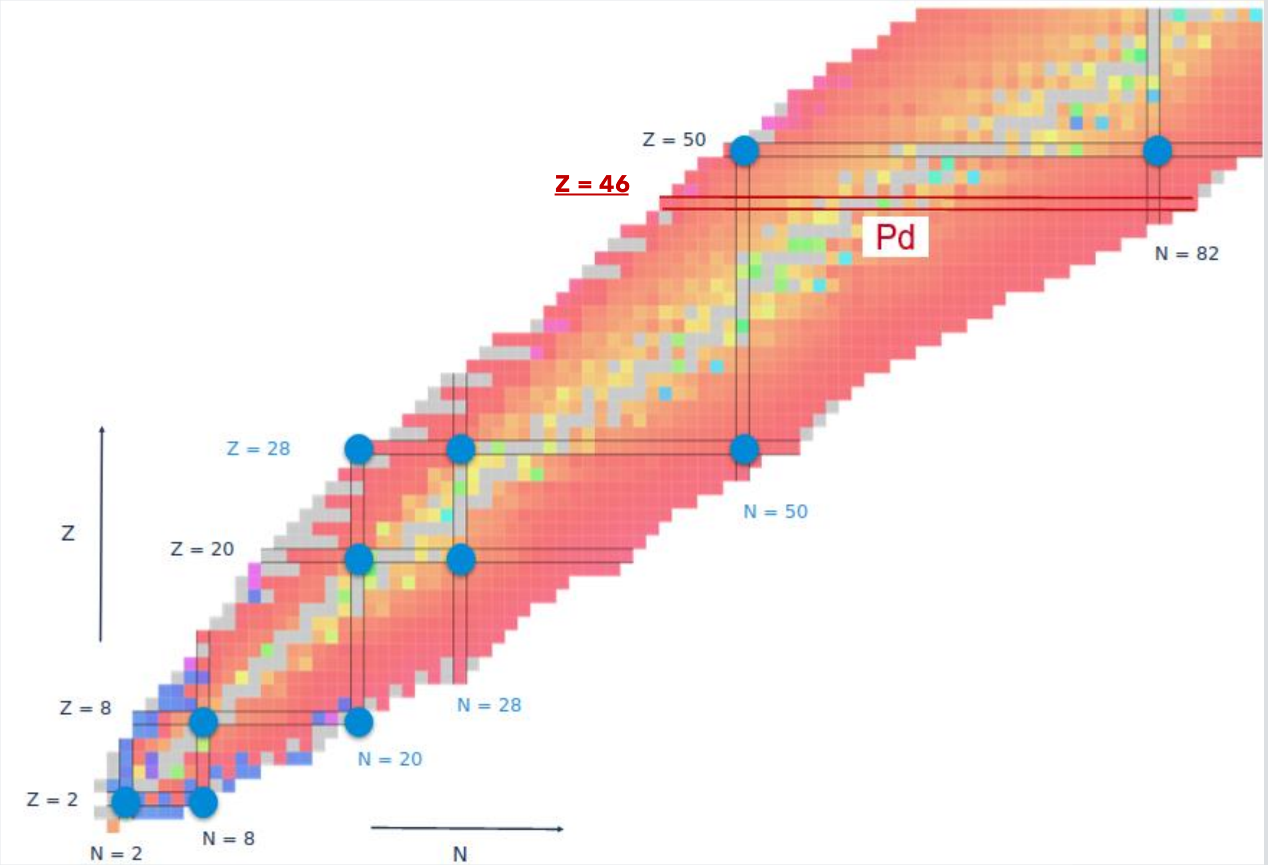
Naomi Marchini

University of Florence – INFN Florence section

Searching for intruder bands in ^{106}Pd via Coulomb Excitation

AGATA+SPIDER Setup

Even-Even Palladium isotopes



Different interpretations of their level schemes:

- A. Giannatiempo, A. Nannini, and P. Sona, Phys. Rev. C 58, 3316 (1998) provided a description of these nuclei as pertaining to a **transitional region from the U(5) limit (vibrational) to the O(6) limit (γ-soft) of this model.**

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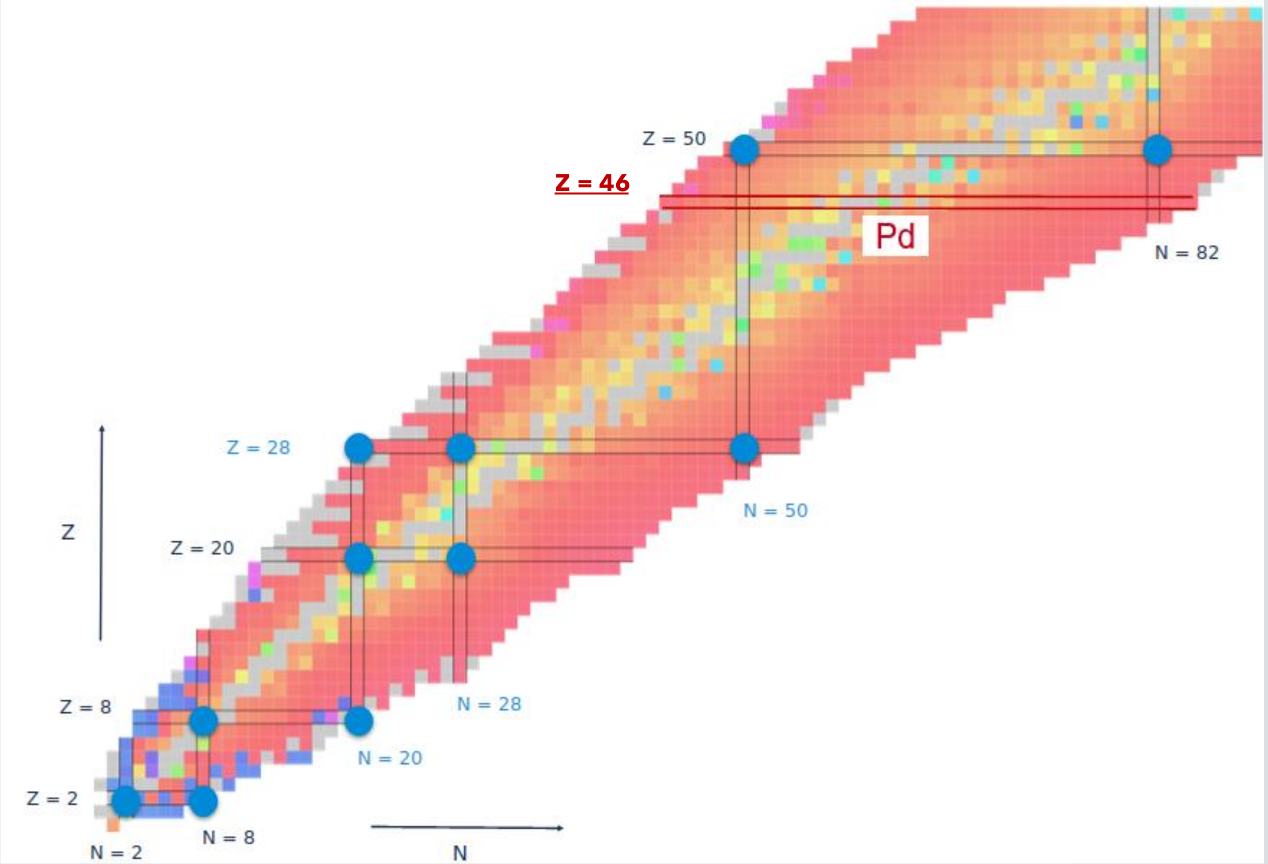

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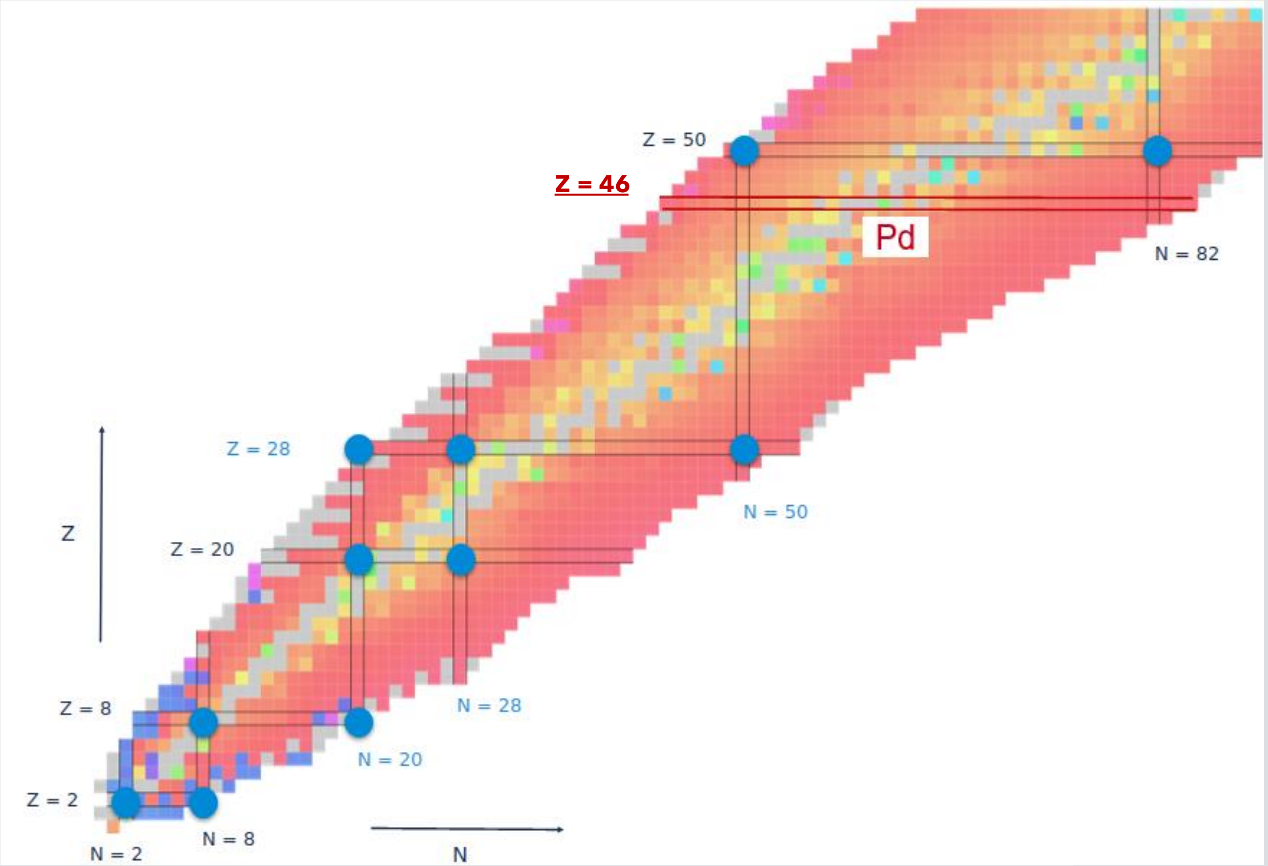
Even-Even Palladium isotopes



