Seminario fine 1° anno dottorato

November 17 - 18, 2014

Study of Ca isotopes via neutron capture reactions

Istituto Nazionale di Fisica Nucleare

Giovanni Bocchi
Milano - 2014

Outline

- Physics motivation
  - ✓ coupling between collective phonon excitation and single particle states: focused on doubly magic ^{48}Ca
- ^{49}Ca: previous results from Prisma-Clara Campaign (LNL)
- The (n,γ) campaign with EXOGAM @ ILL(Grenoble)
  - ✓ Exogam: $^{48}Ca(n,\gamma)^{49}Ca$
  - ✓ Exogam + $LaBr_3$: $^{46}Ca(n,\gamma)^{47}Ca$
- Preliminary results on $^{41,45,49}Ca$ isotopes
  - ✓ Level Scheme
  - ✓ Binding Energy
  - ✓ Angular Correlations Spin-Parity & Multipolarity
- Conclusions & Future perspective

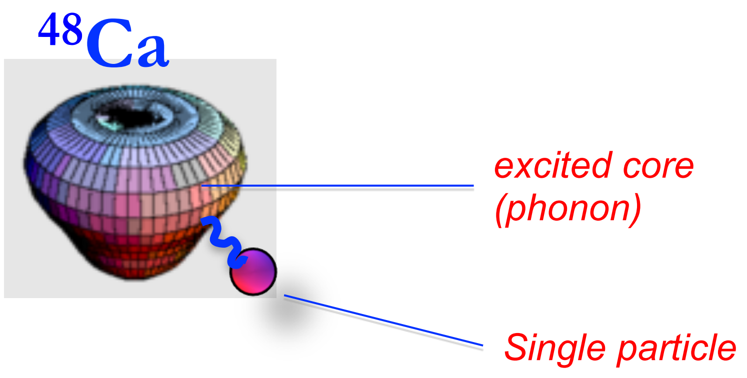
Study of the nuclear correlation around shell closure

- Focus on doubly magic ^{48}Ca
- Coupling between Particles and Core Vibrations (PVC)

Coupling between Particles and Phonon

Key Ingredient for:

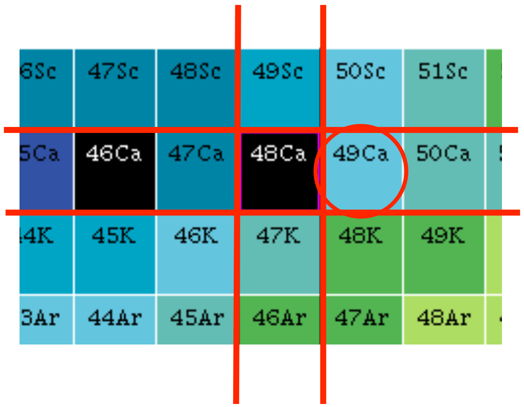
✓ Anharmonicity of vibrational spectra
✓ Damping of Giant Resonances
✓ Quenching of Spectroscopic Factors, …



Signature of Particle Vibration Coupling (PVC)

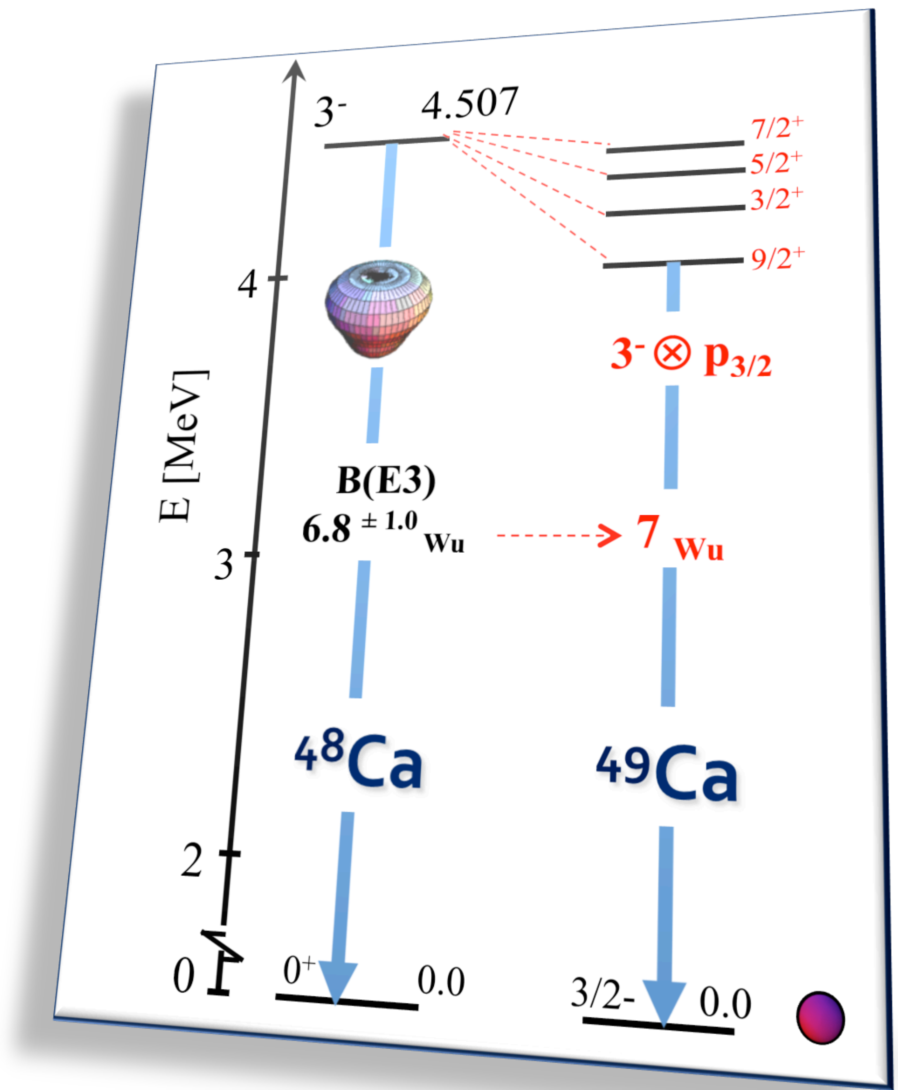
- Multiplet of States: $|\lambda - j| \leq I \leq \lambda + j$
- B(Eλ) of phonon

Z = 20



N = 28

$$^{49}Ca = {}^{48}Ca + 1\nu$$



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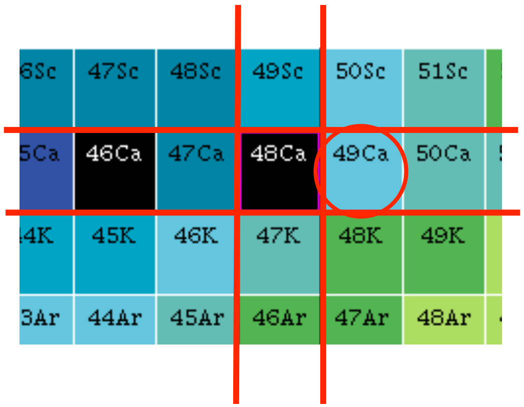
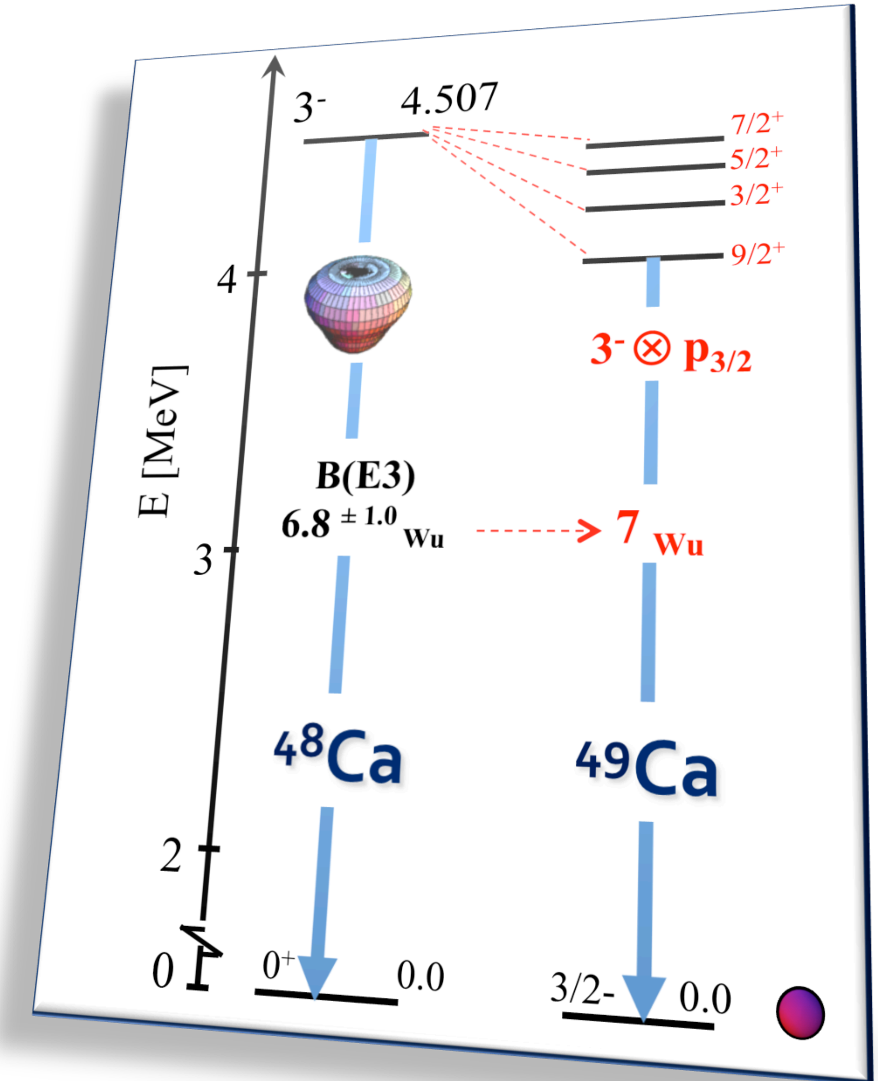


