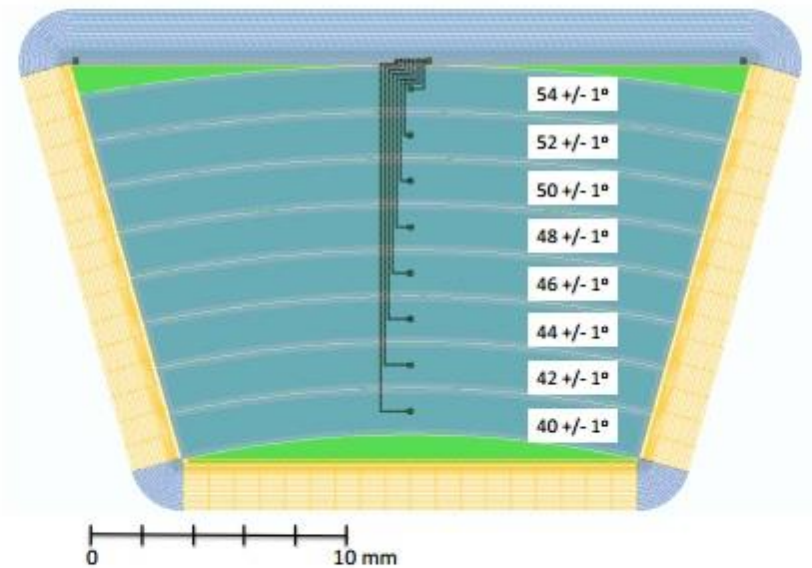
Oslo Cyclotron Laboratory (OCL)

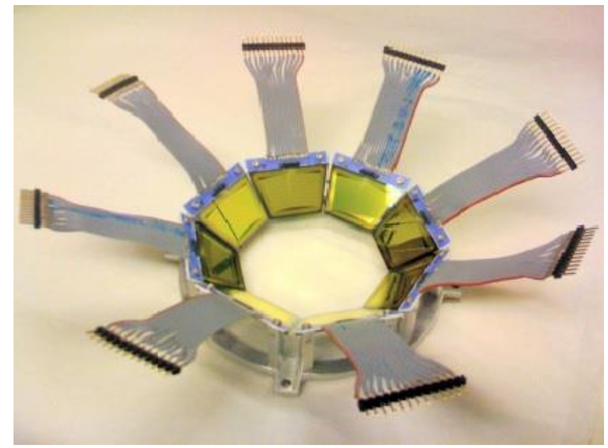


Ionized beams

Particle type	**Energy (MeV)**	**Intensity (μA)**
Proton	2 – 35	100
Deuteron	4 – 18	100
^{3}He	6 – 47	50
^{4}He	8 – 35	50

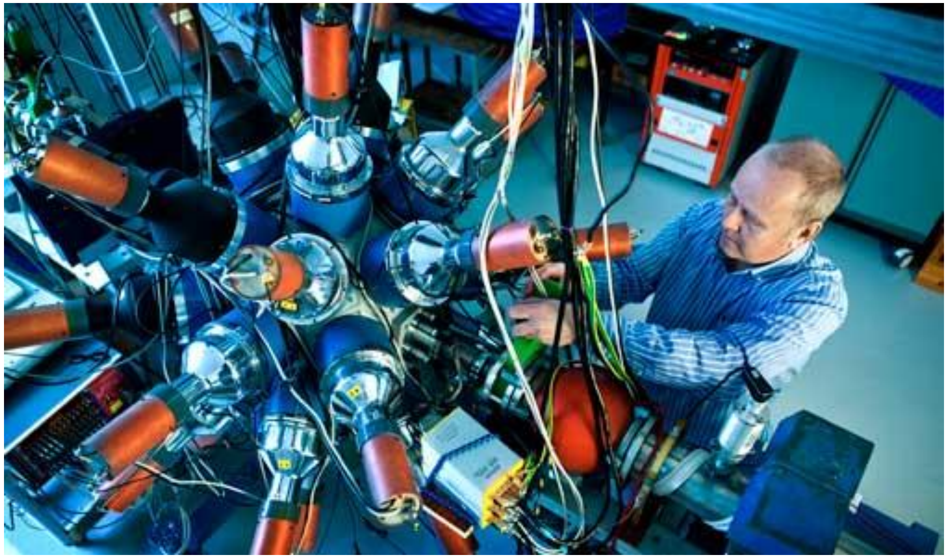
The SIRI Particle Detector System

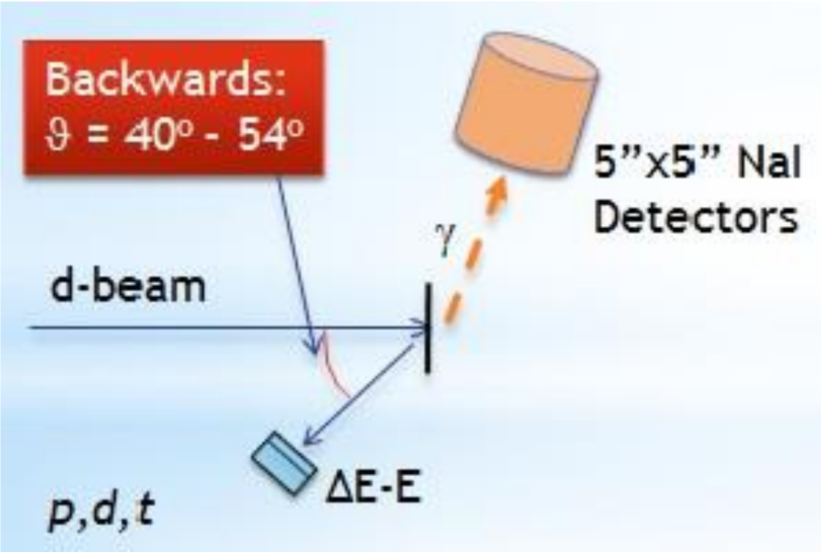




- The layout of one silicon chip with its eight ΔE detectors for different reaction angles.
- The whole detector including cables to read out the signal. A total of 8x8=64 particle detectors.