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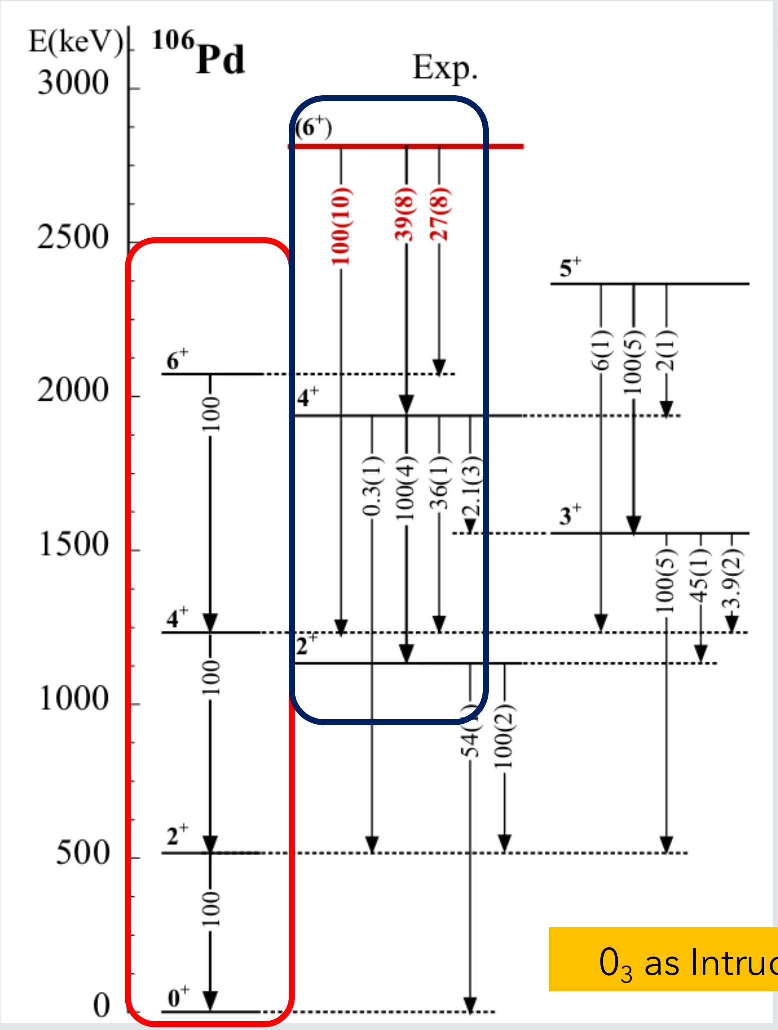
- P. E. Garrett, M. Zielinska, and E. Clement, Prog. Part. Nucl. Phys. 124, 103931 (2022) supports this interpretation by a systematic study of the even-even isotopes of Mo, Ru, Pd, Cd, and Te.