N = 28

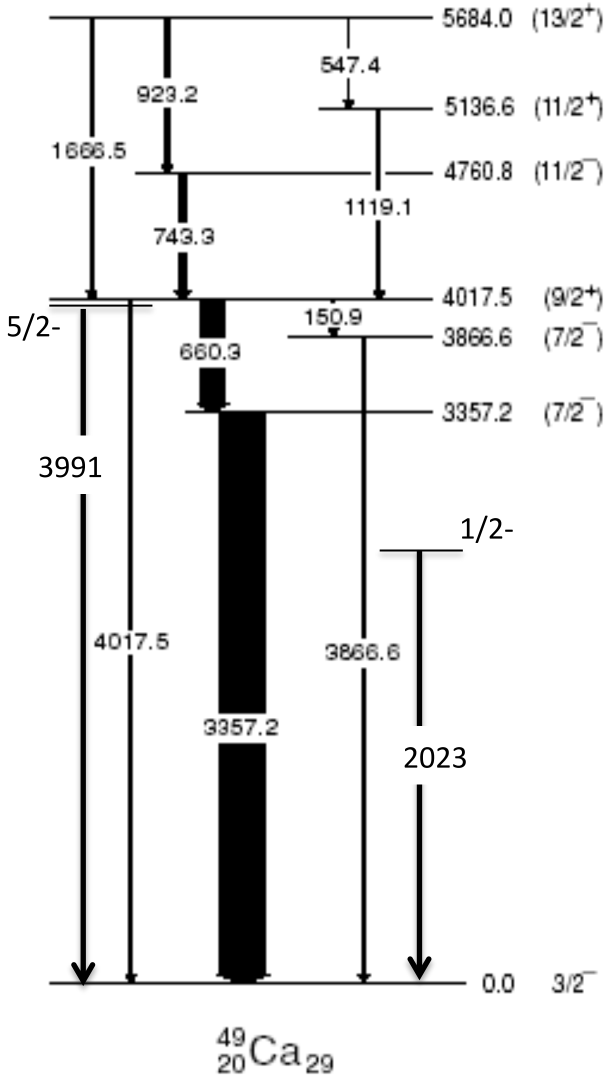
$$^{49}Ca = {}^{48}Ca + 1\nu$$

- **Angular Correlation or Distributions**
- **Polarizations**
- **Lifetimes**

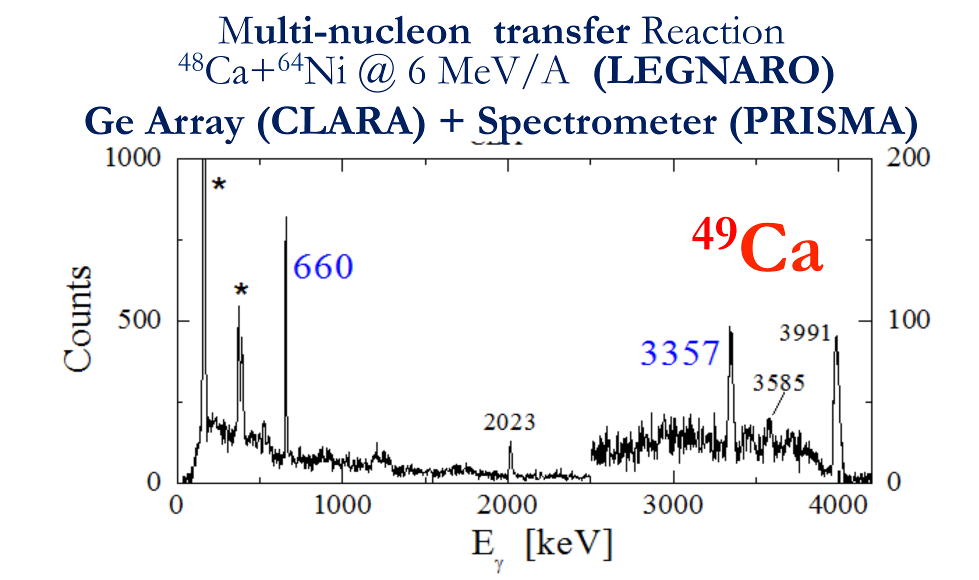
to firmly establish I^{π} and $B(E/M\lambda)$



^{49}Ca: ^{48}Ca +1ν

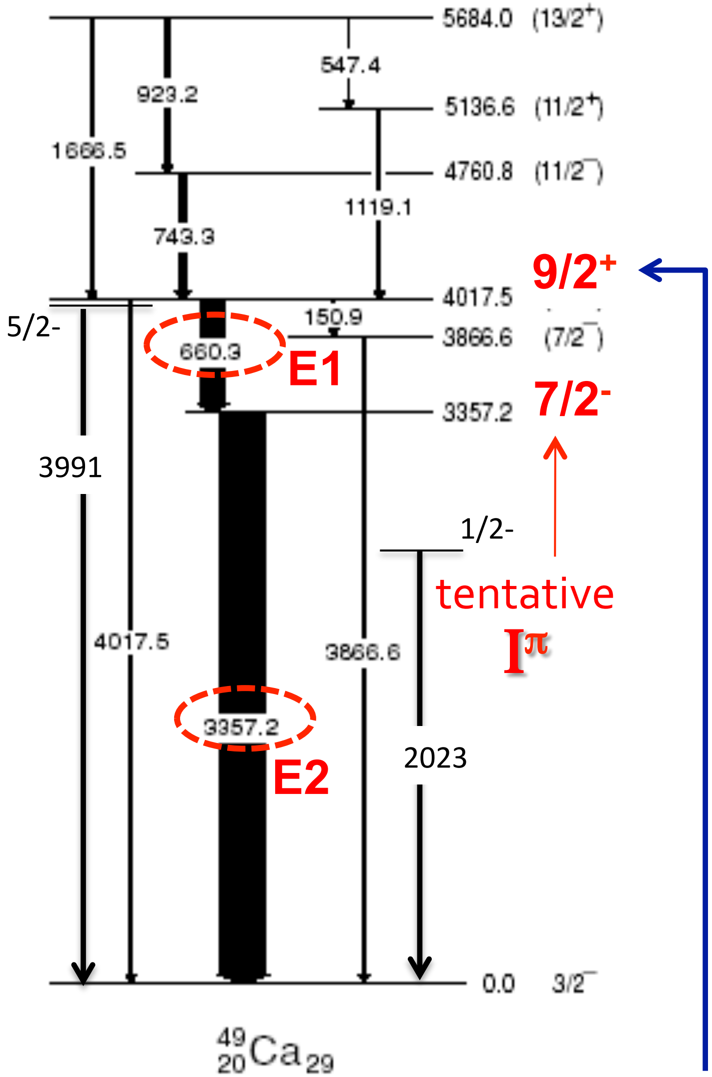


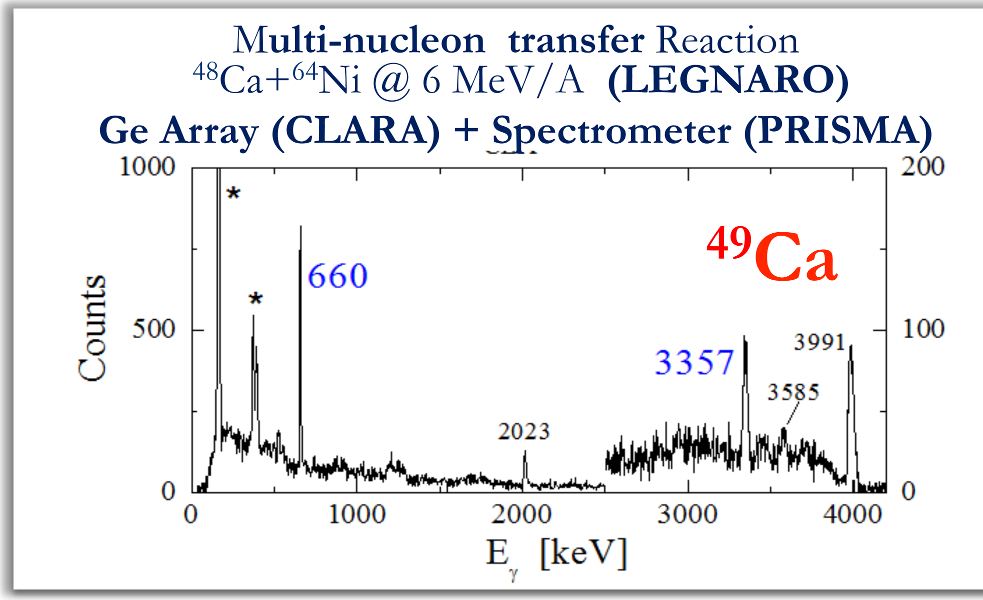
5684.0 (13/2+)
547.4
923.2
5136.6 (11/2+)
1666.5
4760.8 (11/2−)
1119.1
743.3
4017.5 (9/2+)
5/2-
150.9
3866.6 (7/2−)
660.3
3357.2 (7/2−)
3991
1/2-
4017.5
3866.6
3357.2
2023
0.0 3/2−
$^{49}_{20}$Ca$_{29}$



Multi-nucleon transfer Reaction
^{48}Ca+^{64}Ni @ 6 MeV/A (LEGNARO)
Ge Array (CLARA) + Spectrometer (PRISMA)
Counts
E_γ [keV]
^{49}Ca
660
3357
3991
3585
2023