CACTUS Array and the Experiment



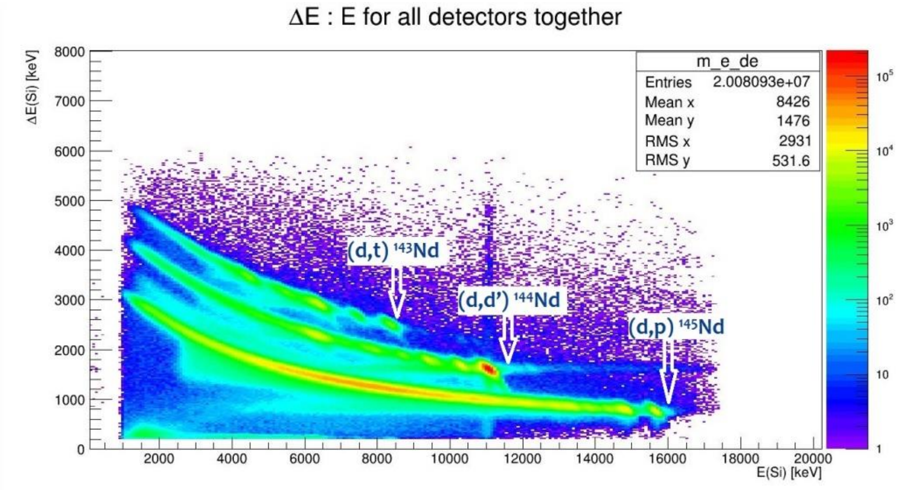


- 13.5 MeV d-beam was sent on ^{144,148,150}Nd targets.

Reactions Obtained

Target	Physical Properties	Reactions
^{144}Nd	(97% enrichment and 2 mg/cm^2 thickness)	**^{144}Nd(d,p)^{145}Nd** ^{144}Nd(d,d')^{144}Nd ^{144}Nd(d,t)^{143}Nd (Insufficient Data)
^{148}Nd	(95% enrichment and 1.9 mg/cm^2 thickness)	**^{148}Nd(d,p)^{149}Nd** ^{148}Nd(d,d')^{148}Nd ^{148}Nd(d,t)^{147}Nd (Insufficient Data)
^{150}Nd	(97% enrichment and 1.9 mg/cm^2 thickness)	**^{150}Nd(d,p)^{151}Nd** ^{150}Nd(d,d')^{150}Nd ^{150}Nd(d,t)^{149}Nd (Insufficient Data)

ΔE-E Bananas for ^{144}Nd



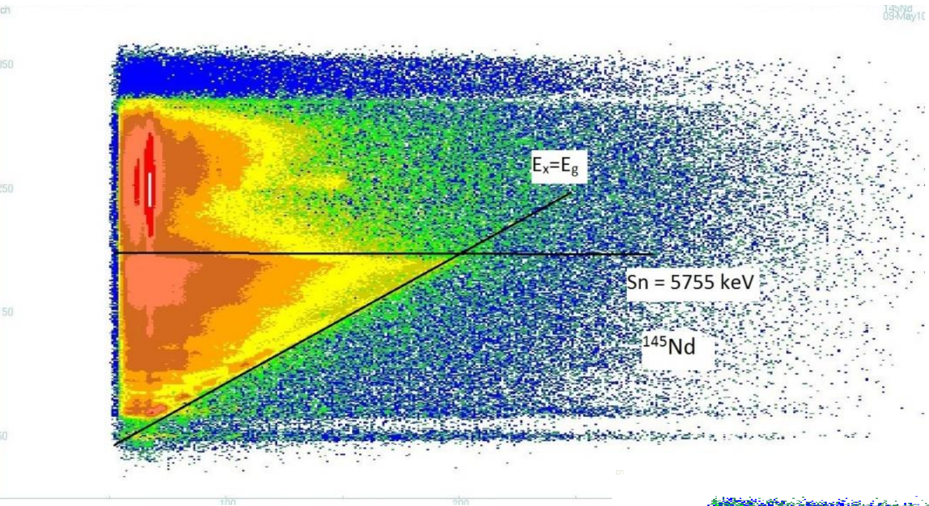
Reaction channels:

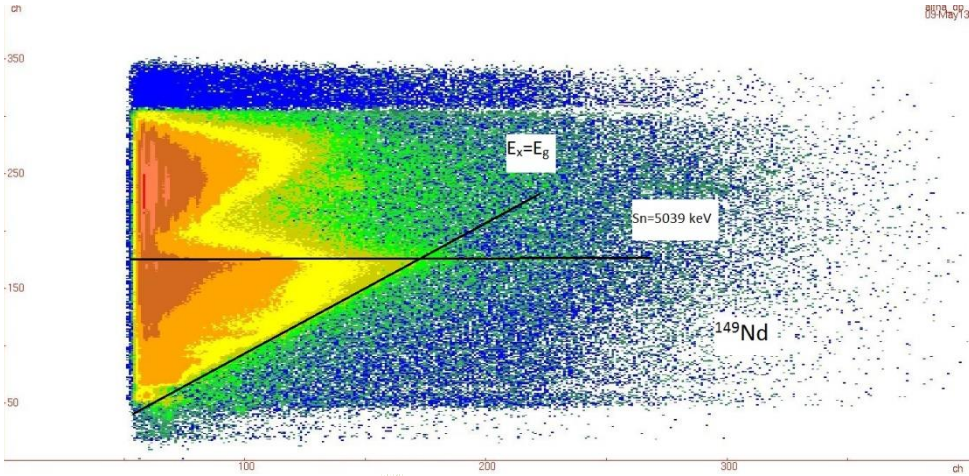
$^{144}Nd(d,p)^{145}Nd$

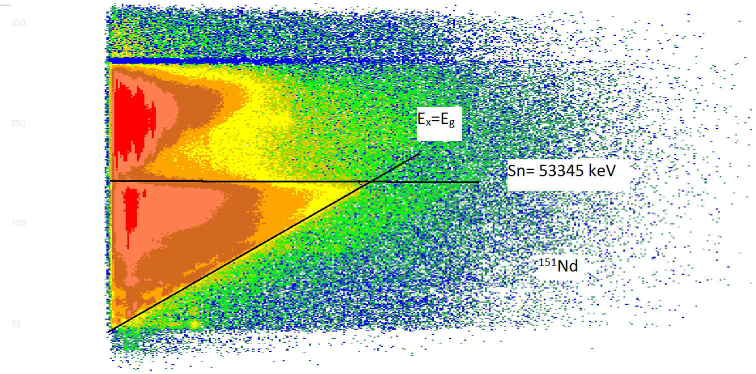
$^{148}Nd(d,p)^{149}Nd$

$^{150}Nd(d,p)^{151}Nd$

Particle – γ Ray Coincidence Matrix: Alfna Matrix

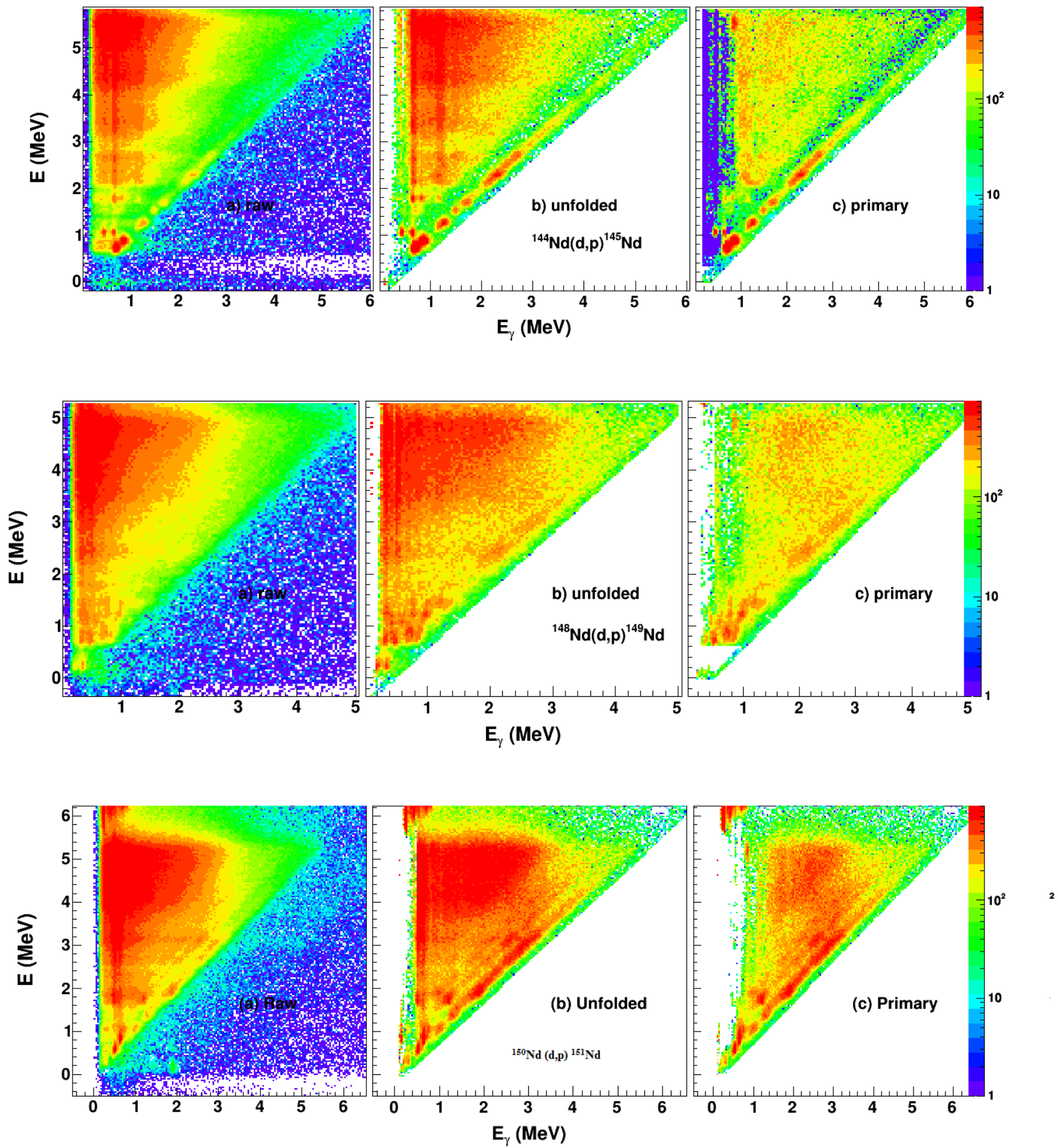






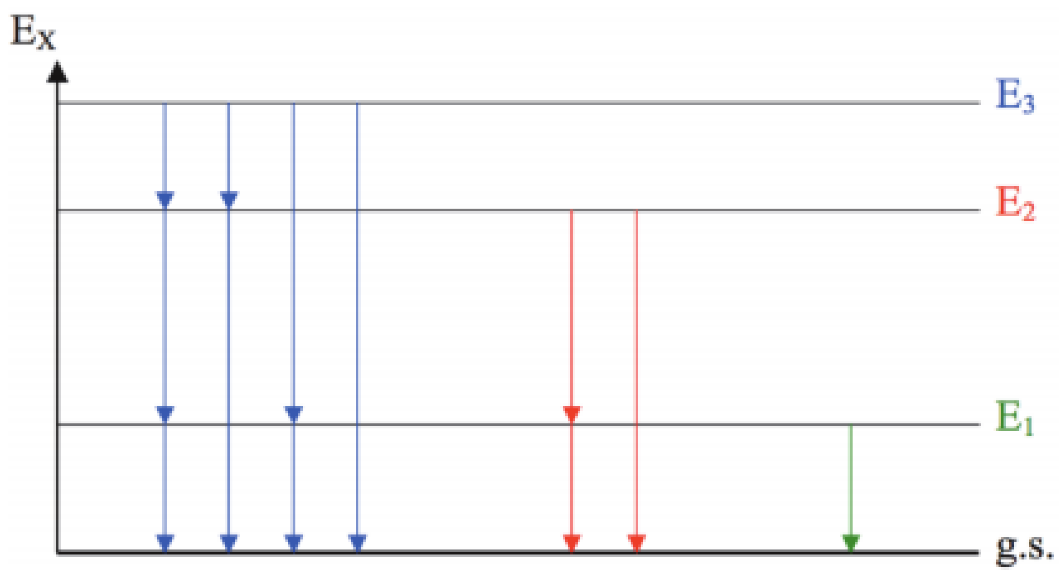
- The diagonal $E_x=E_g$ highlights direct decays into the ground state.
- Horizontal line gives the neutron separation enegy S_n

Raw – Unfolded – Primary Matrices