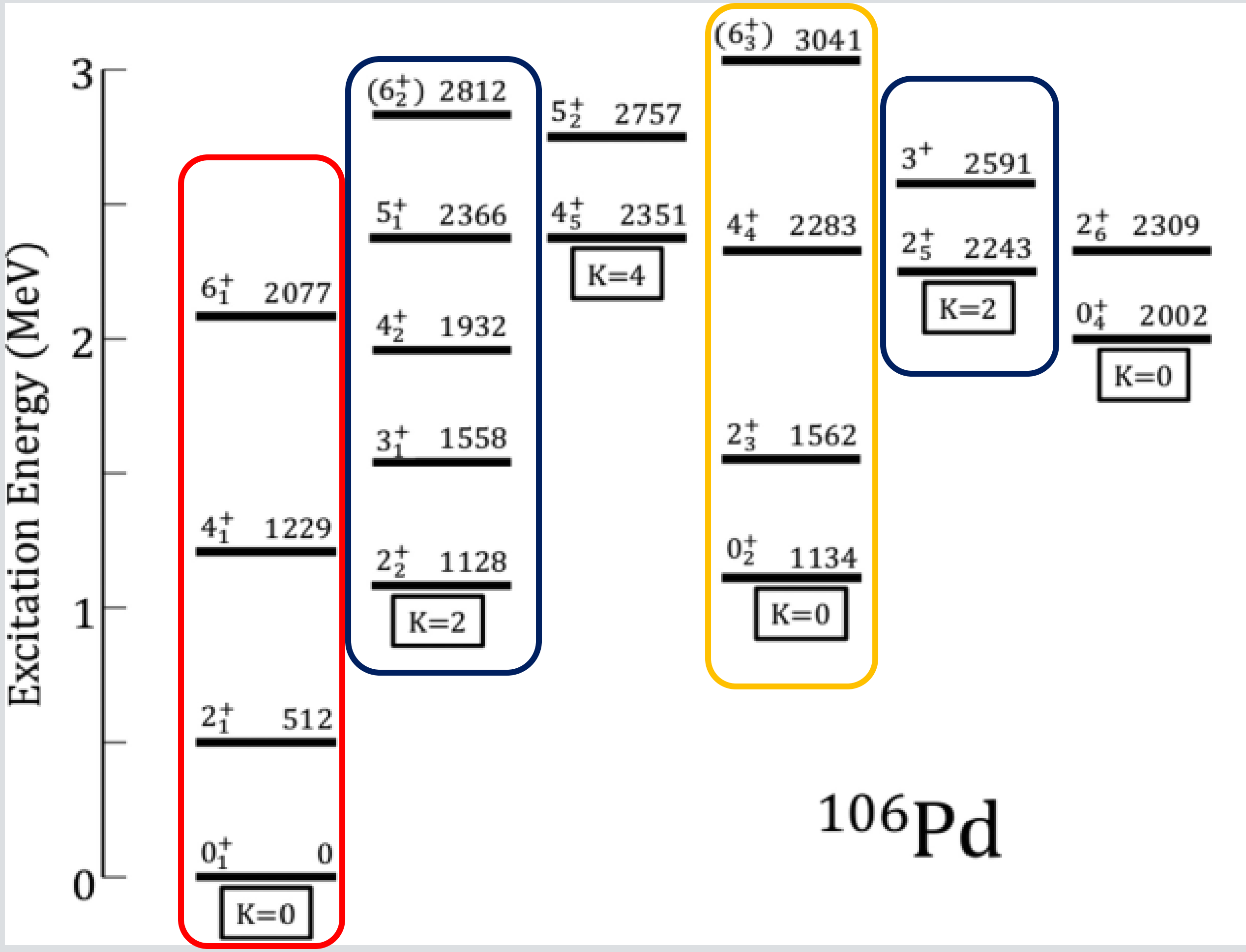
The ^{106}Pd isotope

A. Giannatiempo et al. Phys. Rev. C (2018) 98, 034305



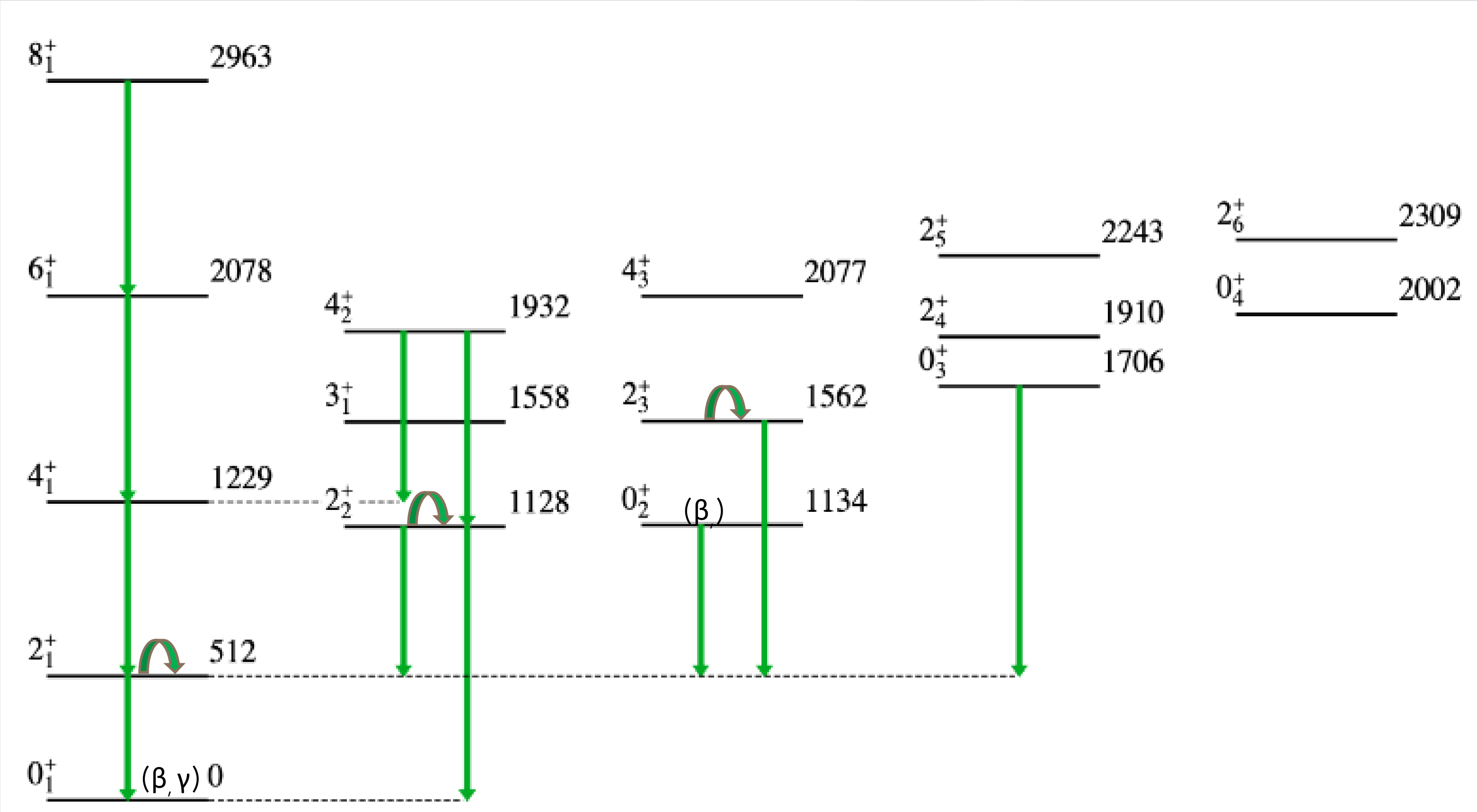
0_3 as Intruder State

F. M. Prados-Estévez et al. PRC (2017) 95, 034328



The ^{106}Pd isotope – Previous Exp. - Coulex

L. Svensson, et al., Nucl. Phys. A 584, 547 (1995)



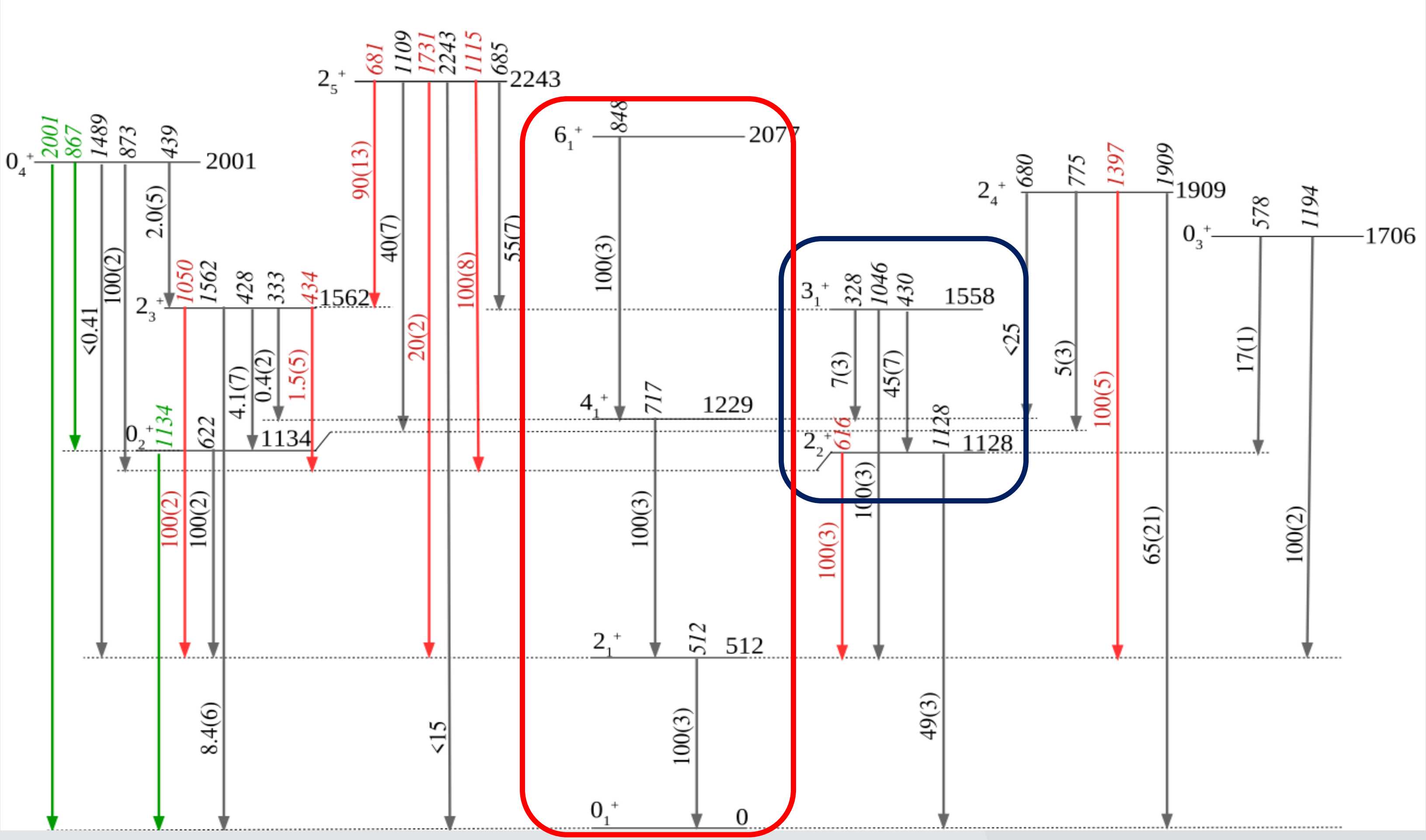
The setup consisted of four circular Si-detectors and one annular Si-detector coupled to only two Ge detectors

Coulomb Excitation performed years ago:

- 0_1^+ : Determination of β and γ quadrupole invariants
- 0_2^+ : Determination of β quadrupole invariant
- Quadrupole moments of the $2_{1,2,3}^+$

The ^{106}Pd isotope – Previous Exp. - ICE

N. Marchini et al. Phys. Rev. C 105, 054304 (2022)

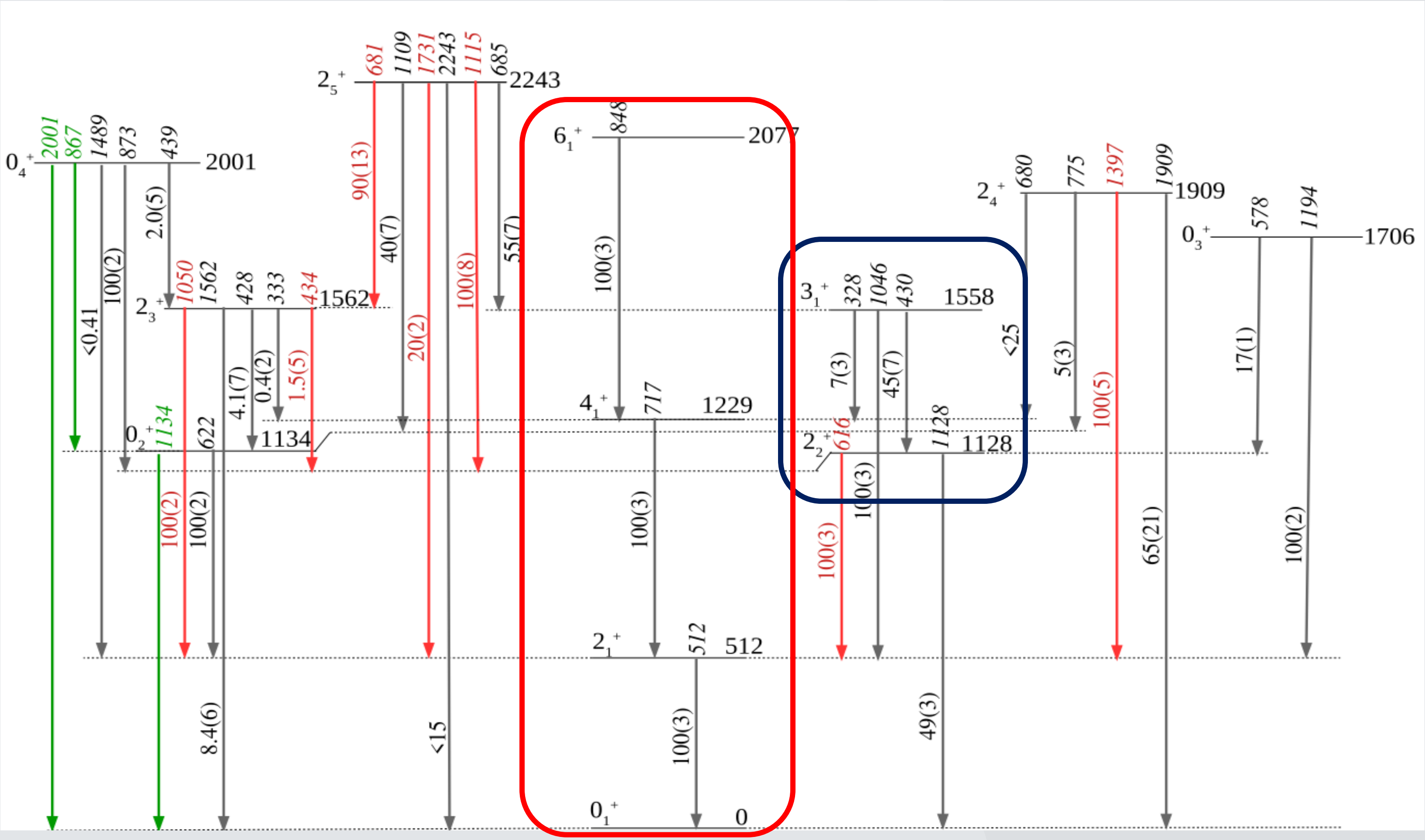


Internal Conversion Electron spectroscopy performed:

- ρ^2(E0) between low-lying 2^+ and 0^+ states deduced
- Confirmation of transitions from the 2_4^+ state observed for the first time in *F. M. Prados-Estévez et al. PRC (2017) 95, 034328* paper

The ^{106}Pd isotope – Previous Exp. - ICE

N. Marchini et al. Phys. Rev. C 105, 054304 (2022)



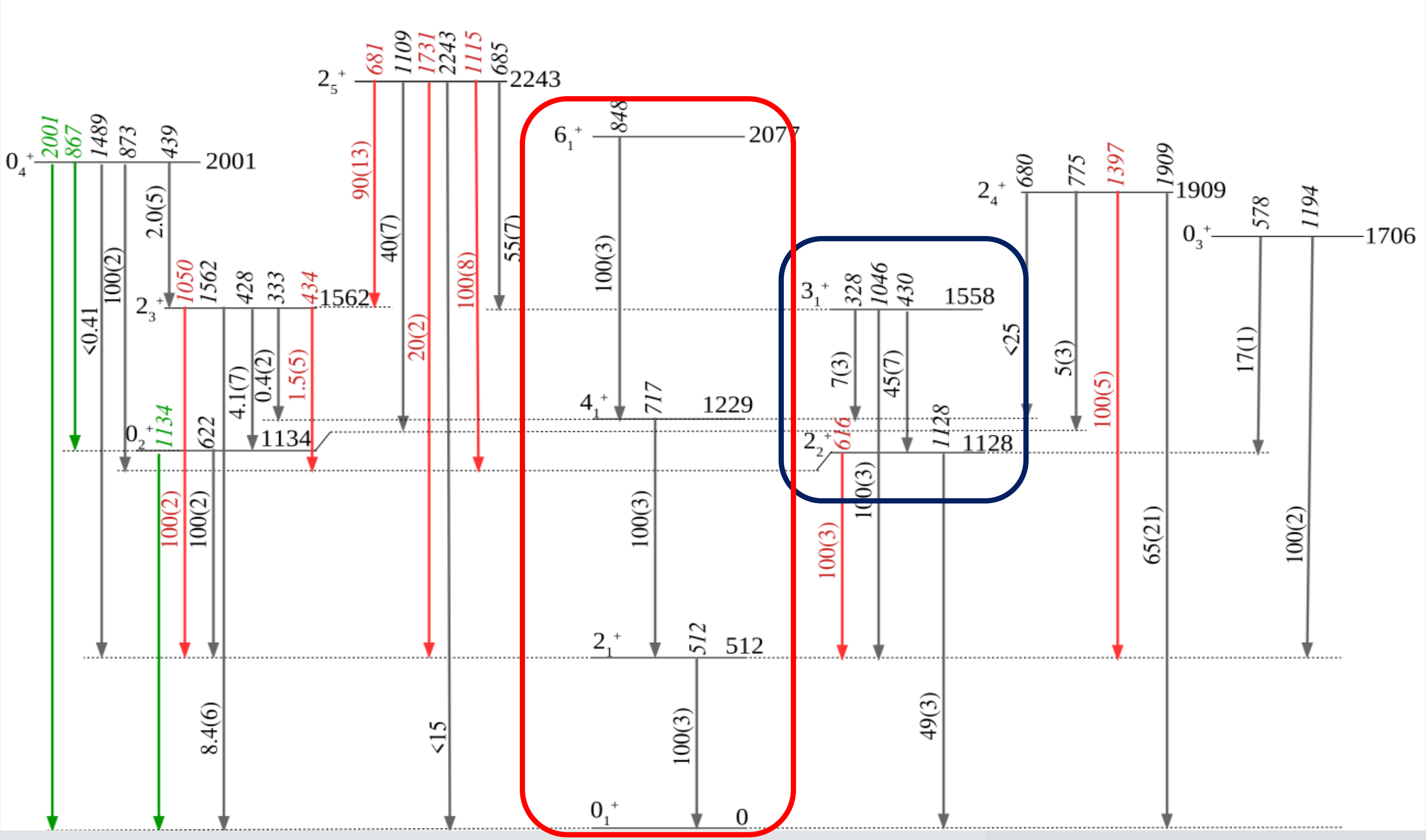
IBM-2 calculations performed:

(parameters from Giannatiempo et al. Phys. Rev. C 98, 034305 (2018))

- 0_2^+ and 2_3^+ states well reproduced by the IBM model
- 0_3^+ state suggested as intruder bandhead

The ^{106}Pd isotope – Previous Exp. - ICE

N. Marchini et al. Phys. Rev. C 105, 054304 (2022)

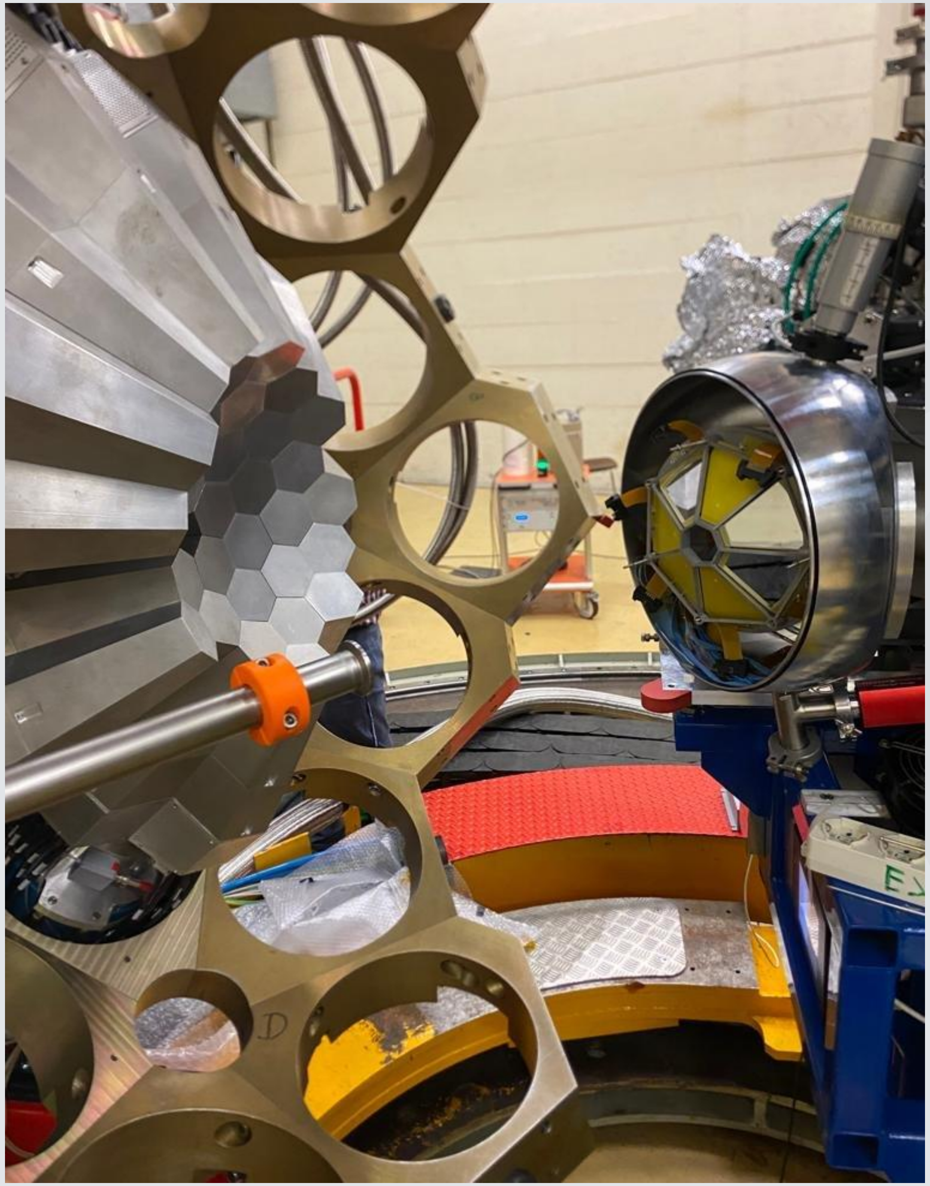


The experimental $\rho^2(E0; 0^+_2 \rightarrow 0^+_1)$ value has been compared to that calculated in a simple two-state mixing model and the coexistence of different shape has been suggested

Shape coexistence scenario

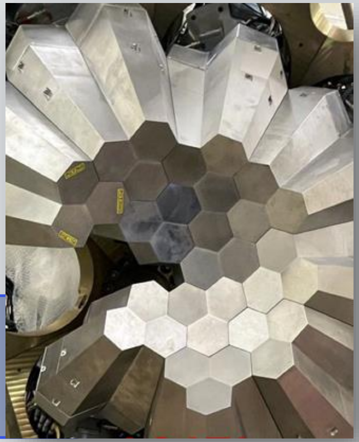
($\beta_1 = 0.29$, $\gamma_1 = 20°$, $\beta_2 = 0.21$, $\gamma_2 = 45°$)

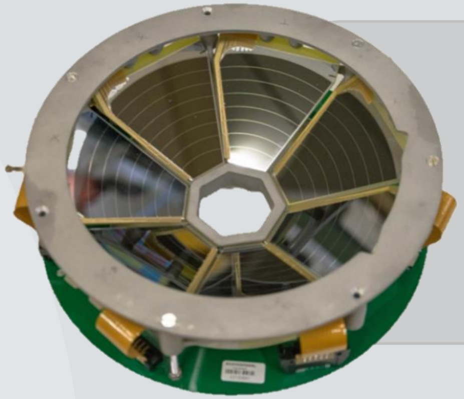
^{106}PD– COULEX EXPERIMENT @LNL



- Beam : ^{60}Ni 175 MeV 1 pnA
- Target : self-supporting ^{106}Pd 1mg/cm^2

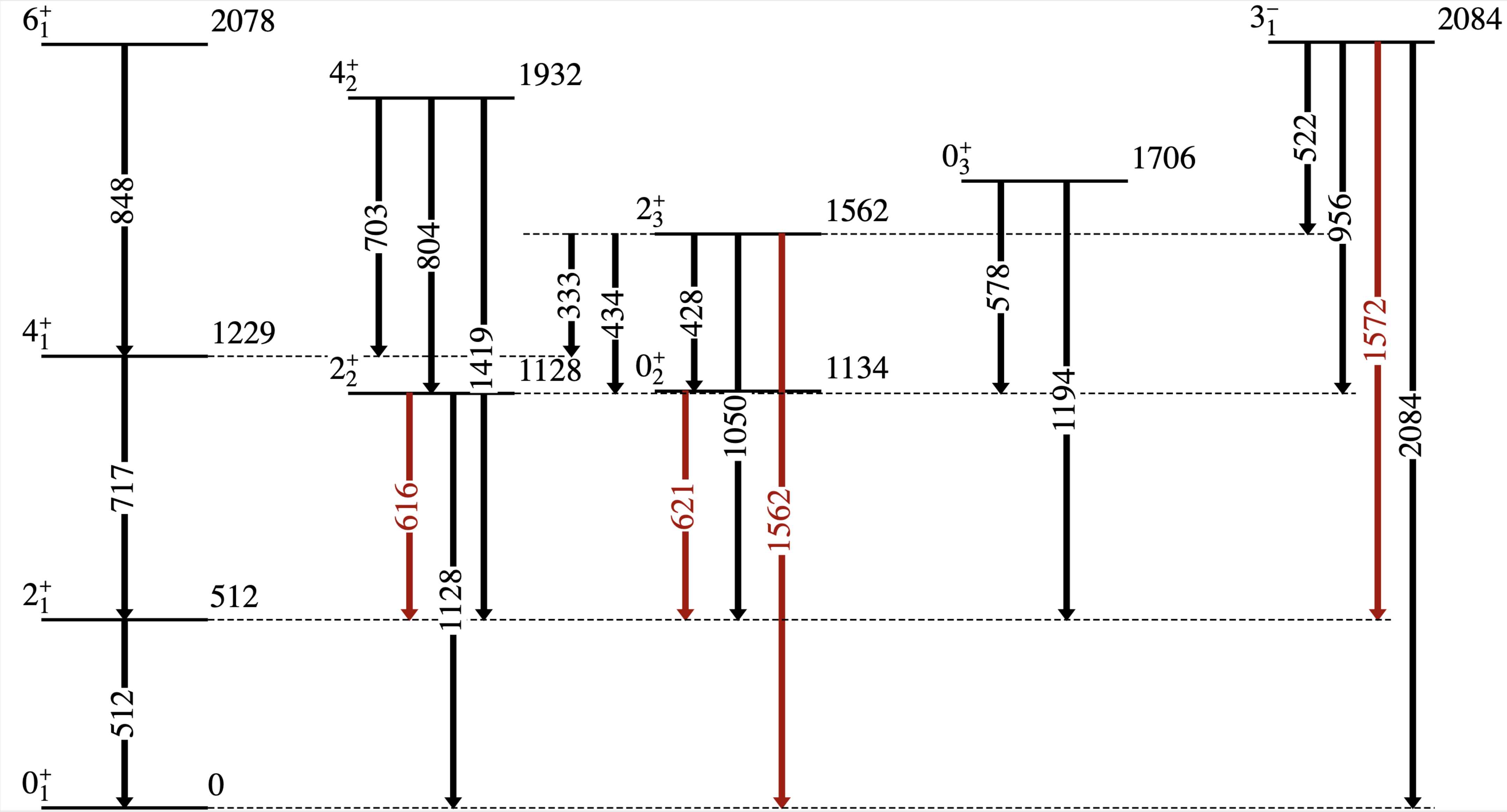
AGATA array (10 ATCs), close-up position.