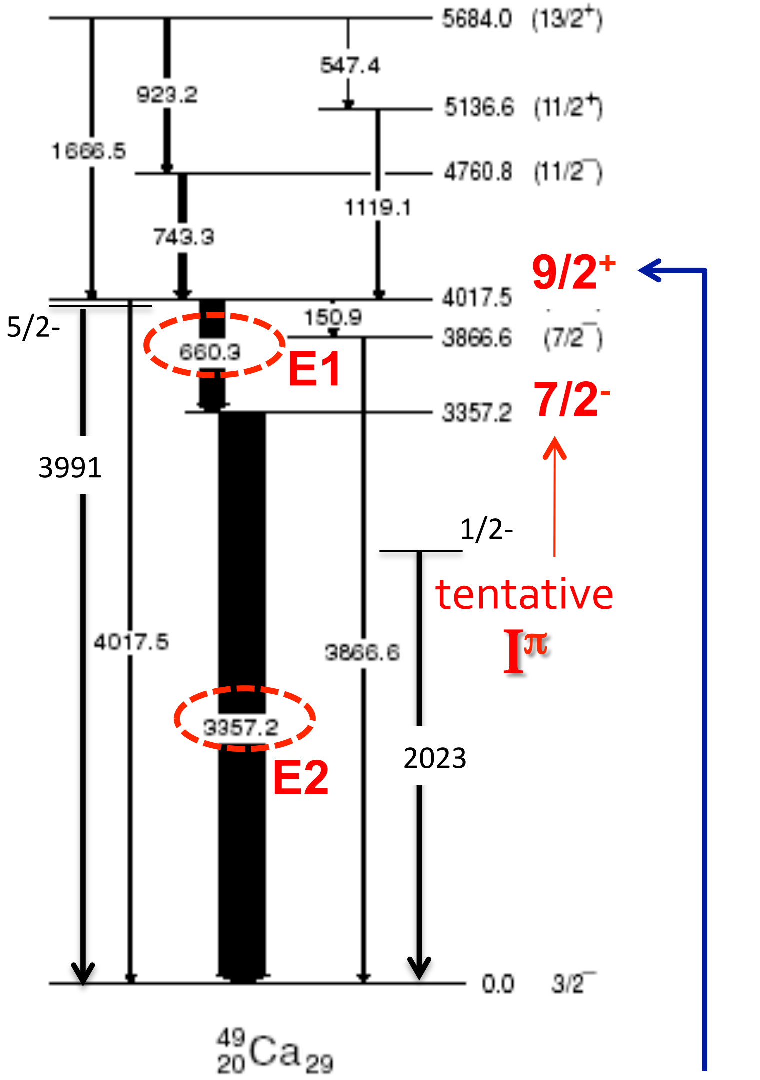
^{49}Ca: ^{48}Ca +1ν





$3^{-} \otimes p_{3/2} = 3/2^{+}, 5/2^{+}, 7/2^{+}, 9/2^{+}$

^{49}Ca: ^{48}Ca +1ν



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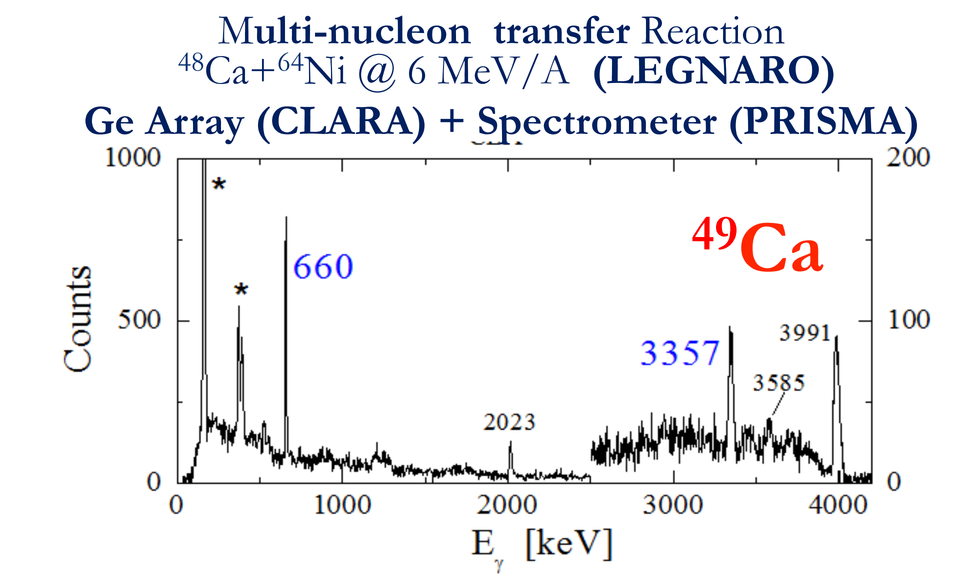


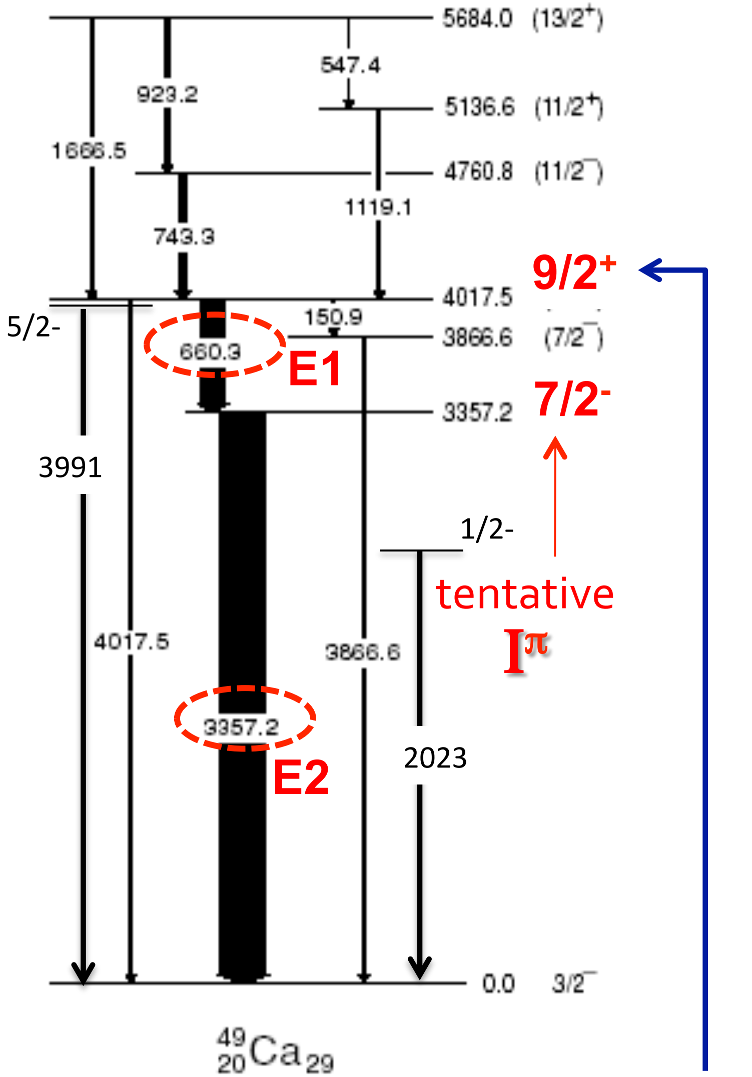
Prisma: selection of ^{49}Ca

Clara:

- 3 ring at 100° 130° and 150°: angular distribution
- Clover: polarization

→ **Determination of spin and parity of 9/2^{+}**

^{49}Ca: ^{48}Ca +1ν



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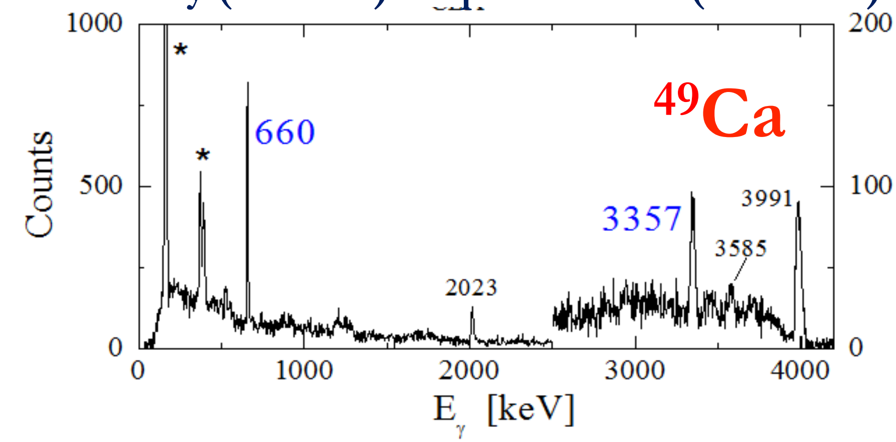
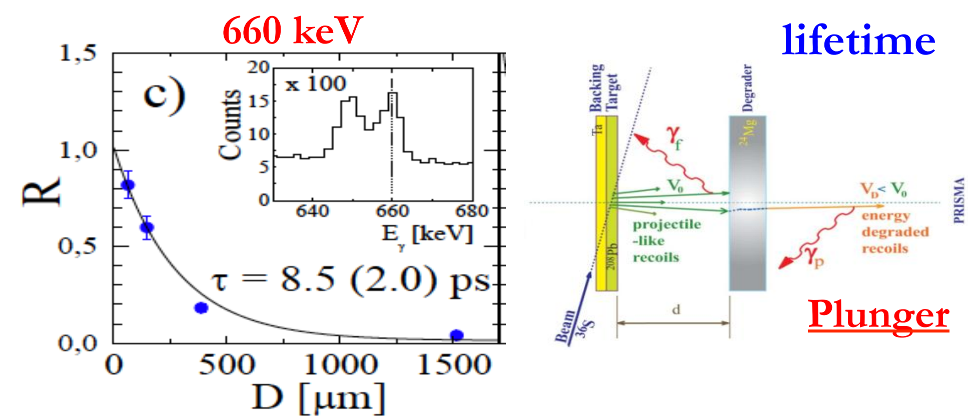
Multi-nucleon transfer Reaction

^{48}Ca+^{64}Ni @ 6 MeV/A **(LEGNARO)**

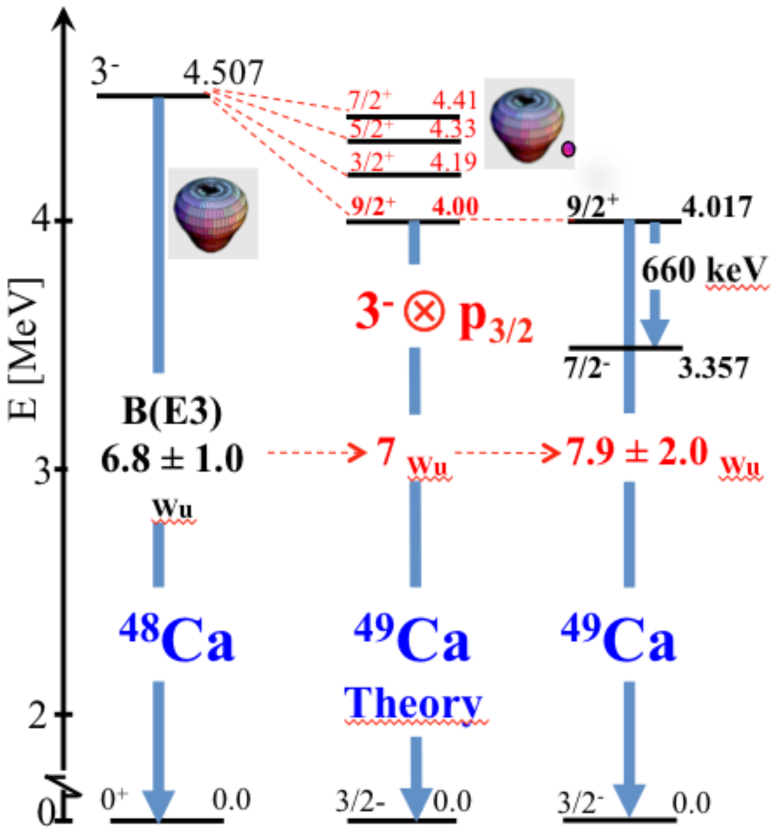
Ge Array (CLARA) + Spectrometer (PRISMA)





B(E3; 9/2^{+} → 3/2^{-}) = 7.9±2 W.u.