Subtracting the Spectra

Decay cascades for a hypothetical nucleus*:



- The first emitted photon in the cascade is called a primary or first generation γ-ray.
- The primary γ rays from the level E_3 can be obtained by subtracting the spectra from the levels below, E_2 and E_1 .
- Image taken from Fabio Zeiser's master's thesis.

Subtracting the Spectra

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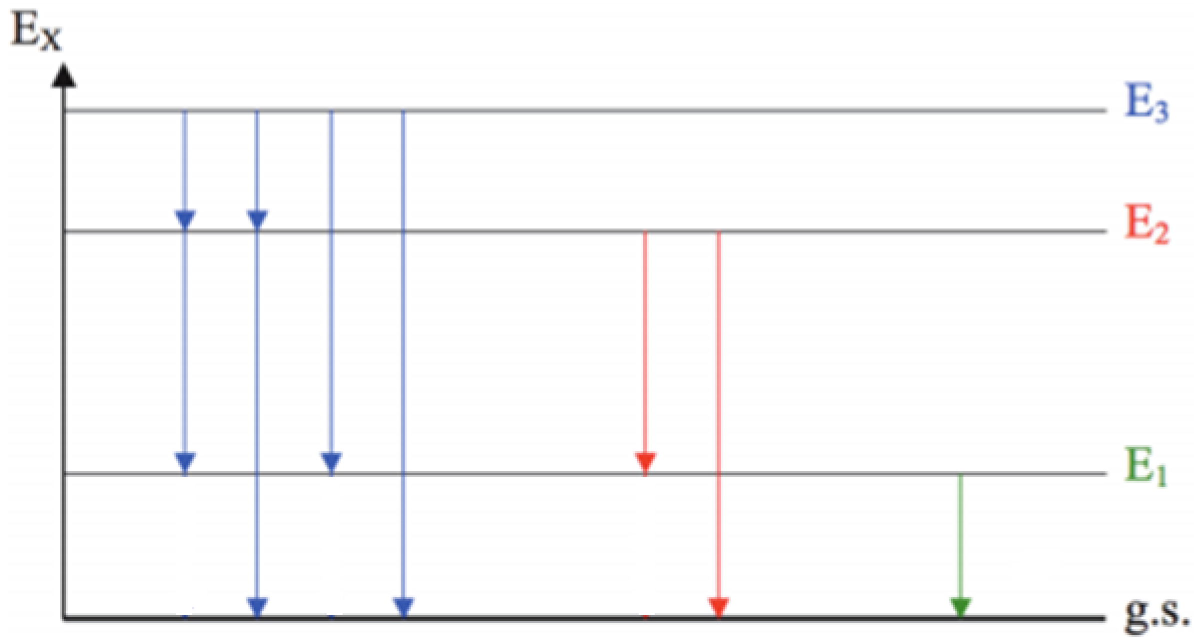