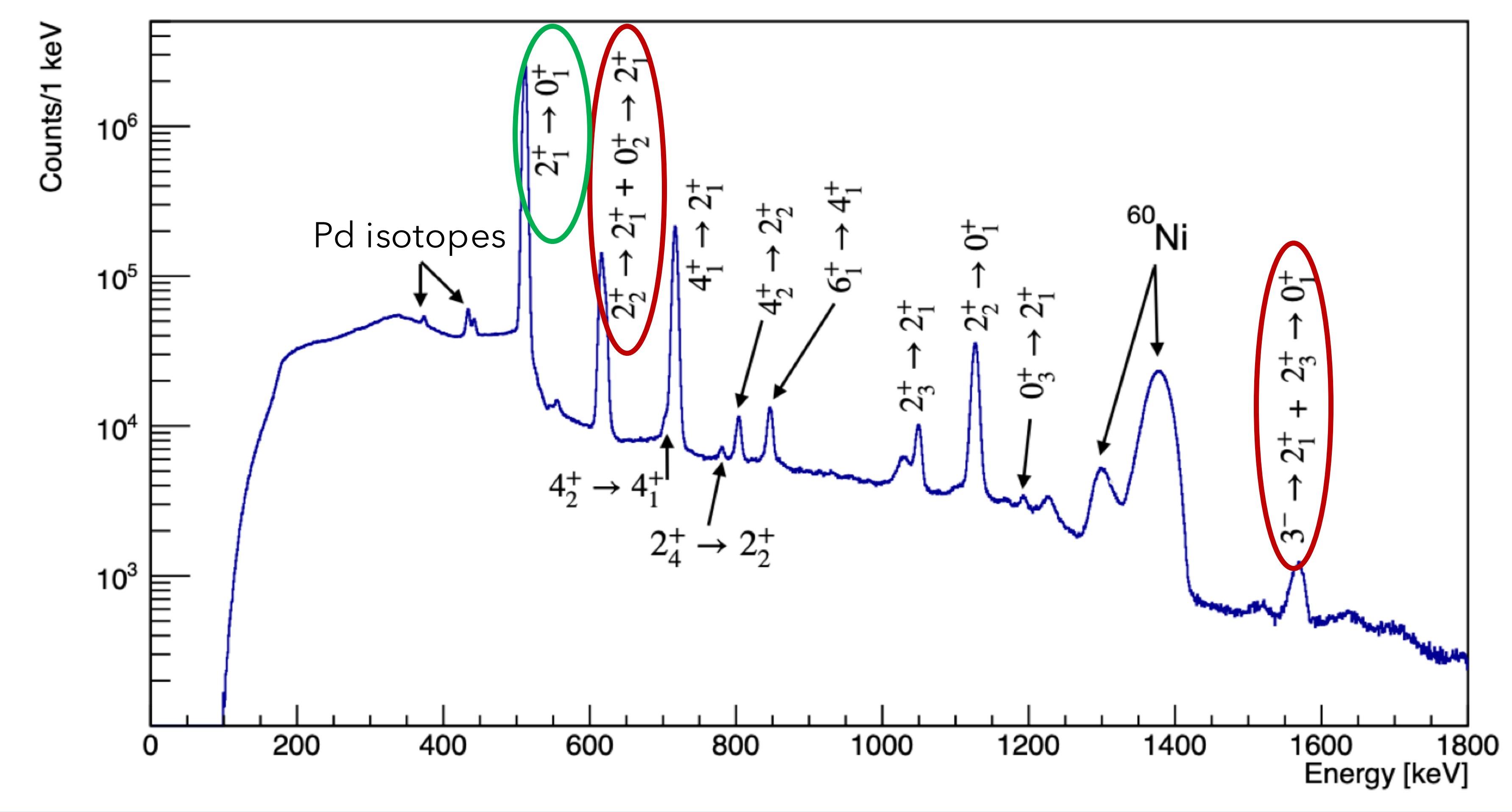
SPIDER modular array of Si detectors segmented into 8 annular strips (junction side).
Θ_{Lab} = 124° - 161°(detection of backscattered ^{60}Ni ions)

^{106}PD– COULEX EXPERIMENT @LNL



^{106}PD– COULEX EXPERIMENT @LNL

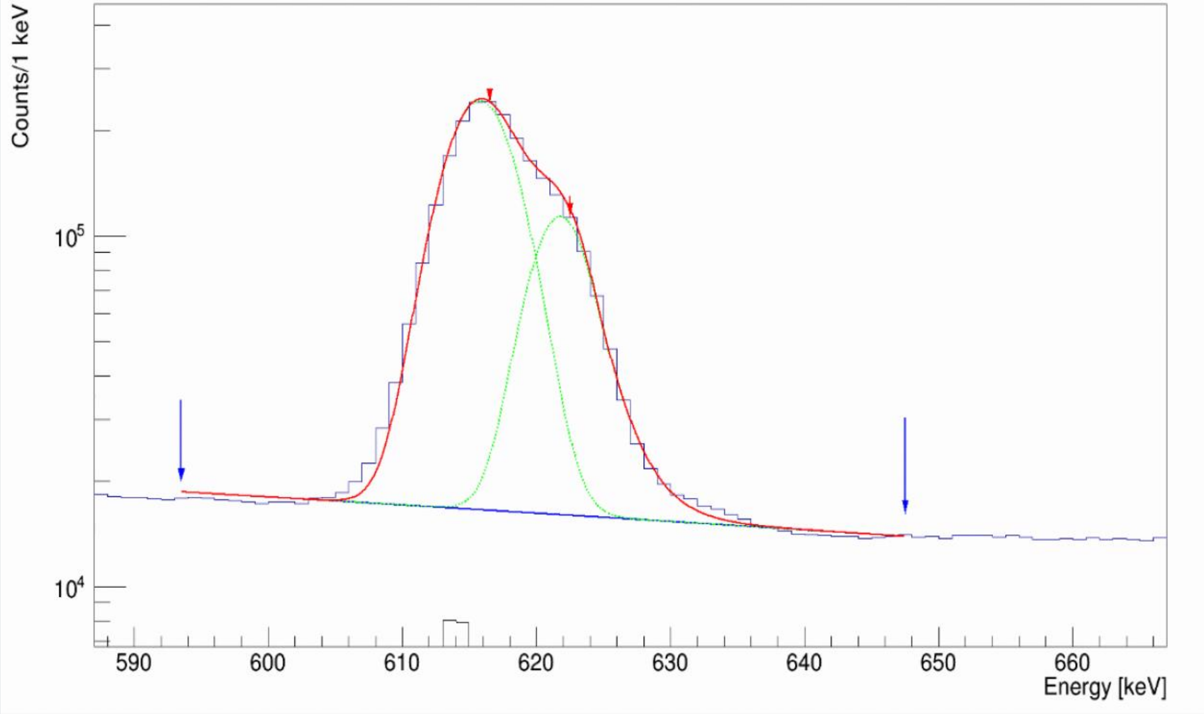
Preliminary (half statistics)



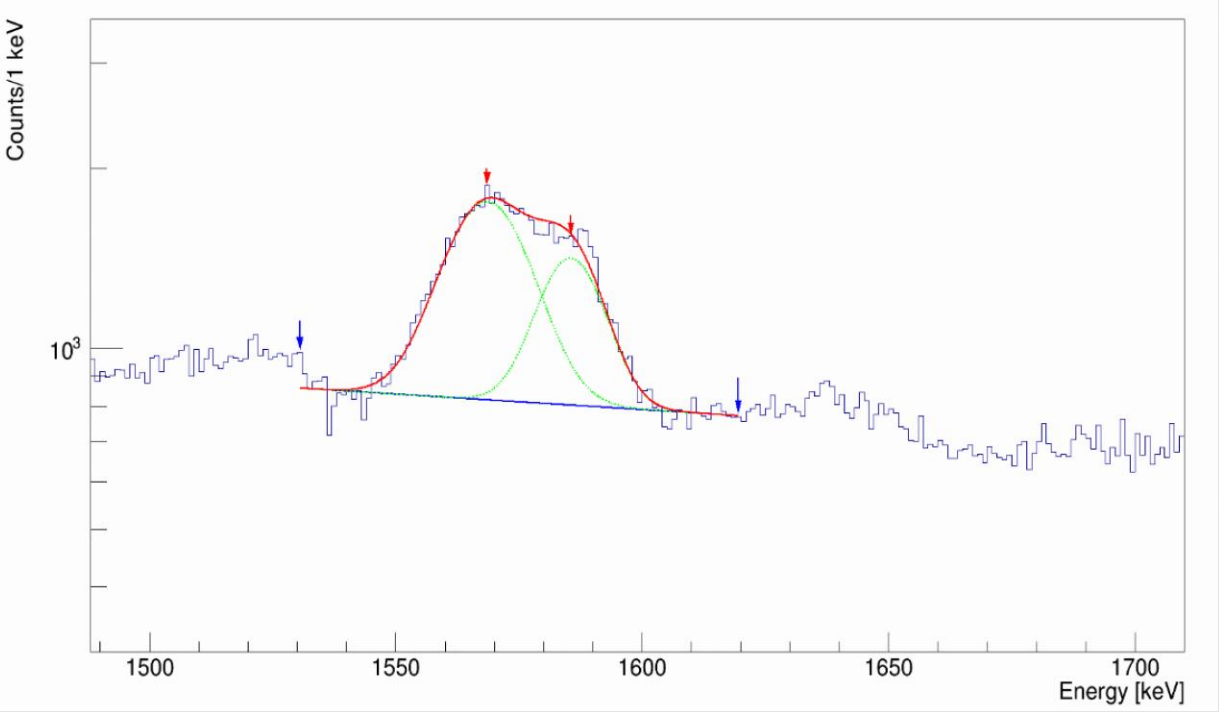
FWHM @512 keV = 5.9 keV

Preliminary (half statistics)