^{49}Ca: ^{48}Ca +1ν



Theoretical interpretation:

(G.Colò & P.F. Bortignon)

Particle phonon weak coupling model

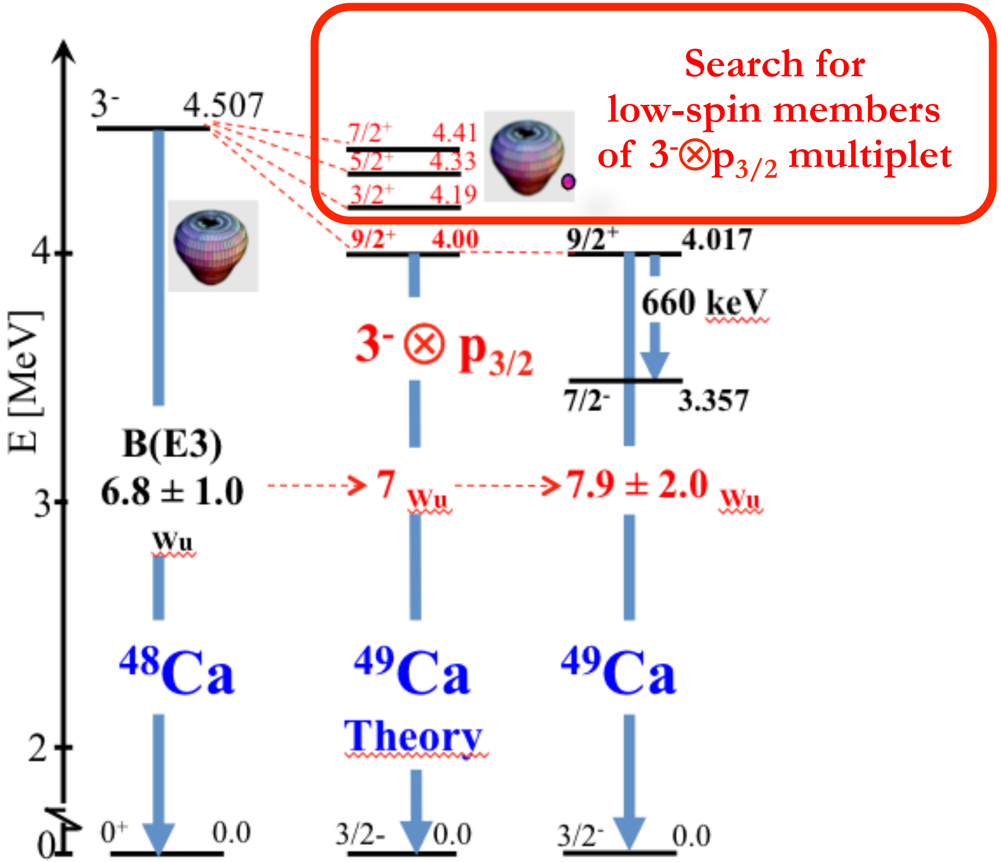
E_{th} = 4.00 MeV
E_{exp} = 4.017 MeV

$B(E3)_{th}$ = 7 W.u.
$B(E3)_{exp}$ = 7.9(20) W.u.

→ **Good agreement between theory and experiment**

D. Montanari, S. Leoni et al., PLB697(2011)288
D. Montanari, S. Leoni et al., PRC85, (2012)044301

^{49}Ca: $^{48}Ca + 1\nu$



What do we need?

- Reaction that favorites low spin states
- High Efficiency.
- Good Energy Resolution
- Very fast detectors: very good time resolution

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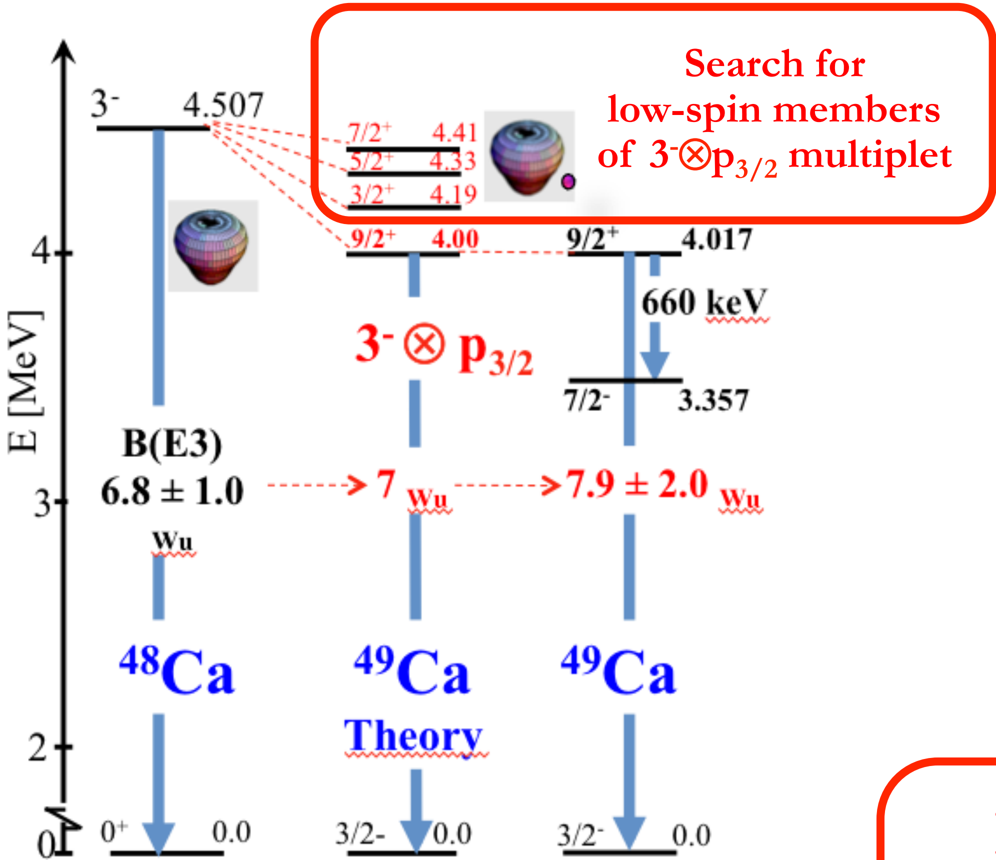

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Exogam campaign @ ILL
(Institut Laue Langevin – Grenoble, F)
Neutron Capture Reaction
→ ^{48}Ca(n,γ)^{49}Ca ←

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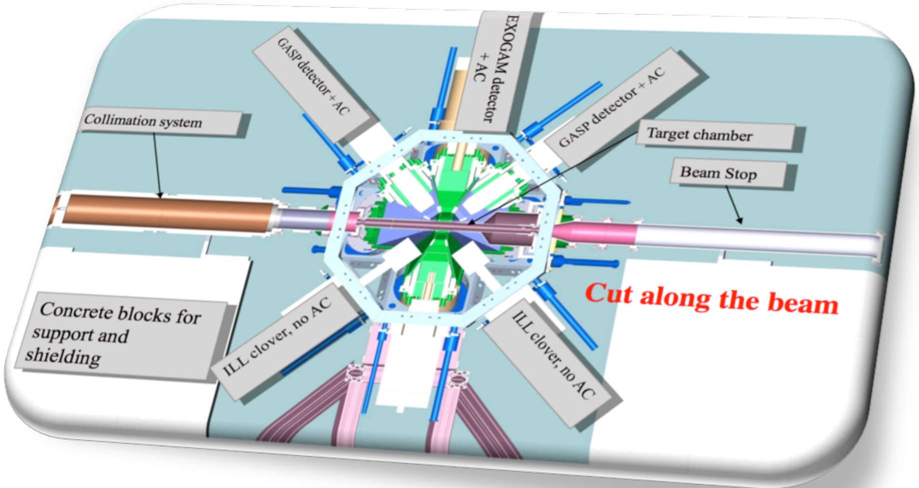
EXILL campaign @ ILL - Grenoble

Exogam

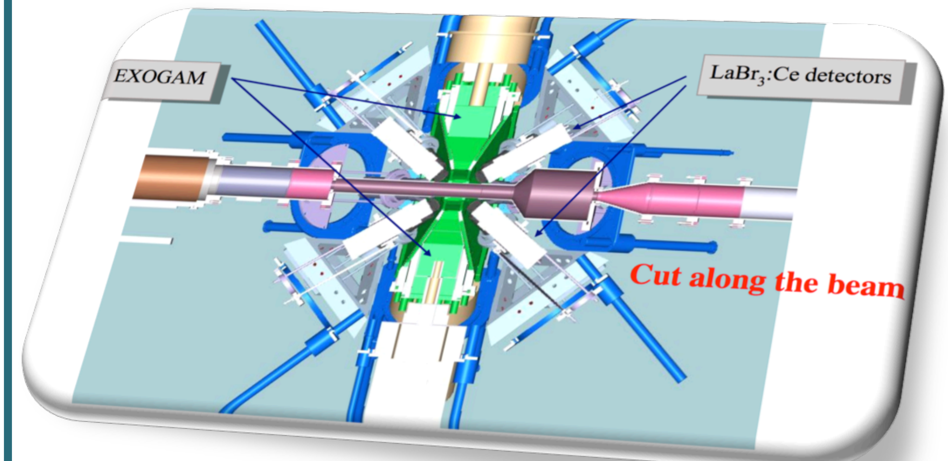


$^{48}Ca(n,\gamma)^{49}Ca$

- 8 EXOGAM clovers + BGO
- 6 GASP detectors
- 2 ILL clovers + BGO

✓ High efficiency for g-g-g
  - ➢ Level scheme (B.E.)
  - ➢ Spin/parity assignment