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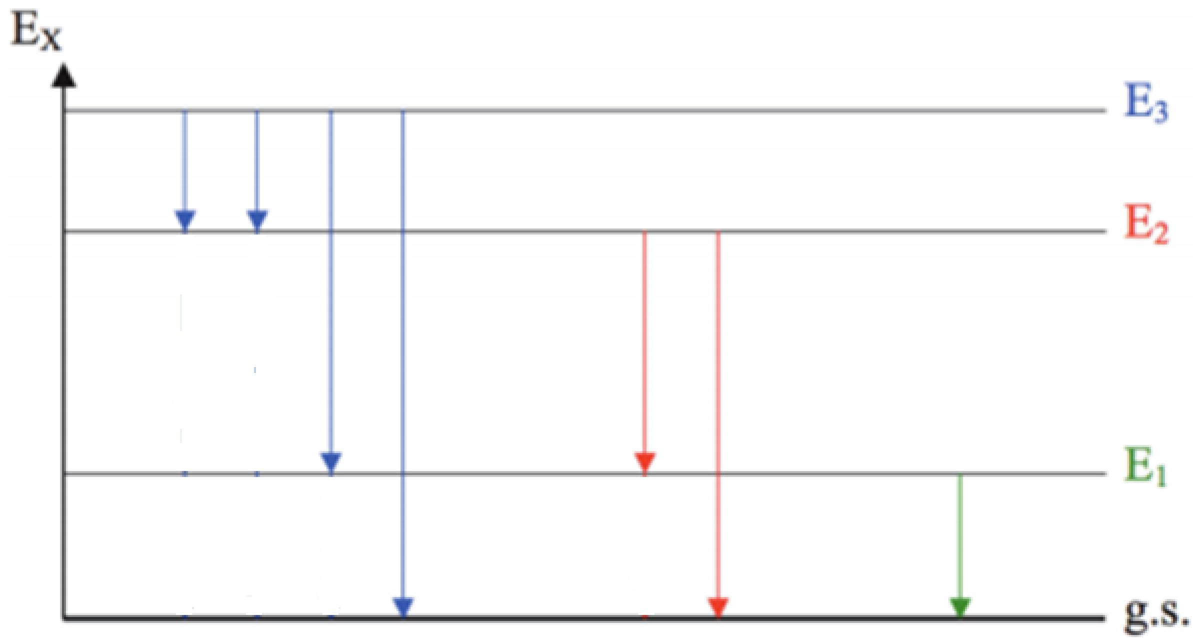

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Determining Level Density

- Until now, the primary γ-ray spectra was obtanied for each excitation energy.

- This spectra forms the first generation matrix : $P\left(E_i, E_\gamma\right)$

- Here comes the Fermi's Golden Rule:

- $$\lambda_{if} = \frac{2\pi}{\hbar} \left|\langle f|\hat{H}|i\rangle\right|^2 \rho(E_f)$$

Determining Level Density and γ-Strength Function

- $$\lambda_{if} = \frac{2\pi}{\hbar} \left|\langle f|\hat{H}|i\rangle\right|^2 \rho(E_f)$$

- Meaning: the decay rate λ_{if} from an initial (i) to a final (f) state - which corresponds to $P(E_i, E_\gamma)$ - can be decomposed into two parts:

- Transition Matrix Element …and… the Level Density

- $\left|\langle f|\hat{H}|i\rangle\right|^2$ $\qquad\qquad$ $\rho(E_f)$

Determining Level Density and γ-Strength Function

- Consequently, we can safely say that, the decay probability - which corresponds to $P(E_i, E_\gamma)$ - can be factorized as follows:

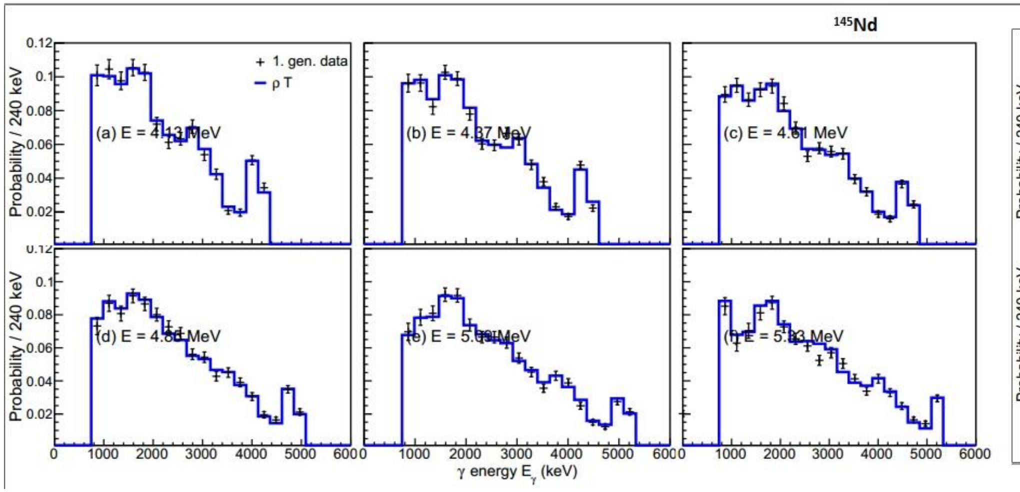
- $$P(E_i, E_\gamma) \propto \rho(E_f)\,\mathcal{T}(E_\gamma)$$