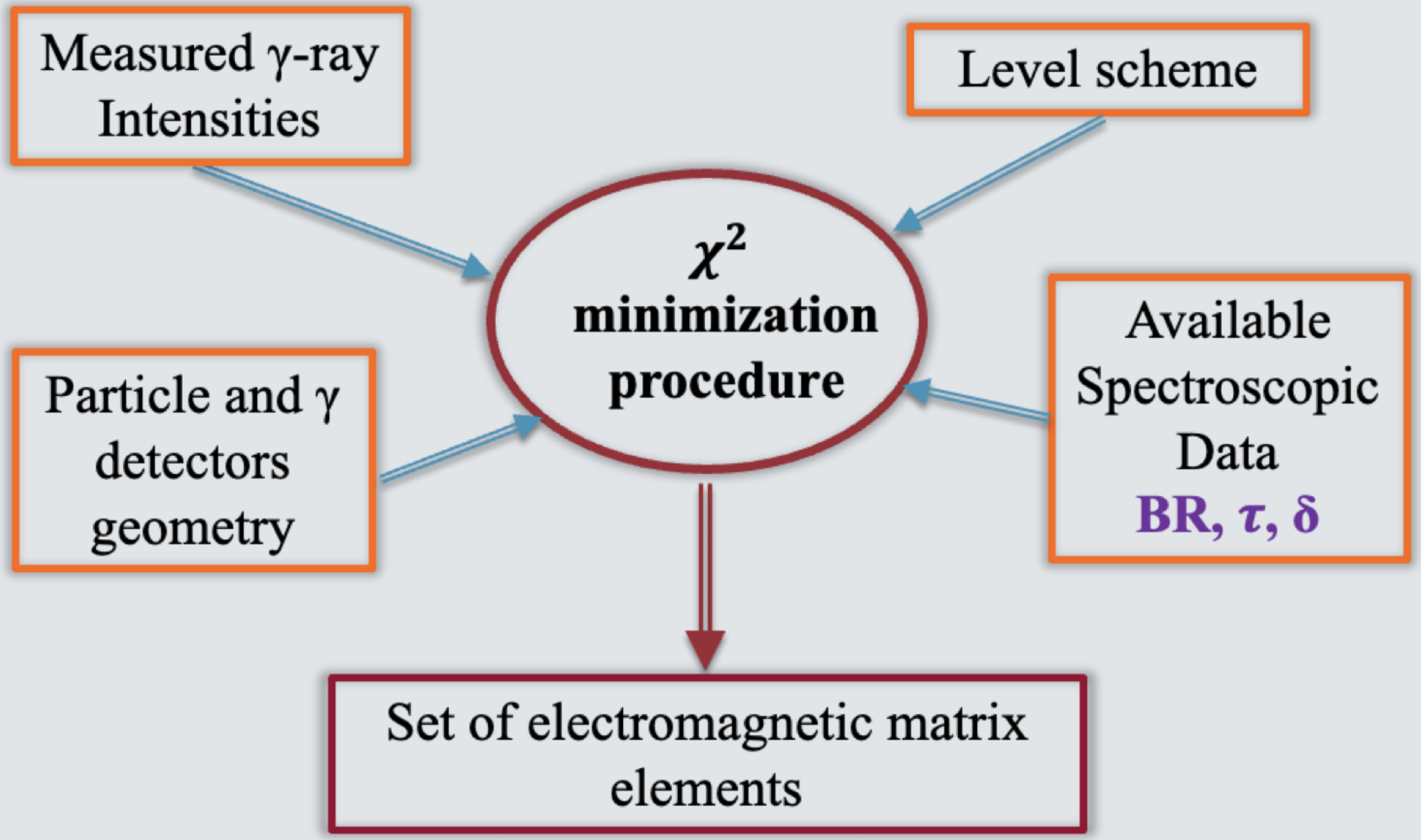
Doublet for $2_2^+ \rightarrow 2_1^+$ and $0_2^+ \rightarrow 2_1^+$



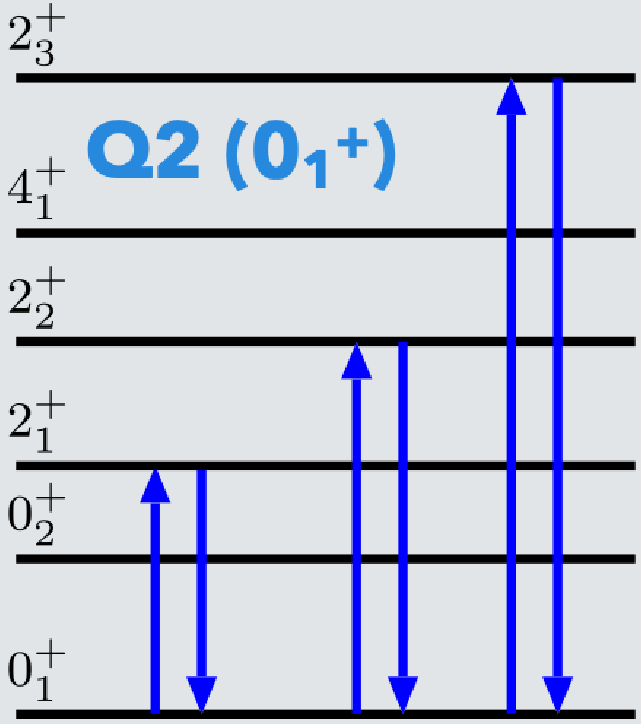
Doublet for $3^- \rightarrow 2_1^+$ and $2_3^+ \rightarrow 0_1^+$

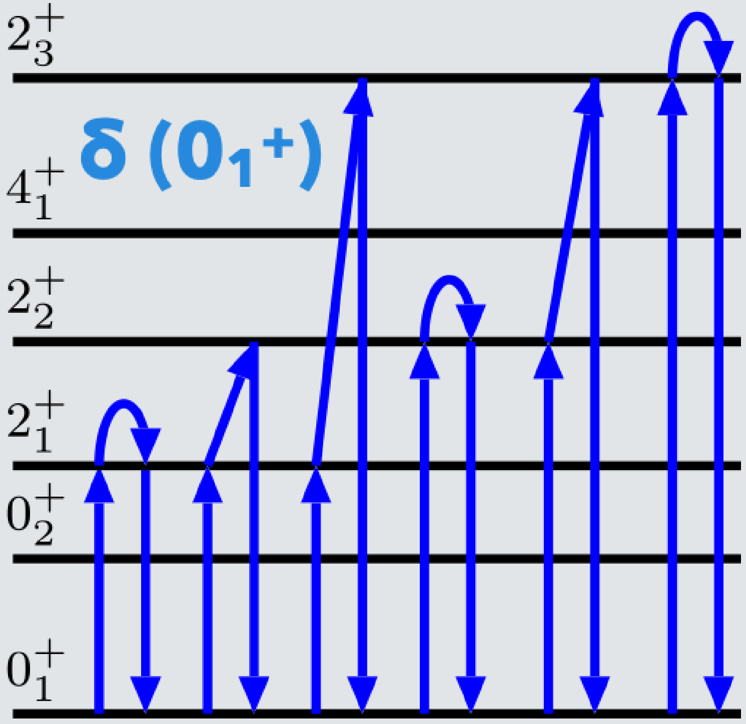


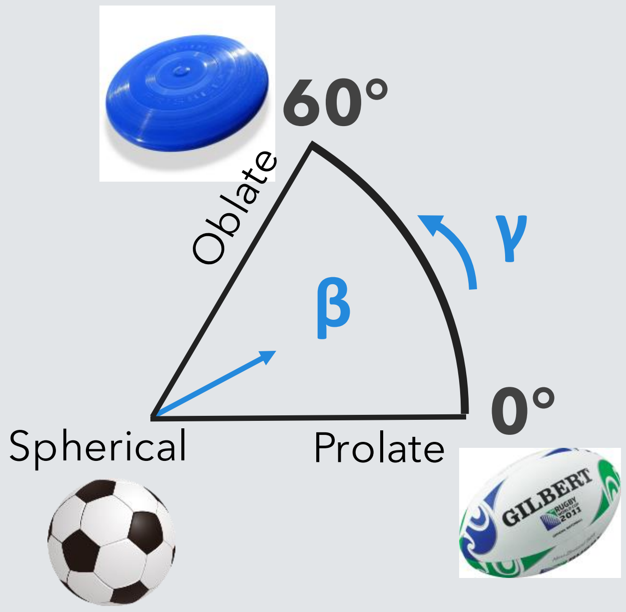
GOSIA Code


Measured γ-ray Intensities
Level scheme
χ² minimization procedure
Particle and γ detectors geometry
Available Spectroscopic Data
BR, τ, δ
Set of electromagnetic matrix elements

Deformation parameters



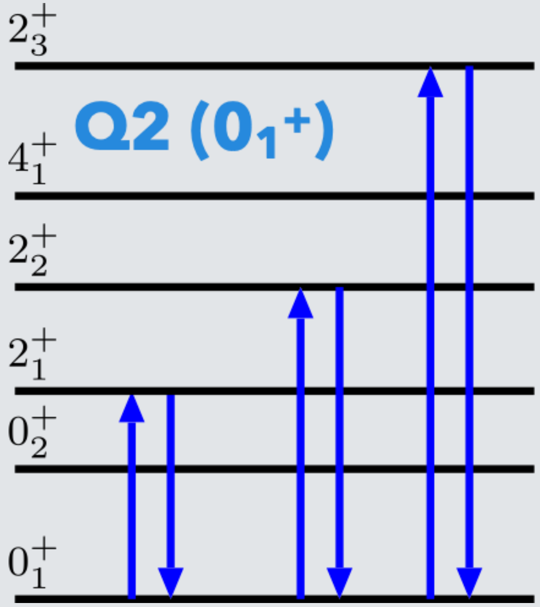


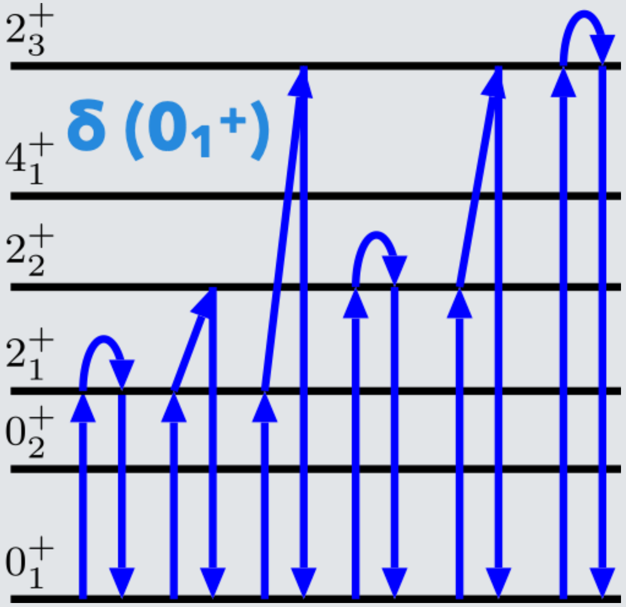


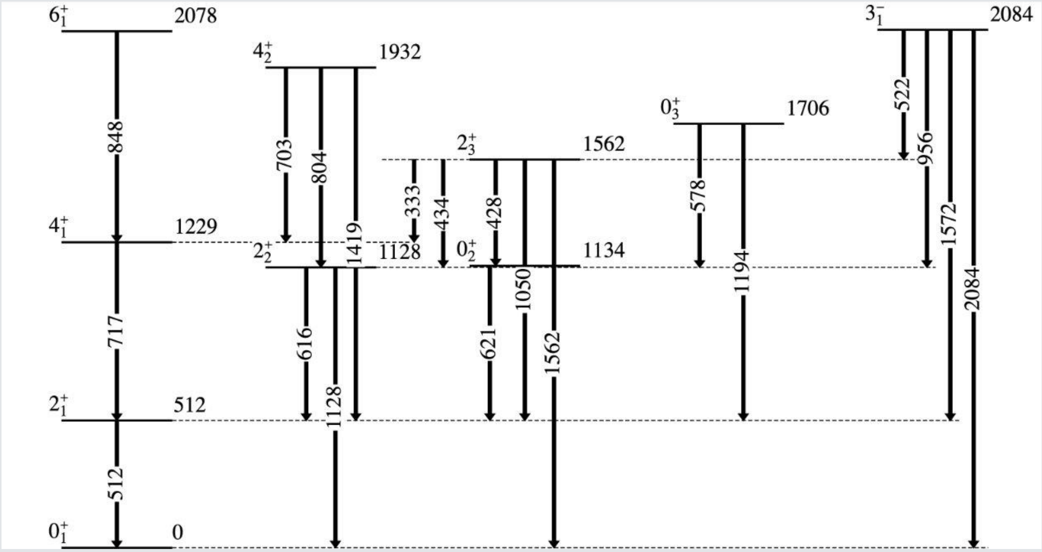
$$\langle J_n | Q^2 | J_n \rangle = \frac{\sqrt{5}\,(-1)^{2J_n}}{\sqrt{2J_n+1}} \sum_i M_{ni} M_{in} \begin{Bmatrix} 2 & 2 & 0 \\ J_n & J_n & J_i \end{Bmatrix}$$

$$\langle J_n | Q^3 \cos 3\delta | J_n \rangle = -\sqrt{\frac{35}{2}} \frac{(-1)^{2J_n}}{2J_n+1} \sum_{ij} M_{ni} M_{ij} M_{jn} \begin{Bmatrix} 2 & 2 & 2 \\ J_n & J_j & J_i \end{Bmatrix}$$