Exogam + Fast TIMing Array



$^{46}Ca(n,\gamma)^{47}Ca$

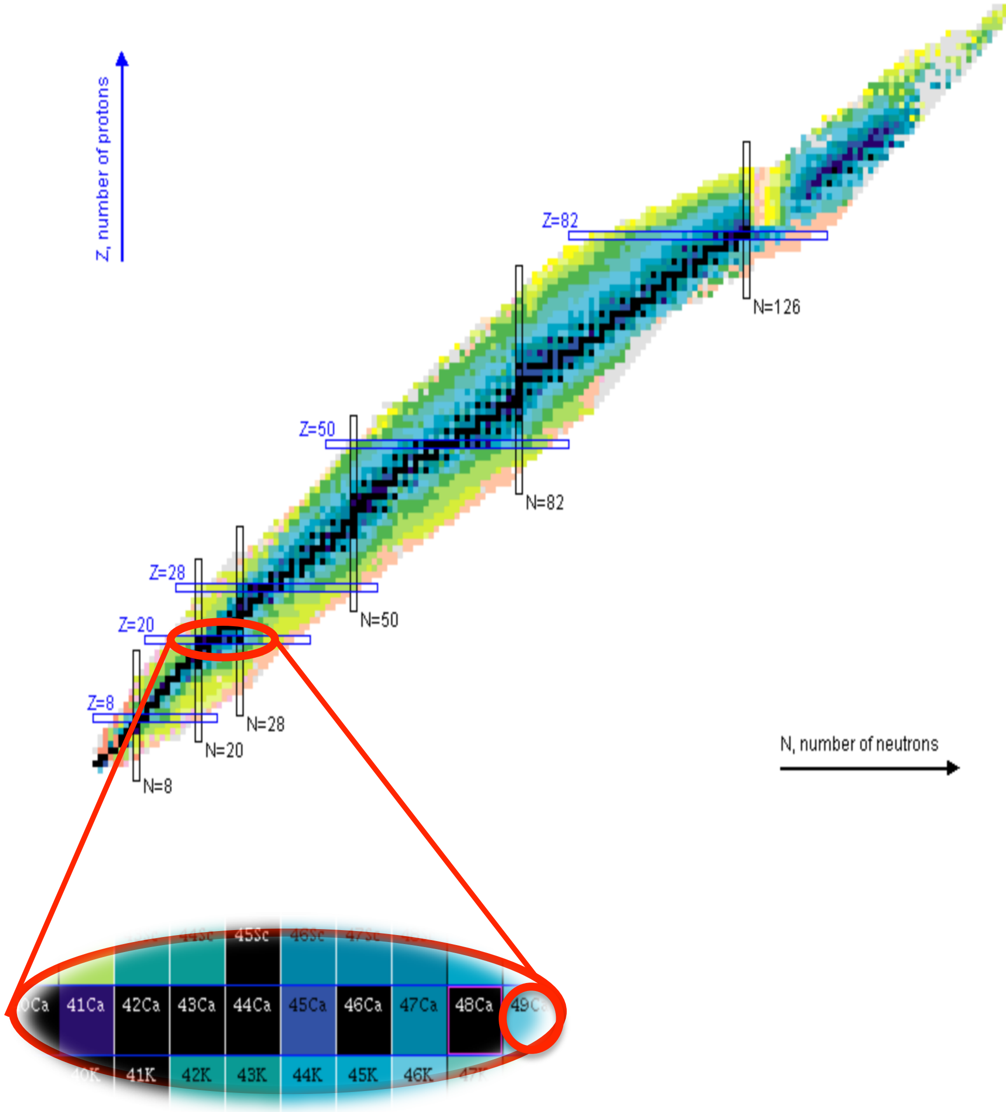
- 8 EXOGAM clovers + BGO
- 16 $LaBr_3$:Ce detectors

✓ Fast timing study
  - ➢ Lifetime measurements
  - ➢ Transition probability B(Eλ)

Ca target

Target of ^{48}Ca

(n,γ) reactions



<u>Isotopic composition</u>

%	Nucleus	σ(n,γ)(b)
27.9%	^{40}Ca	0.40760
0.30%	^{42}Ca	0.68310
0.10%	^{43}Ca	11.6600
2,50%	^{44}Ca	0.88840
<0.1%	^{46}Ca	0.74020
69.2%	^{48}Ca	1.09300

Target of ^{48}Ca
(n,γ) reactions

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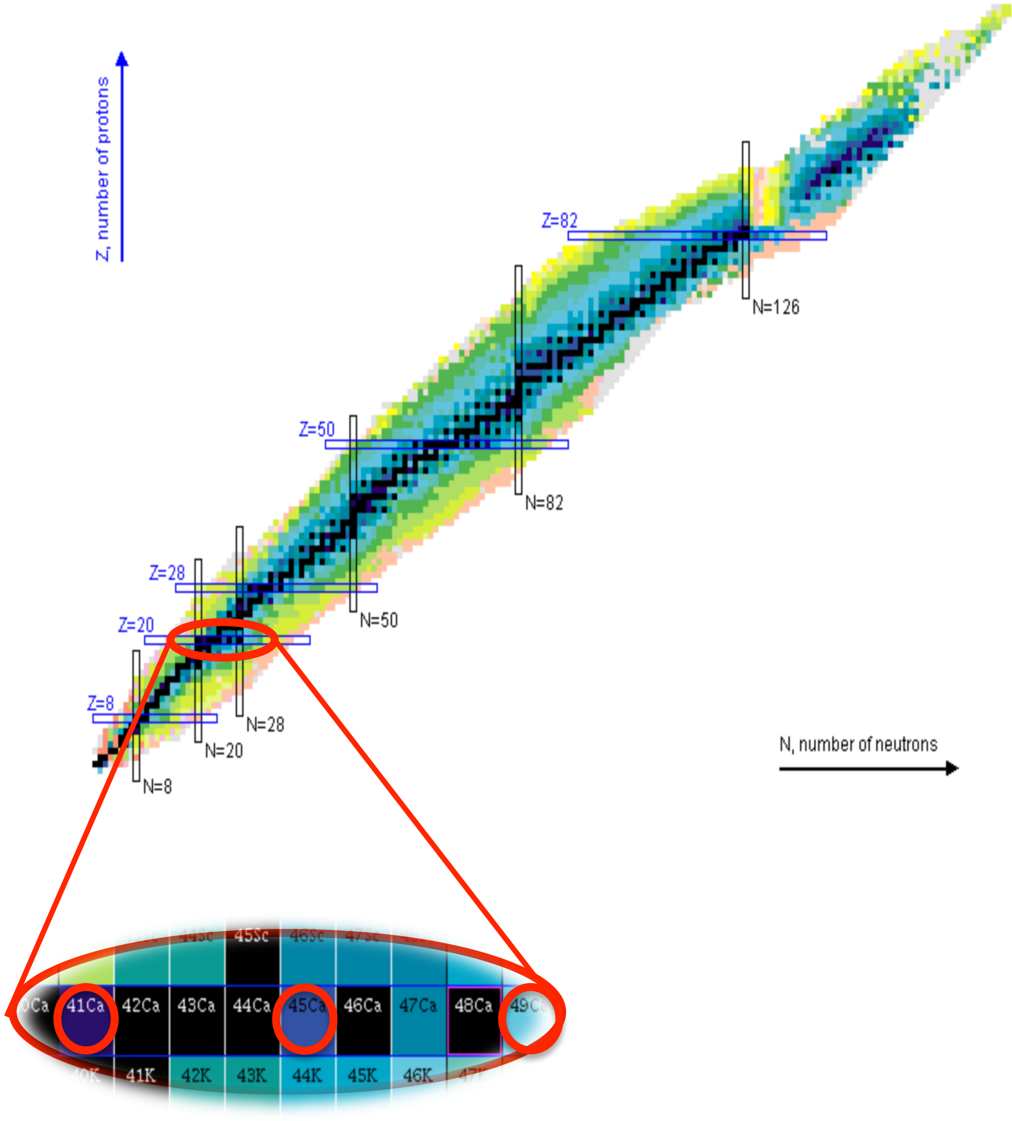
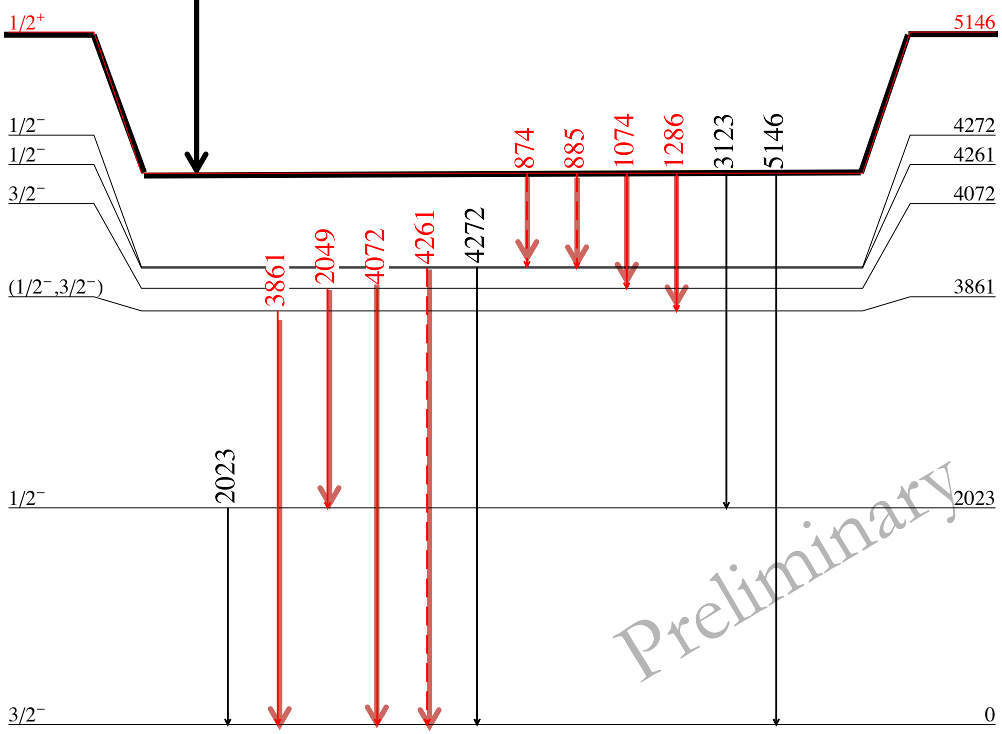


$^{48}Ca(n,\gamma)^{49}Ca$

Binding Energy (B.E.)