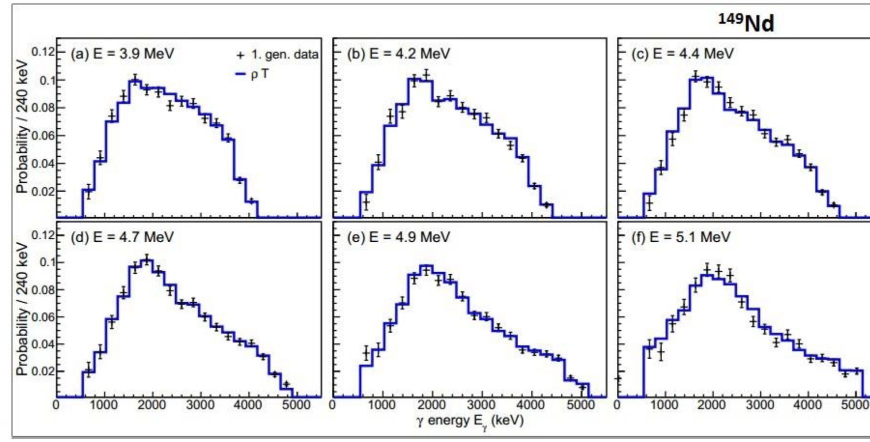
- First Generation Matrix Level Density Transmission Coefficient

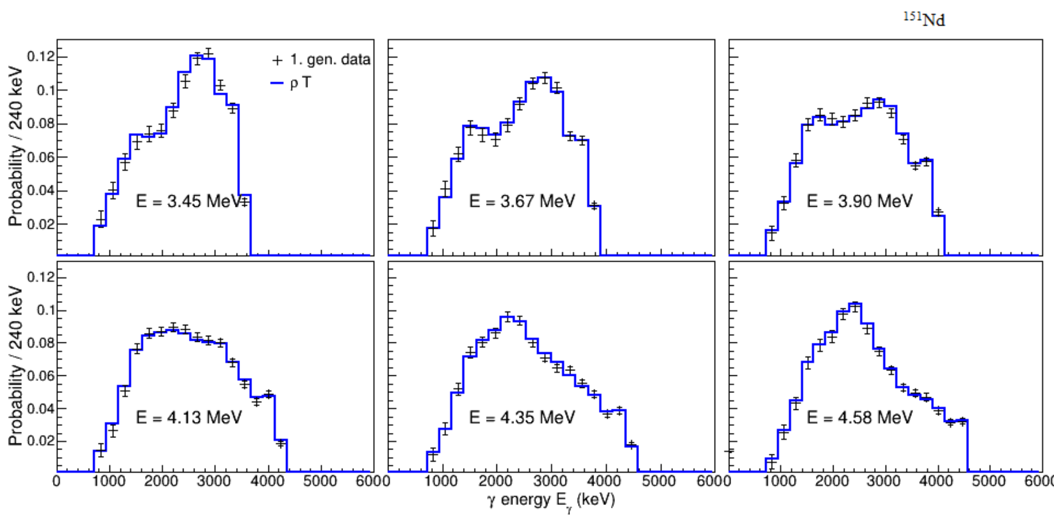
$$\tilde{\rho}(E_i - E_\gamma) = \rho(E_i - E_\gamma)Aexp[\propto (E_i - E_\gamma)]$$
$$\tilde{\mathcal{T}}(E_\gamma) = \mathcal{T}(E_\gamma)Bexp[\propto E_\gamma]$$

$$P(E_i, E_\gamma) \propto \rho(E_f)\,\mathcal{T}(E_\gamma)$$

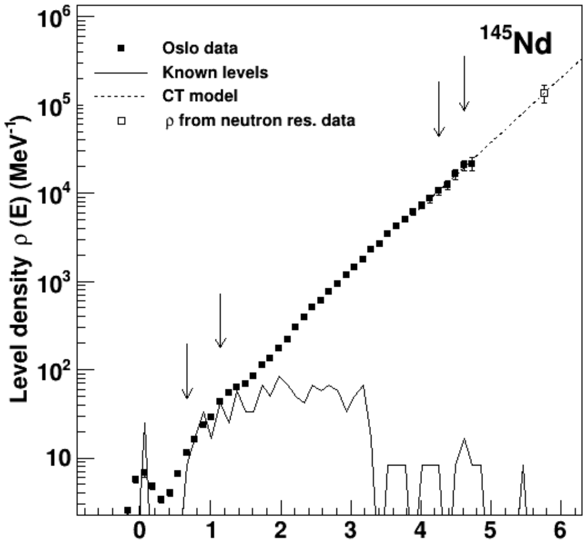
Does it work?