Deformation parameters







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Preliminary – Deformation parameters
Master Thesis A. Fini

Stato	Q^2 [e^{2}b^2]	$\cos 3\delta$	$\delta°$ ($\gamma°$)	β	Q^2_{Sven} [e^{2}b^2]	$\delta°_{Sven}$
0_1^+	0.68(2)	0.47(4)	20.7(9)	0.233(3)	0.63(3)	20(2)

$$\langle Q^2 \rangle = q_0^2 \langle \beta^2 \rangle$$
$$\langle Q^3 \cos 3\delta \rangle = q_0^3 \langle \beta^3 \cos 3\gamma \rangle$$

L. Svensson et al. Nucl. Phys A, 584(547), 1995.

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0_2^+	1.00(2)	??	??	0.282(3)	0.87(4)	

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0_2^+	1.00(2)	??	??	0.282(3)	0.87(4)	
0_3^+	>0.05					

$$\langle Q^2 \rangle = q_0^2 \langle \beta^2 \rangle$$
$$\langle Q^3 \cos 3\delta \rangle = q_0^3 \langle \beta^3 \cos 3\gamma \rangle$$

Thank You for your Attention

TANDEM ACCELERATOR

Searching for intruder bands in ^{106}Pd via Coulomb excitation

AGATA + SPIDER

Spokespersons: N. Marchini, A. Nannini, D. Kalaydjieva, M. Rocchini

N. Marchini[1,2], A. Nannini[2], D. Kalaydjieva[3], M. Rocchini[2], M. Balogh[4], G. Benzoni[5], D. Brugnara[4], G. Colucci[6], D. T. Doherty[7], A. Ertoprak[8], C. Fahlander[9], F. Galtarossa[10], P. E. Garrett[11], A. Goasduff[4], A. Gottardo[4], K. Hadyńska-Klęk[6], G. Jaworski[6], M. Komorowska[6], W. Korten[12], M. Matejska-Minda[13], D. Mengoni[10,14], P. Napiorkowski[6], G. Pasqualato[3], I. Pietka[15], R. M. Perez-Vidal[16], L. Prochniak[6], T. Rodríguez[17], M. Siciliano[8], J. Srebrny[6], K. Stoychev[3], J. J. Valiente-Dobón[4], K. Wrzosek-Lipska[6], M. Zielińska[12]

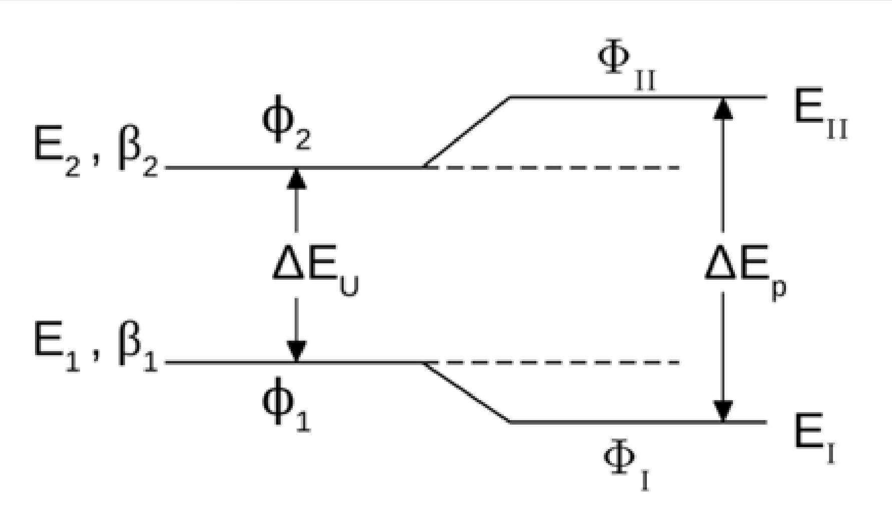
[1] *Università degli Studi di Firenze, Firenze, Italy.* [2] *INFN Sezione di Firenze, Firenze, Italy.* [3] *IJCLab, IN2P3/CNRS, Universite Paris-Saclay, Orsay, France.* [4] *INFN Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy.* [5] *INFN Sezione di Milano, Milano, Italy.* [6] *Heavy Ion Laboratory, University of Warsaw, Warsaw, Poland.* [7] *University of Surrey, Guildford, UK.* [8] *Argonne National Laboratory, Argonne, USA.* [9] *University of Lund, Lund, Sweden.* [1]*0 INFN Sezione di Padova, Padova, Italy.* [11] *University of Guelph, Guelph, Canada.* [12] *IRFU, CEA Saclay, Université Paris-Saclay, France.* [13] *IFJ-PAN, Kraków, Poland.* [14] *Università degli Studi di Padova, Padova, Italy.* [15] *University of Warsaw, Warsaw, Poland.* [16] *IFIC, CSIC-Universidad de Valencia, Valencia, Spain.* [17] *Universidad Complutense de Madrid, Madrid, Spain.*

The ^{106}Pd isotope

N. Marchini et al. Phys. Rev. C 105, 054304 (2022)

Two Level Mixing model

$$\rho^2(0_2^+ \to 0_1^+) = \left(\frac{3Z}{4\pi}\right)^2 a^2(1-a^2)[(\beta_1^2 - \beta_2^2) + \frac{5\sqrt{5}}{21\sqrt{\pi}}(\beta_1^3 cos3\gamma_1 - \beta_2^3 cos3\gamma_2)]^2$$



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Second Order in β
E. Svensson et al. In: Nuclear Physics A, 584, 547 (1995)

$$\beta^2(0_1) = a^2\beta_1^2 + b^2\beta_2^2$$
$$\beta^2(0_2) = b^2\beta_1^2 - a^2\beta_2^2$$

Small Mixing

The ^{106}Pd isotope

N. Marchini et al. Phys. Rev. C 105, 054304 (2022)

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β_1,β_2 and γ_1 are extracted in Coulex exp.
E. Svensson et al. In: Nuclear Physics A, 584, 547 (1995)

Small Mixing Assumption

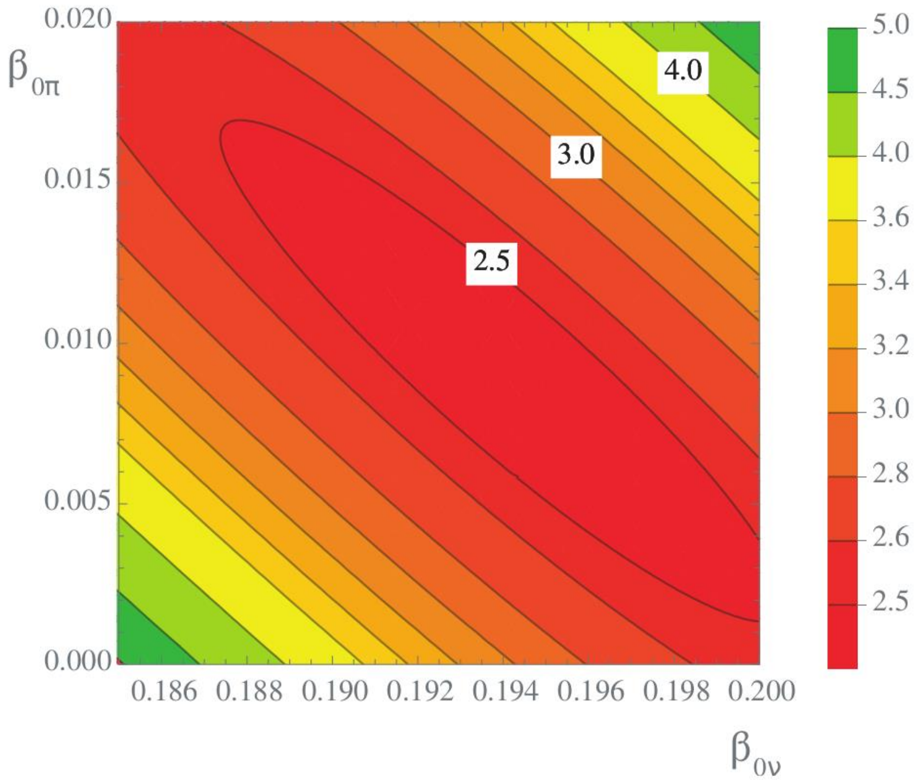
Shape coexistence scenario

(β_1 = 0.29, γ_1 = 20°, β_2 = 0.21 , γ_2 = 45°)

IBM-2 Calculations

Focusing on the E0 transitions, in the IBM-2 model the E0 strength is defined as:

$$\rho^2(E0; J_i^+ \rightarrow J_f^+) = \frac{Z^2}{e^2 R^4} |\beta_{0\nu} \langle J_f | \hat{T}_\nu(E0) | J_i \rangle + \beta_{0\pi} \langle J_f | \hat{T}_\pi(E0) | J_i \rangle|^2$$



$\beta_{0\pi}$= 0.009 efm^2
$\beta_{0\nu}$= 0.194 efm^2

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Nuclide	$J_i^\pi \longrightarrow J_f^\pi$	E_γ [keV]	$\rho^2_{exp} \cdot 10^3$		$\rho^2_{calc} \cdot 10^3$
^{104}Pd	$0_2^+ \longrightarrow 0_1^+$	1334	11(2)	*	10
^{104}Pd	$2_2^+ \longrightarrow 2_1^+$	786	5(4)	*	1
^{104}Pd	$4_2^+ \longrightarrow 4_1^+$	759	< 90		0.5
^{106}Pd	$0_2^+ \longrightarrow 0_1^+$	1134	17(4)	*	16
^{106}Pd	$0_4^+ \longrightarrow 0_1^+$	2001	< 19		0.3
^{106}Pd	$0_4^+ \longrightarrow 0_2^+$	867	< 90		4
^{106}Pd	$2_2^+ \longrightarrow 2_1^+$	616	5(8)		1
^{106}Pd	$2_3^+ \longrightarrow 2_1^+$	1050	26(11)	*	28
^{106}Pd	$2_4^+ \longrightarrow 2_1^+$	1398	21^{+10}_{-21}		0.1
			18^{+10}_{-18}		
^{106}Pd	$2_5^+ \longrightarrow 2_2^+$	1115	96^{+43}_{-61}		18
^{100}Ru	$0_2^+ \longrightarrow 0_1^+$	1130	10.3(18)	*	11.4
^{102}Ru	$0_2^+ \longrightarrow 0_1^+$	944	14(3)	*	17