^{49}Ca

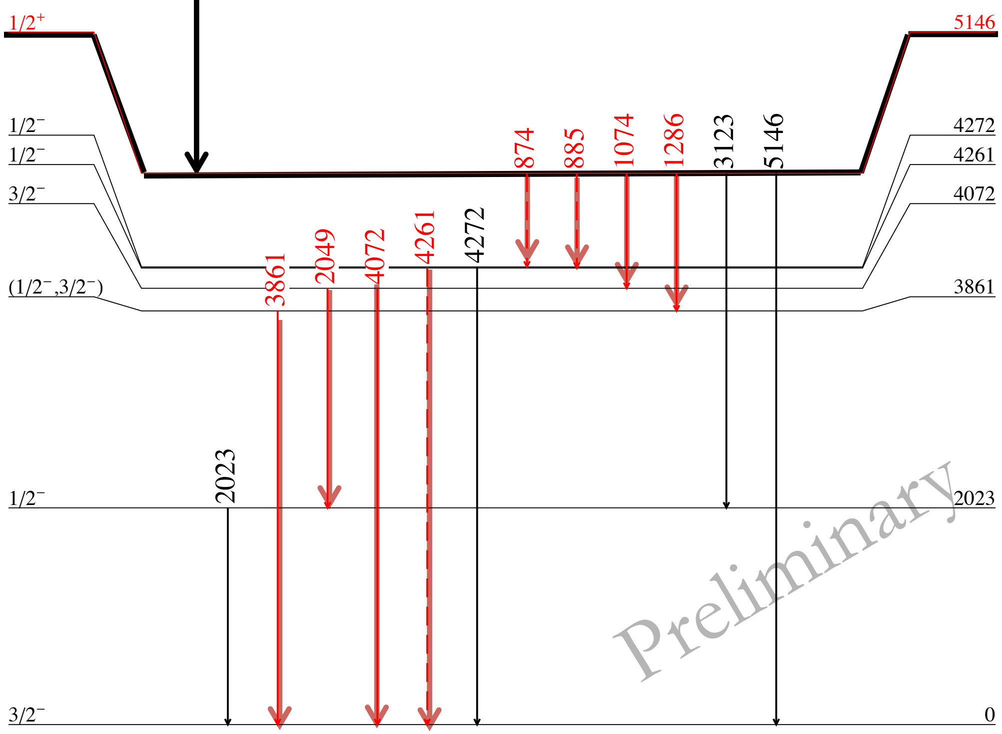
Only **NEGATIVE** Parity States are observed **$1/2^-$, $3/2^-$** (populated by *primary transitions*)

B.E. = 5146.46(50) keV

B.E. = 5146.45(18) keV (nndc)

$^{48}Ca(n,\gamma)^{49}Ca$

Binding Energy (B.E.)



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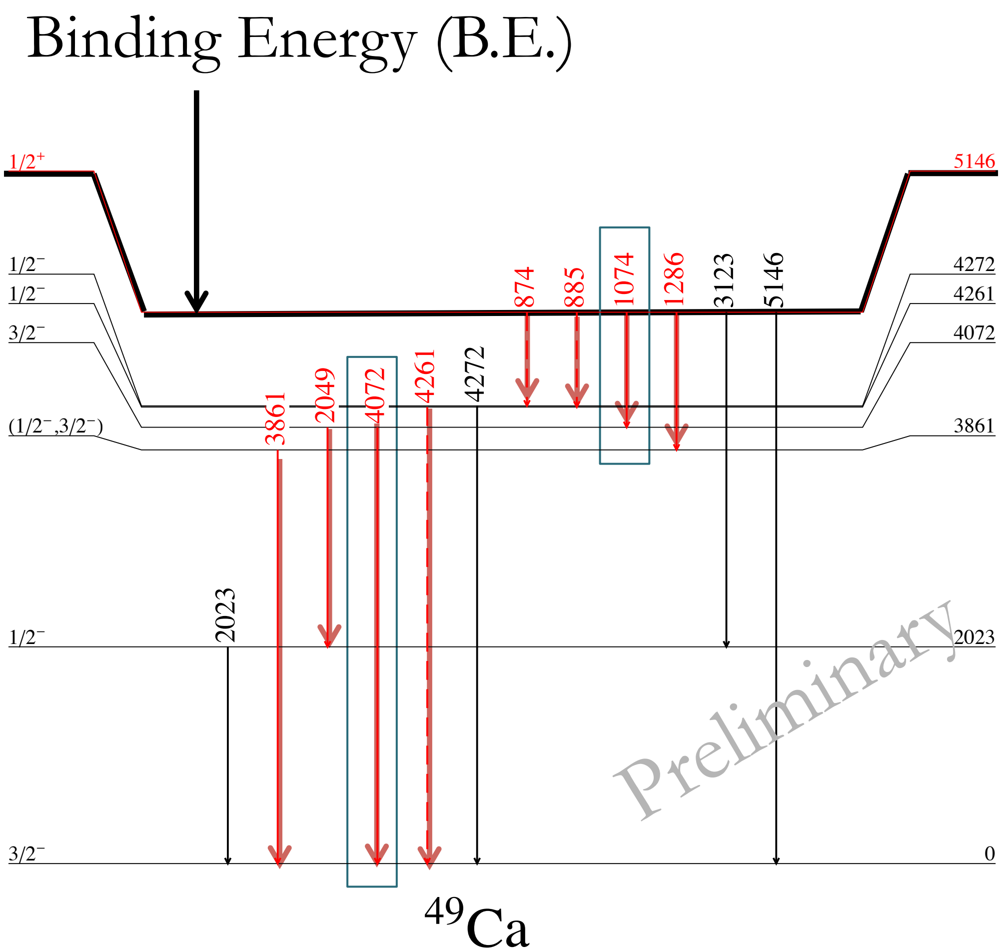
Difficult to observe positive parity $3^- \otimes p_{3/2}$ states around 4 MeV due to low-binding energy

$^{48}Ca(n,\gamma)^{49}Ca$



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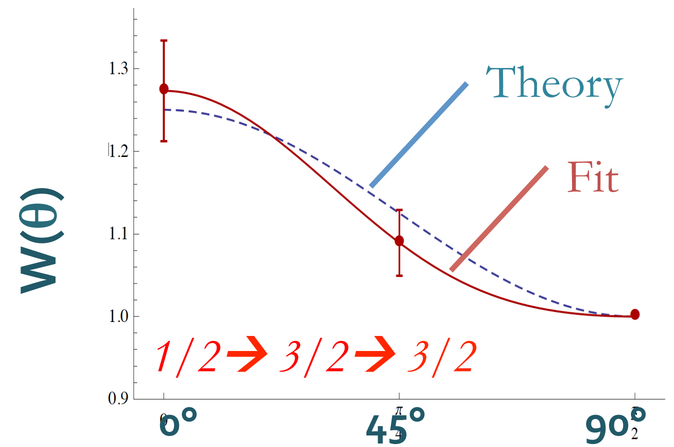
$$W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$$



Angular Correlation

Energy	M_γ	δ
1074	D+Q	-1.87
4072	D	//

$^{44}Ca(n,\gamma)^{45}Ca$

^{45}Ca

$\sigma(n,\gamma)$ (b) = 0.88840

$T_{1/2}$ = 162 d (β^-)

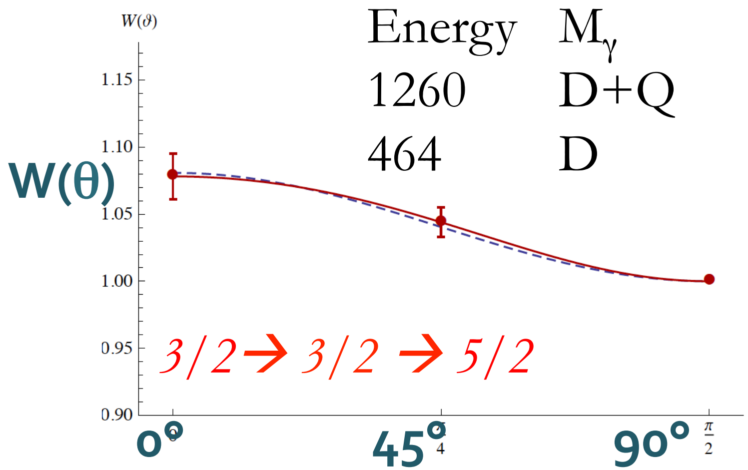
Binding Energy (B.E.)