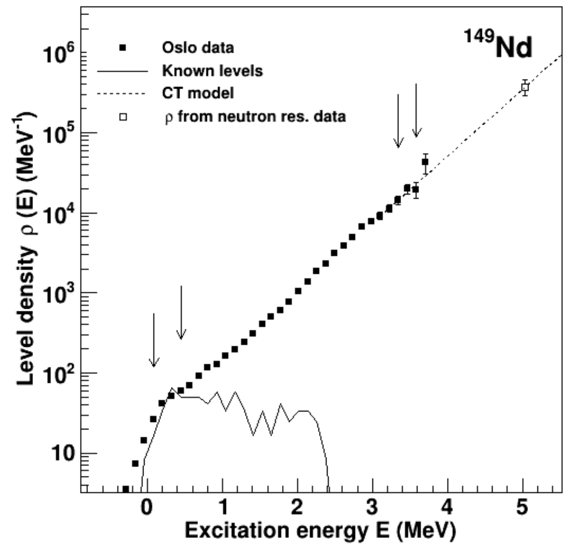


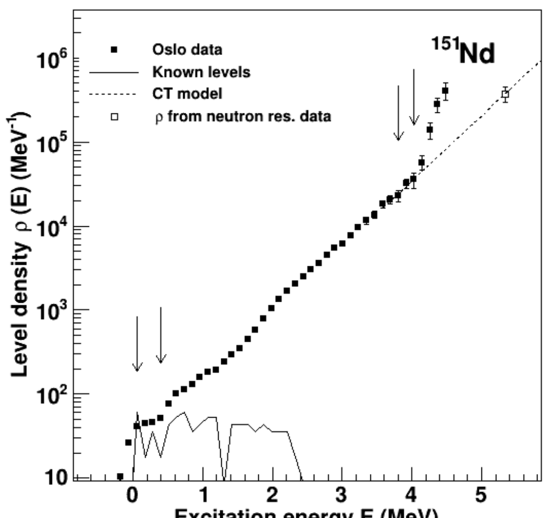


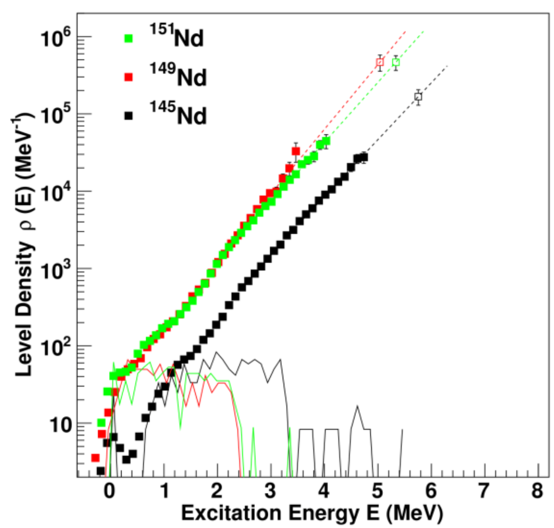


$\rho(E_f)$ for $^{145,149,151}Nd$









Parameters Used to Extract the Level Densities (Data is taken from RIPL3 database)

Nucleus	Neutron Separation Energy	Level Density Parameter	Back-Shift Parameter	Spin-Cutoff Parameter
	S_n (MeV)	a (MeV^{-1})	E_1 (MeV)	σ
^{145}Nd	5.755	15.942	-0.052	6.09
^{149}Nd	5.039	17.867	-0.446	5.97
^{151}Nd	5.335	17.820	-0.596	6.15
	Resonance Spacing Parameter	Constant Temperature	Level Density at S_n	
	D_0 (eV)	T (MeV)	ρ (S_n) ($10^6 MeV^{-1}$)	
^{145}Nd	450	0.590	1.673E+05	
^{149}Nd	155	0.520	4.662E+05	
^{151}Nd	165	0.560	4.278E+05	

Microcanonical Combinatorial Model

- Makes use of the Nilsson Model and BCS theory to calculate level densities.
- Nilsson Model:
  - Accounts for most of the observed features of single-particle levels in deformed nuclei.
  - Provides a microscopic basis for the existence of rotational and vibrational motion.

Nilsson Model

- Applied to generate a set of single-particle ortibals*.

- The Nilsson ortibal energies (e_{sp}) are transferred to single quasi-particle energies by the Bardeen-Cooper-Schrieffer (BCS) theory**:

- $$e_{qp} = \sqrt{\left(e_{sp} - \lambda\right)^2 + \Delta^2}$$

- λ: Fermi level, determined by the number of protons and neutrons.

- Include orbitals from 8 MeV below the Fermi level up to 8 MeV above the Fermi level.

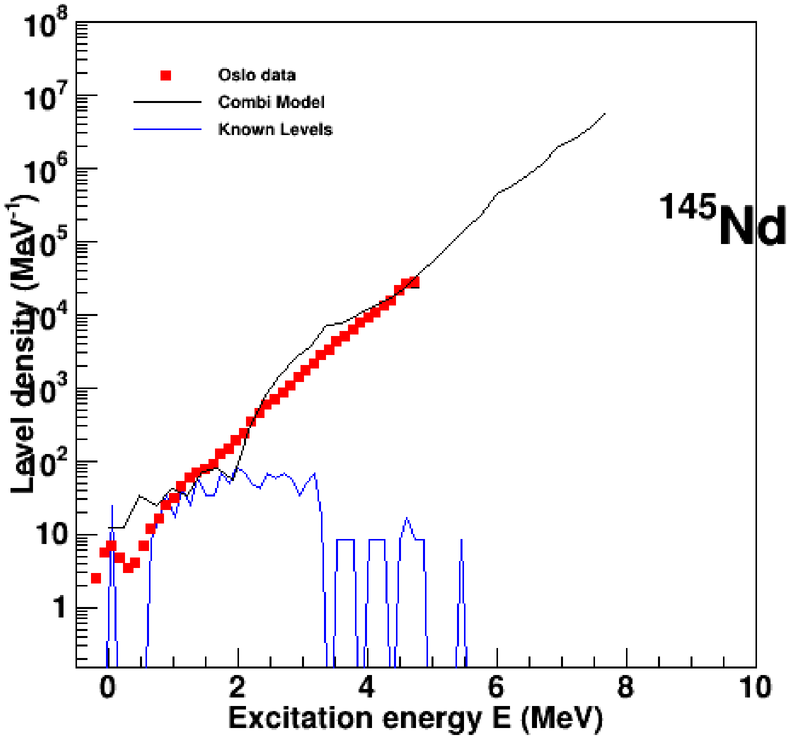
- For pairing energy parameters we use:

Nuclei	Δ_π(MeV)	Δ_ν (MeV)
145Nd	2.098	1.936
149Nd	1.789	2.086
151Nd	1.690	1.994

- Finally, the level density is given by:
- $$\rho(E) = {}^{N(E)}/_{\Delta E}$$

- * S. G. Nilsson, Mat. Fys. Medd. Dan. Vid. Selsk. **16**, 29 (1955).
- ** J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. **108**, 1175 (1957)