IBM-2 Calculations

Focusing on the E0 transitions, in the IBM-2 model the E0 strength is defined as:

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Nuclide	$J_i^\pi \longrightarrow J_f^\pi$	E_γ [keV]	$\rho^2_{exp} \cdot 10^3$		$\rho^2_{calc} \cdot 10^3$
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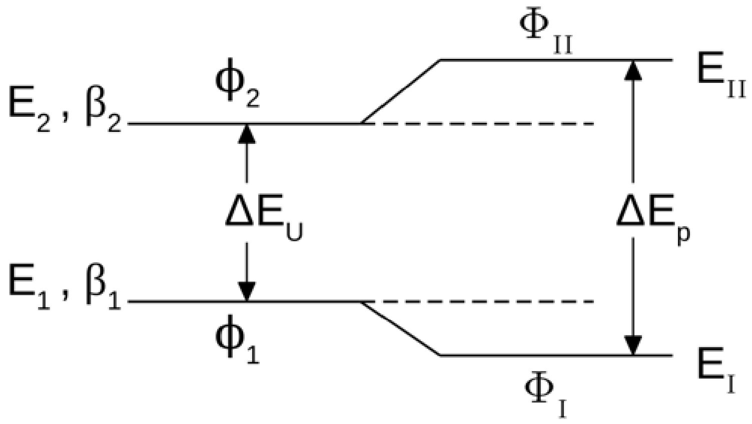
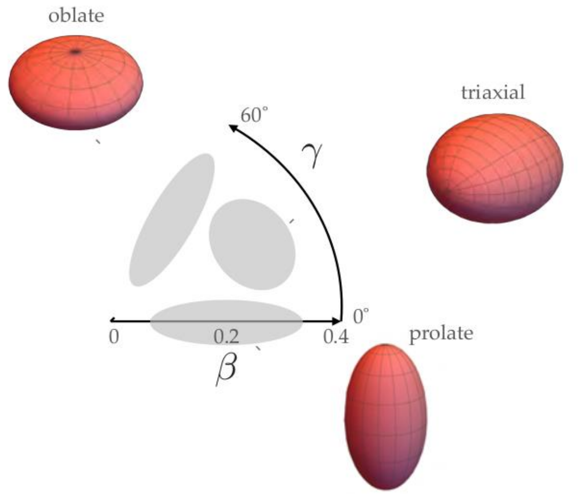
0_3 as Intruder State

Two-Level Mixing



$$\rho^2(0_2^+ \rightarrow 0_1^+) = (\frac{3Z}{4\pi})^2 a^2(1-a^2)[(\beta_1^2 - \beta_2^2) + \frac{5\sqrt{5}}{21\sqrt{\pi}}(\beta_1^3 cos3\gamma_1 - \beta_2^3 cos3\gamma_2)]^2$$

A. S. Davydov et al., Nucl. Phys. 27, 134 (1961)



Two-Level Mixing

As a first step, only the terms up to the second order in β have been considered. In this approximation the expression for the E0 strength becomes:

$$\rho^2(0_2^+ \to 0_1^+) = (\frac{3Z}{4\pi})^2 a^2 (1-a^2) |(\beta_1^2 - \beta_2^2)|^2 \quad = 17$$

β unmixed could be linked with the $\beta(0_1)$ and $\beta(0_2)$ thank to the Quadrupole Sum Rules

$$\beta^2(0_1) = \frac{1}{k_0^2}\frac{1}{5}\sum_m \langle 0_1 ||E2|| 2_m\rangle \langle 2_m ||E2|| 0_1\rangle$$

$$\begin{aligned}\beta^2(0_1) = \frac{1}{k_0^2}\frac{1}{5}[a^2 &\sum_m \langle 1 ||E2|| 2_m\rangle \langle 2_m ||E2|| 1\rangle \\ &+ ab\sum_m \langle 1 ||E2|| 2_m\rangle \langle 2_m ||E2|| 2\rangle \\ &+ ba\sum_m \langle 2 ||E2|| 2_m\rangle \langle 2_m ||E2|| 1\rangle \\ &+ b^2\sum_m \langle 2 ||E2|| 2_m\rangle \langle 2_m ||E2|| 2\rangle]\end{aligned}$$

→

$$\beta^2(0_1) = a^2\beta_1^2 + b^2\beta_2^2$$
$$\beta^2(0_2) = b^2\beta_1^2 - a^2\beta_2^2$$

Two-Level Mixing

As a first step, only the terms up to the second order in β have been considered. In this approximation the expression for the E0 strength becomes:

$$\rho^2(0_2^+ \to 0_1^+) = (\frac{3Z}{4\pi})^2 a^2(1-a^2)|(\beta_1^2 - \beta_2^2)|^2 \quad = 17$$

$\beta(0_1)$ and $\beta(0_2)$ are extracted in E. Svensson et al. In: Nuclear Physics A, 584, 547 (1995)

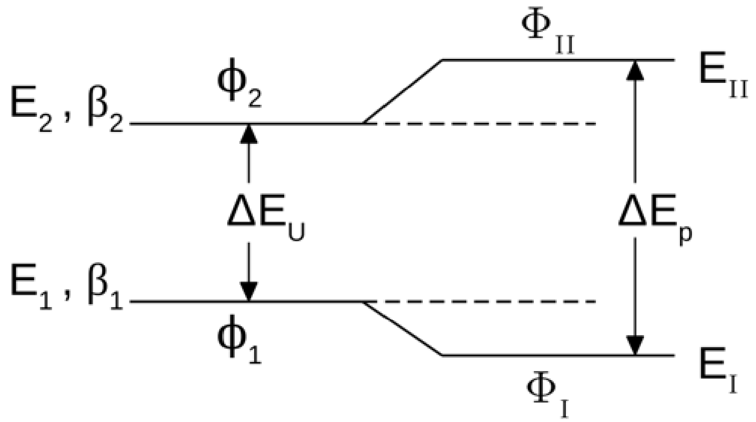
$$\beta^2(0_1) = a^2\beta_1^2 + b^2\beta_2^2 \quad = 0{,}47$$

$$\beta^2(0_2) = b^2\beta_1^2 - a^2\beta_2^2 \quad = 0{,}51$$

↓

$a^2 = 0.1$ Small Mixing

Two-Level Mixing



$$\rho^2(0_2^+ \to 0_1^+) = (\frac{3Z}{4\pi})^2 a^2(1-a^2)[(\beta_1^2 - \beta_2^2) + \frac{5\sqrt{5}}{21\sqrt{\pi}}(\beta_1^3 cos3\gamma_1 - \beta_2^3 cos3\gamma_2)]^2$$

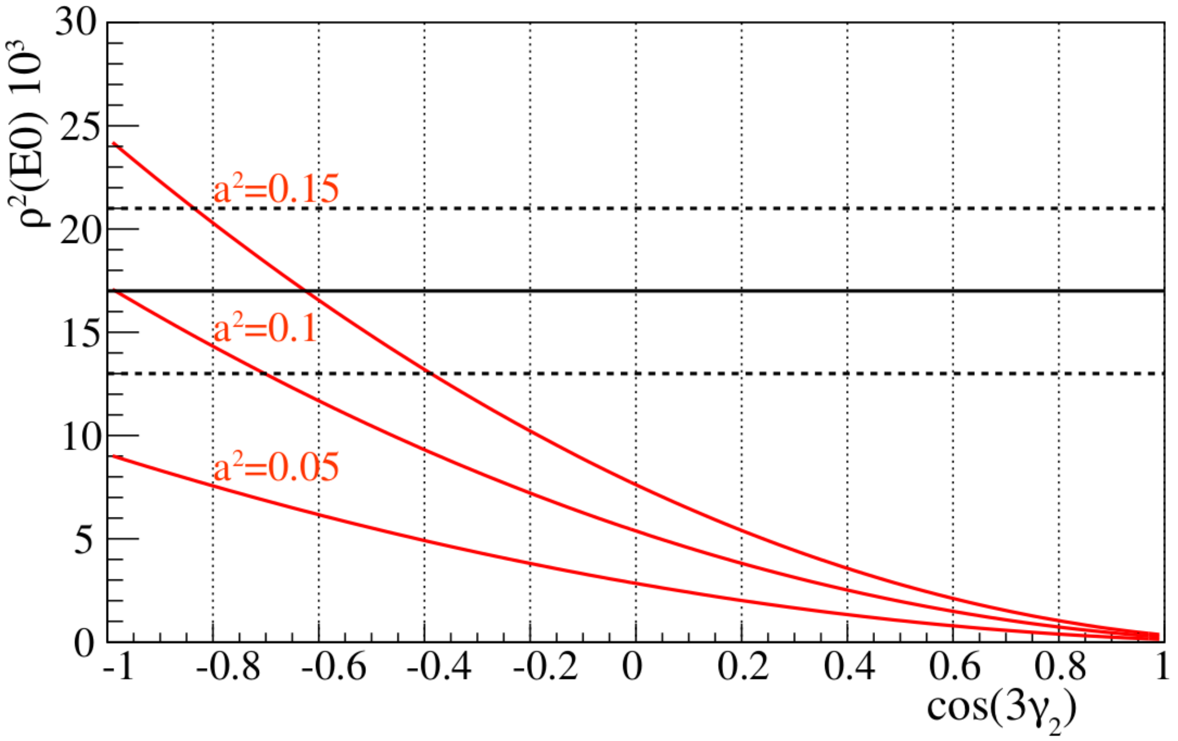
$$\beta^2(0_1) = a^2\beta_1^2 + b^2\beta_2^2$$
$$\beta^2(0_2) = b^2\beta_1^2 - a^2\beta_2^2$$

Case of Small Mixing ($a^2 = 0.1$) :
Assumption : Deformation of the 0_1^+ and the 0_2^+ states are similar to those of the $|1\rangle$ and $|2\rangle$ one

Two-Level Mixing – Small Mixing

$$\rho^2(0_2^+ \rightarrow 0_1^+) = (\frac{3Z}{4\pi})^2 a^2(1-a^2)[(\beta_1^2 - \beta_2^2) + \frac{5\sqrt{5}}{21\sqrt{\pi}}(\beta_1^3 cos3\gamma_1 - \beta_2^3 cos3\gamma_2)]^2$$

β_1,β_2 and γ_1 are extracted in E. Svensson et al. In: Nuclear Physics A, 584, 547 (1995)



β_1 = 0,29
β_2 = 0,21
γ_1 = 20°
γ_2 = 45°

Shape coexistence