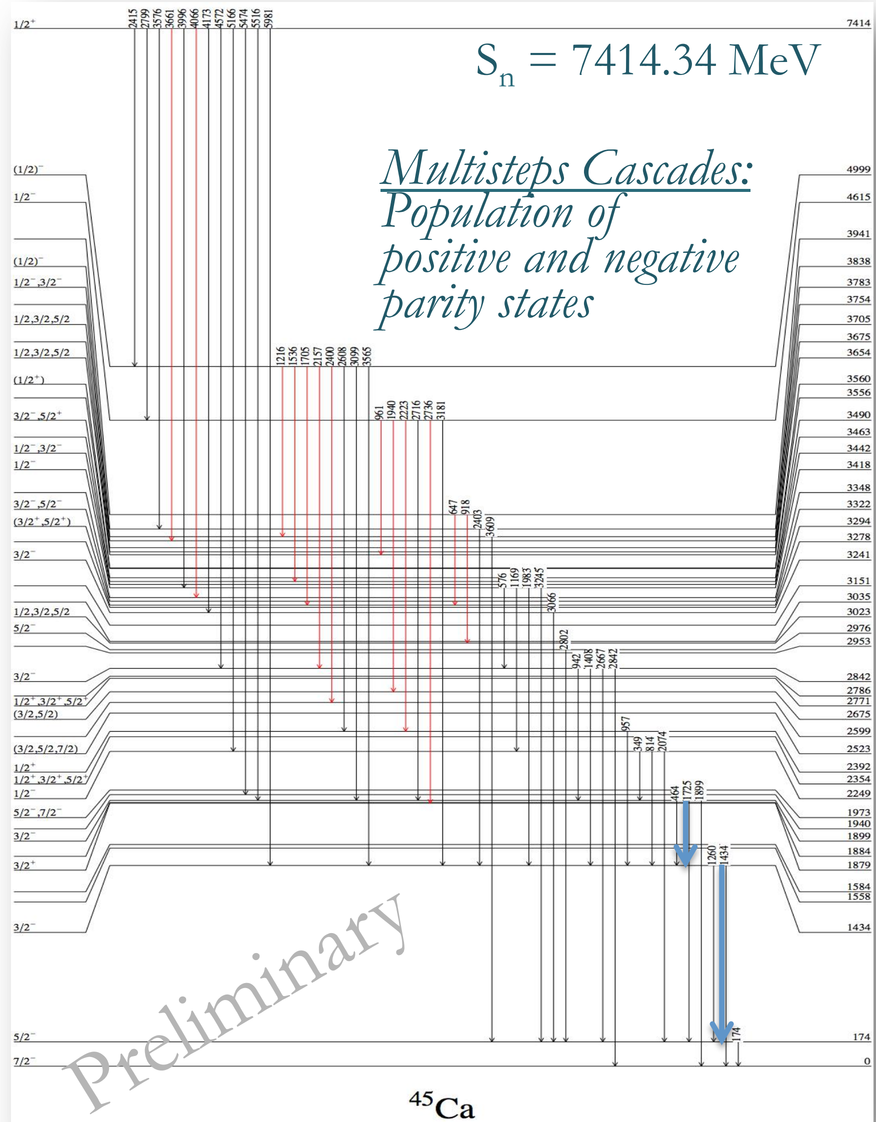
Exp = 7414.34(35) keV

NNDC = 7414.79(17) keV

Angular Correlation

Energy	M_γ	δ
1260	D+Q	-4.45
464	D	//





$^{40}Ca(n,\gamma)^{41}Ca$

^{41}Ca

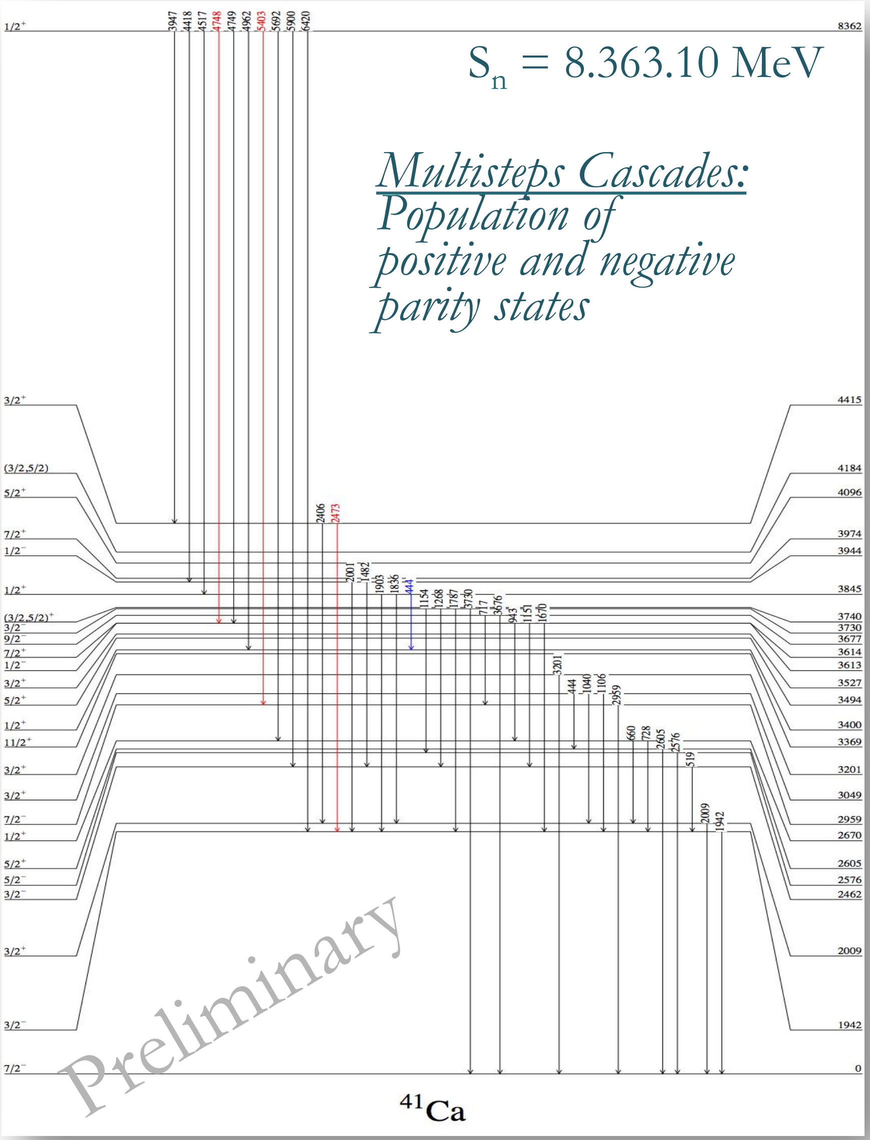
$\sigma(n,\gamma)$ (b) = 0.40760

$T_{1/2}$ = 1.02x10^5 y (β^-)

Binding Energy (B.E.)

Exp = 8363.10(42) keV

NNDC = 8362.70(26) keV



$^{40}Ca(n,\gamma)^{41}Ca$

^{41}Ca

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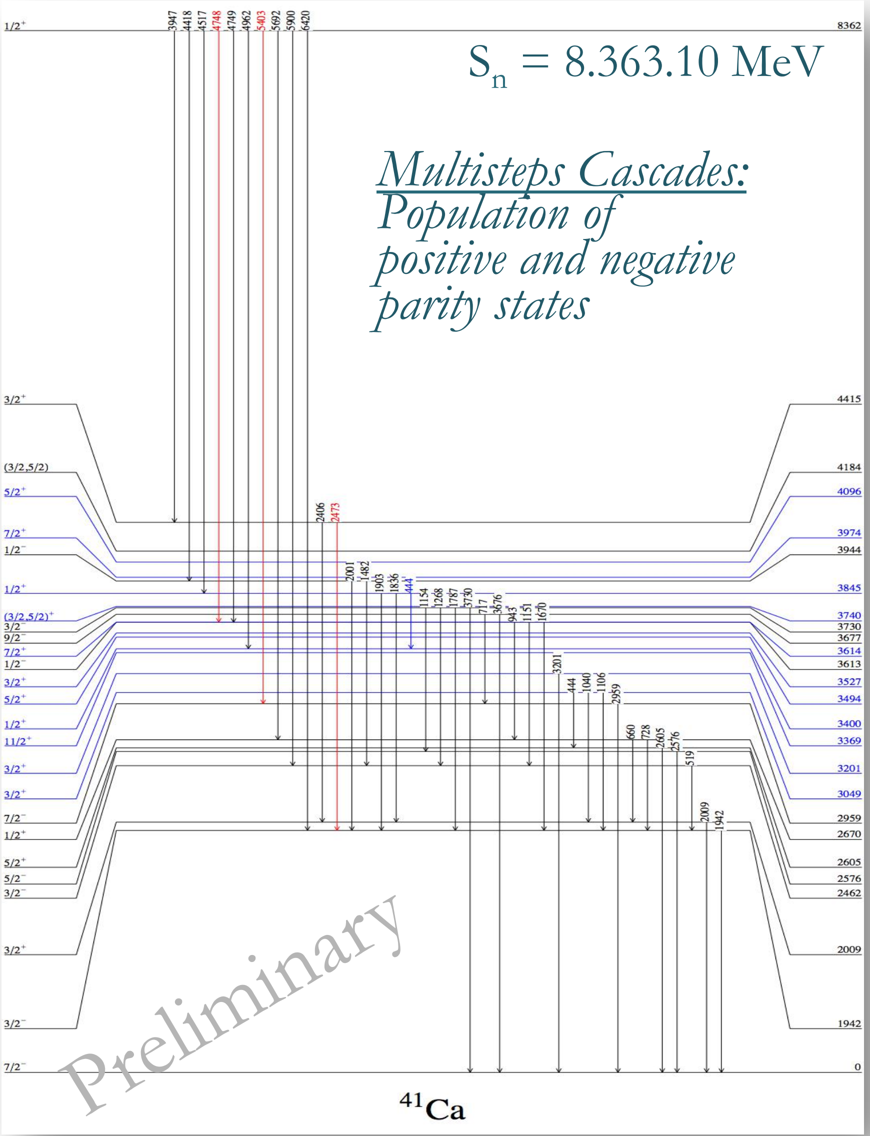


Search for Particle-Phonon (3$^-$) Couplings in ^{41,45}Ca

^{40}Ca: E(3$^-$) = 3737 keV, B(E3) = **30.7 Wu**

^{44}Ca: E(3$^-$) = 3308 keV, B(E3) = **7 Wu**

Multiplets: E= 3-4 MeV, 13/2$^+$, …, 1/2$^+$

→ Comparison with theory ←
(PVC & Shell Model)

Conclusion & Future Prospective

- Study the nuclear structure near close shells
- Study of the ^{49}Ca ^{45}Ca & ^{41}Ca
- Several new transitions
- Determination of spin/parity and multipolarity