Combinatorial Models - ^{145}Nd

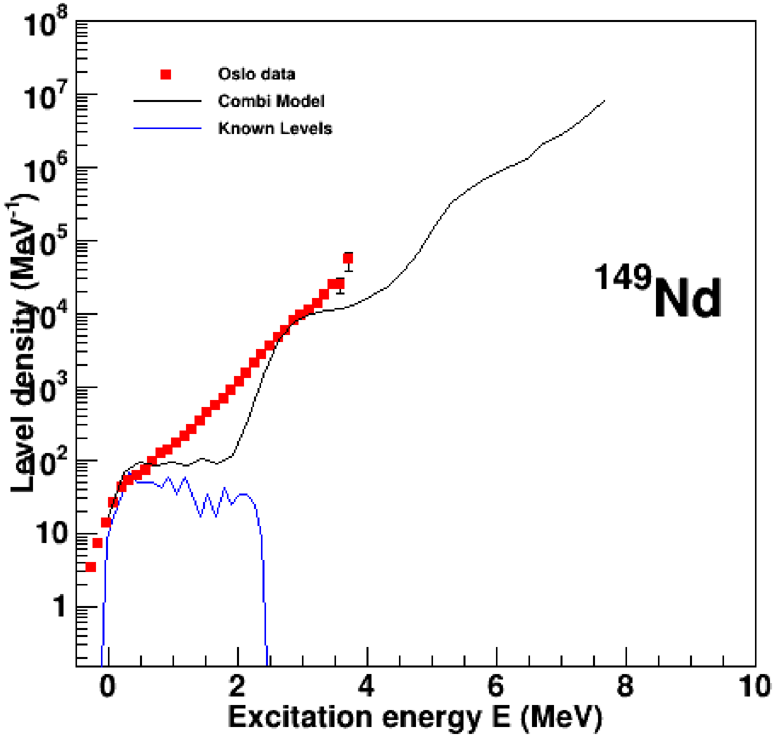


Nilsson Parameters			
	ε_2	κ	μ
	Quadrupole Deformation	Spin-Orbit Splitting	Centrifugal Parameter
Proton	0.160	0.06370	0.6
Neutron	0.160	0.06370	0.42

Deformation parameter is taken from RIPL3 database.

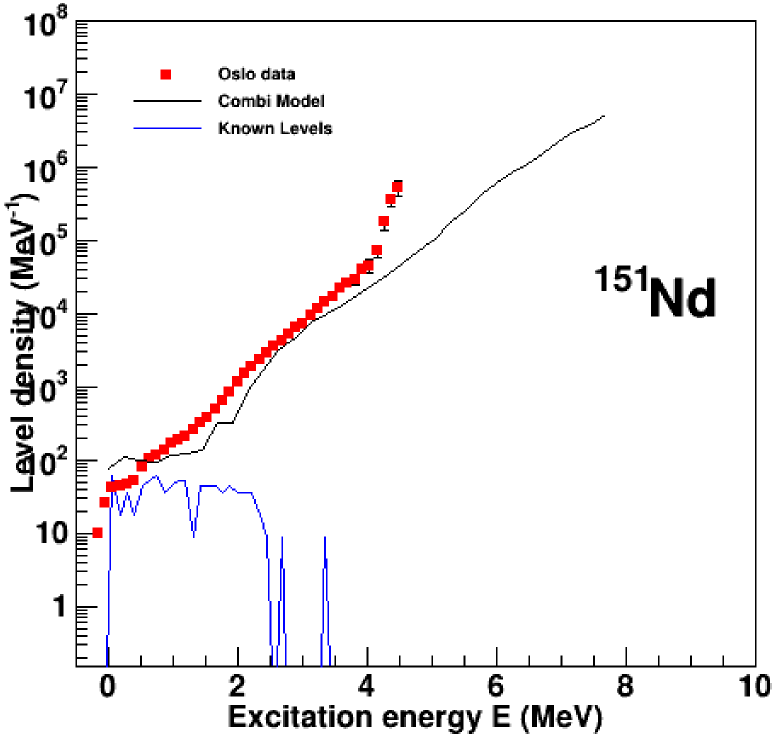
Spin-orbit splitting and centrifugal paramaters are taken from «P. Ring and P. Schuck – The Nuclear Many-Body Problem».

Combinatorial Models – ^{149}Nd



Nilsson Parameters			
	ε_2	κ	μ
	Quadrupole Deformation	Spin-Orbit Splitting	Centrifugal Parameter
Proton	0.270	0.06370	0.6
Neutron	0.270	0.06370	0.42

Combinatorial Models – ^{151}Nd



Nilsson Parameters			
	ε_2	κ	μ
	Quadrupole Deformation	Spin-Orbit Splitting	Centrifugal Parameter
Proton	0.350	0.06370	0.6
Neutron	0.350	0.06370	0.42

Future Plans

- Study even nuclei: ^{144,148,150}Nd
- Perform ^{142}Nd(d,xγ)
- ^{146}Nd(d,xγ) reactions at OCL ☺.

A. Schiller et al., Nucl. Instrum. Methods in Phys. Res. A 447, 494 (2000)

I’m deeply thankful to:

- M Guttormsen, E Algin, M Özgür, F L Bello Garrote, L Crespo Campo, A Görgen, T W Hagen, V W Ingeberg, B V Kheswa, M Klintefjord, A C Larsen, J E Midtbø, V Modamio, T Renstrøm, S J Rose, E Sahin, S Siem, G M Tveten, and F Zeiser.

- TÜBİTAK; for financially supporting the project titled ‘Evolution of the scissors mode in the vicinity of the N = 82 shell closure.’