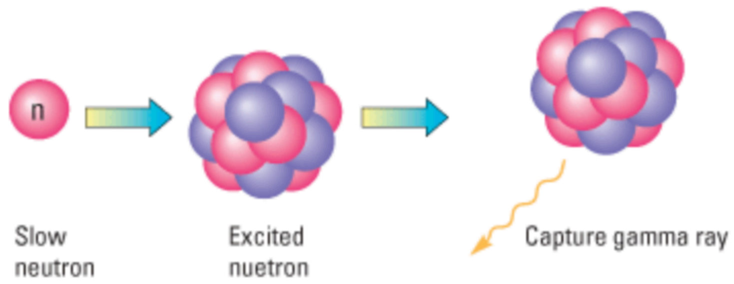
- Complete the study of the low spin members of the multiplet
  - ^{49}Ca: $3^{-} \otimes p_{3/2}$ → $9/2^{+}$, $7/2^{+}$, $5/2^{+}$ and $3/2^{+}$
  - ^{45}Ca: $3^{-} \otimes f_{7/2}$ → $13/2^{+}$, $11/2^{+}$, $9/2^{+}$, $7/2^{+}$, $5/2^{+}$, $3/2^{+}$ and $1/2^{+}$
  - ^{41}Ca: $3^{-} \otimes f_{7/2}$ → $13/2^{+}$, $11/2^{+}$, $9/2^{+}$, $7/2^{+}$, $5/2^{+}$, $3/2^{+}$ and $1/2^{+}$
- Fatima Analysis
  - Lifetime measurements → Determination of the $B(E/M\lambda)$
- Theoretical interpretation:
  - Phenomenological PVC model vs. microscopic approach (G. Colò, P.F. Bortignon)
  - Comparison with Shell Model Predictions (Otsuka group)

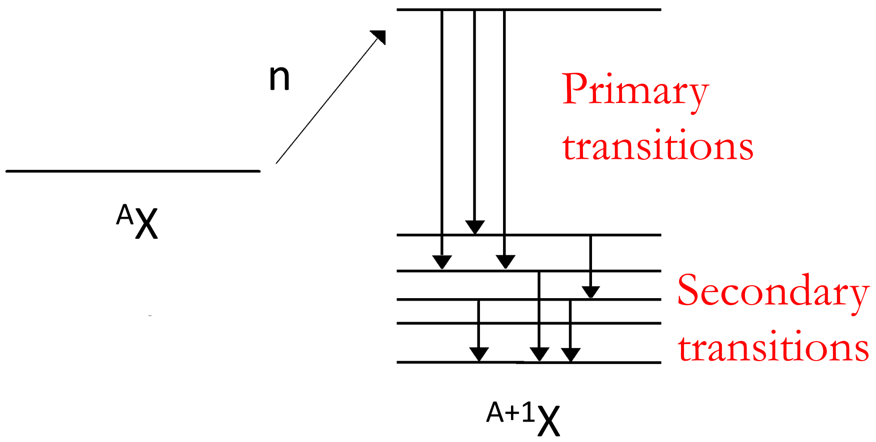
Thanks for the attention

Extra slides

Neutron Capture Reactions

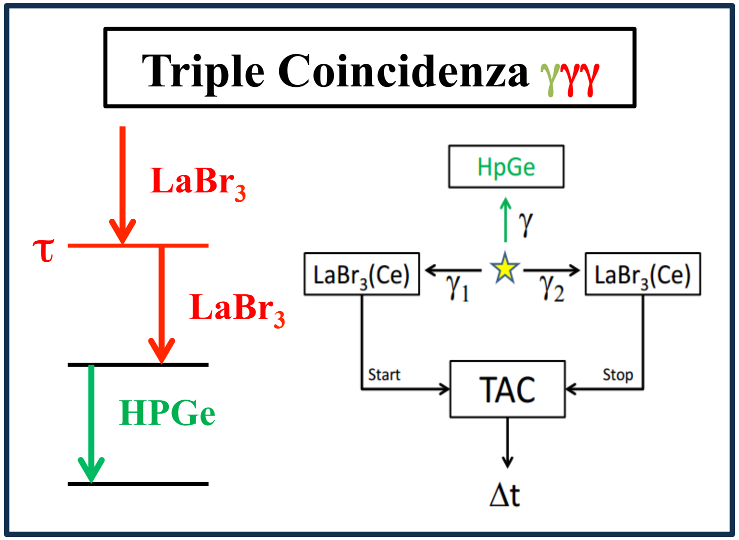
Cold Neutron Capture Reaction

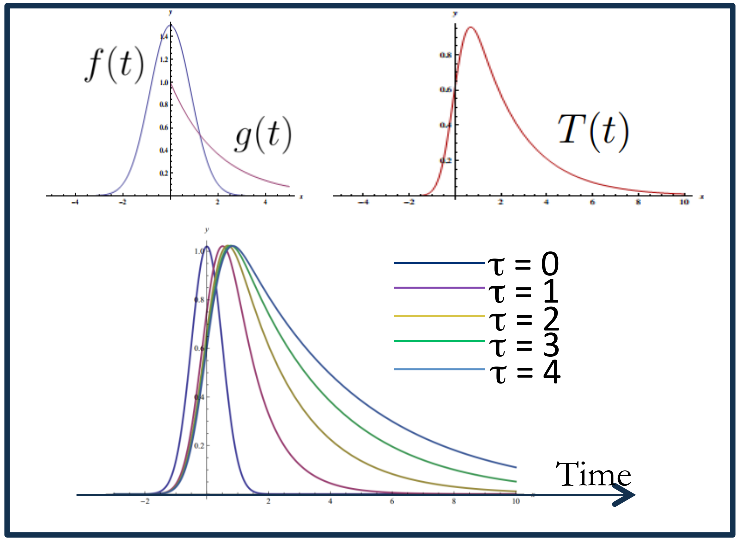




- ✓ Determination of the Binding Energy
- ✓ Construction of the Level scheme
- ✓ Angular correlation & polarization measurement: spin and parity and multipolarity assignment

Fast Timing





$$f(t) = Ae^{-\frac{(t-c)^2}{2\sigma^2}}$$

$$g(t) = \Theta(t)Be^{-\frac{t}{\tau}}$$

$$(f * g)(t) = \int_{-\infty}^{\infty} f(z)g(t-z)dz$$

$$T(t) = C\sqrt{\frac{\pi}{2}}\sigma e^{\frac{\sigma^2+2c\tau-2t\tau}{2\tau^2}}\mathrm{erfc}\left(\frac{\sigma^2+(c-t)\tau}{\sqrt{2}\sigma\tau}\right)$$

Transition Probability

$$\Gamma(\sigma\lambda; I_i \to I_f) = \frac{\hbar}{\tau} = \frac{8\pi(\lambda+1)}{\lambda[(2\lambda+1)!!]^2}\left(\frac{E_\gamma}{\hbar c}\right)^{2\lambda+1} B(\sigma\lambda; I_i \to I_f)$$

- **Particle Vibration WEAK Coupling :**

Energy:	$E(3^-)_{core}$	+	PERTURBATIVE TERMS
B(Eλ):	$B(E\lambda)_{core}$	+	PERTURBATIVE TERMS

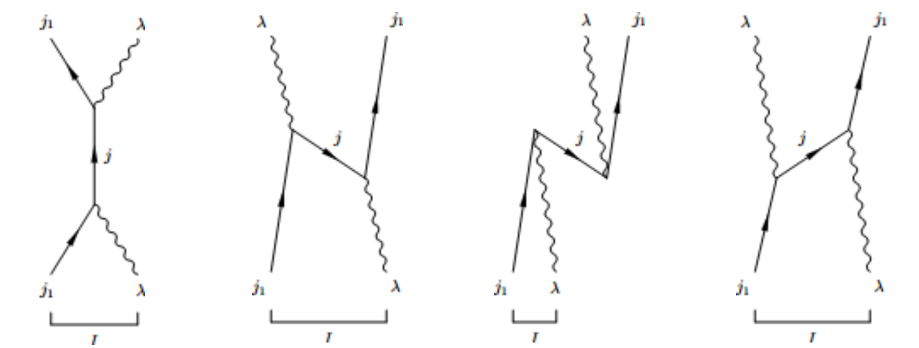
↓ Phonon

↓ Diagrams

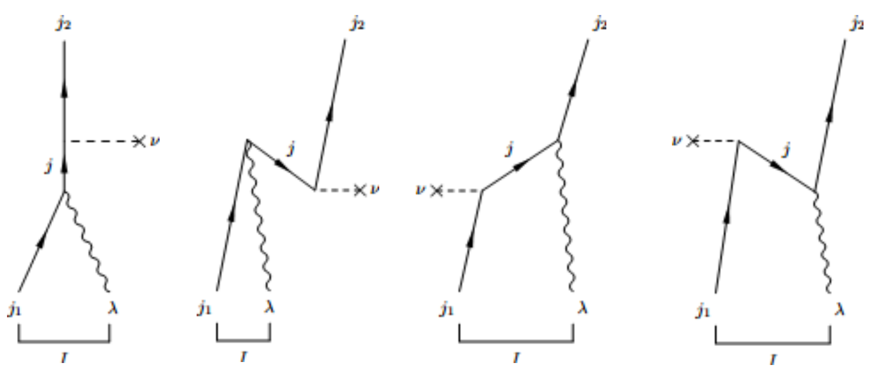
Neutron Capture Reactions

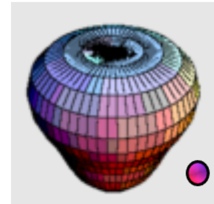
Particle-Phonon
WEAK coupling calculations
(Bohr & Mottelson → Hamamoto)

Energy Shift



Transition Probability B(E3)





$$3^- \otimes p_{3/2} = [\lambda \otimes j_1]_I$$

Multipletto → **9/2⁺, 7/2⁺, 5/2⁺, 3/2⁺**

→

$$\sum_j \frac{h^2(j,j_1,\lambda)}{\varepsilon(j_1)-\varepsilon(j)-\hbar\omega}\delta(j,I)$$

$$\sum_j \frac{h^2(j_1,j,\lambda)}{\varepsilon(j)-\varepsilon(j_1)-\hbar\omega}(2j_1+1)\begin{Bmatrix}\lambda & j_1 & j\\ \lambda & j_1 & I\end{Bmatrix}$$

→

$$\sum_j \langle j|M\nu|j\rangle \frac{\langle j|H'|(j_1\lambda)I\rangle}{\varepsilon_{j_1}-\varepsilon_j+\hbar\omega}\delta(j,I)$$

$$\sum_j \langle j|M\nu|j_1\rangle \frac{\langle j|H'|(j\lambda)j\rangle}{\varepsilon_j-\varepsilon_j-\hbar\omega}\sqrt{2j+1}\sqrt{2I+1}\,\mathcal{W}(j\lambda\nu I;jj_1)$$