Valence particle – core excitations couplings

new experimental investigations and novel theoretical approaches

Simone Bottoni

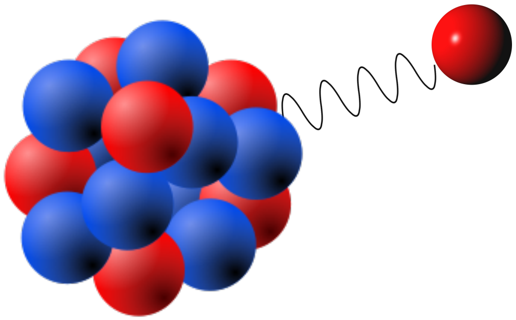
Università degli Studi di Milano and INFN

6th Workshop on Nuclear Level Density and Gamma Strength

Oslo, May 8-12, 2017

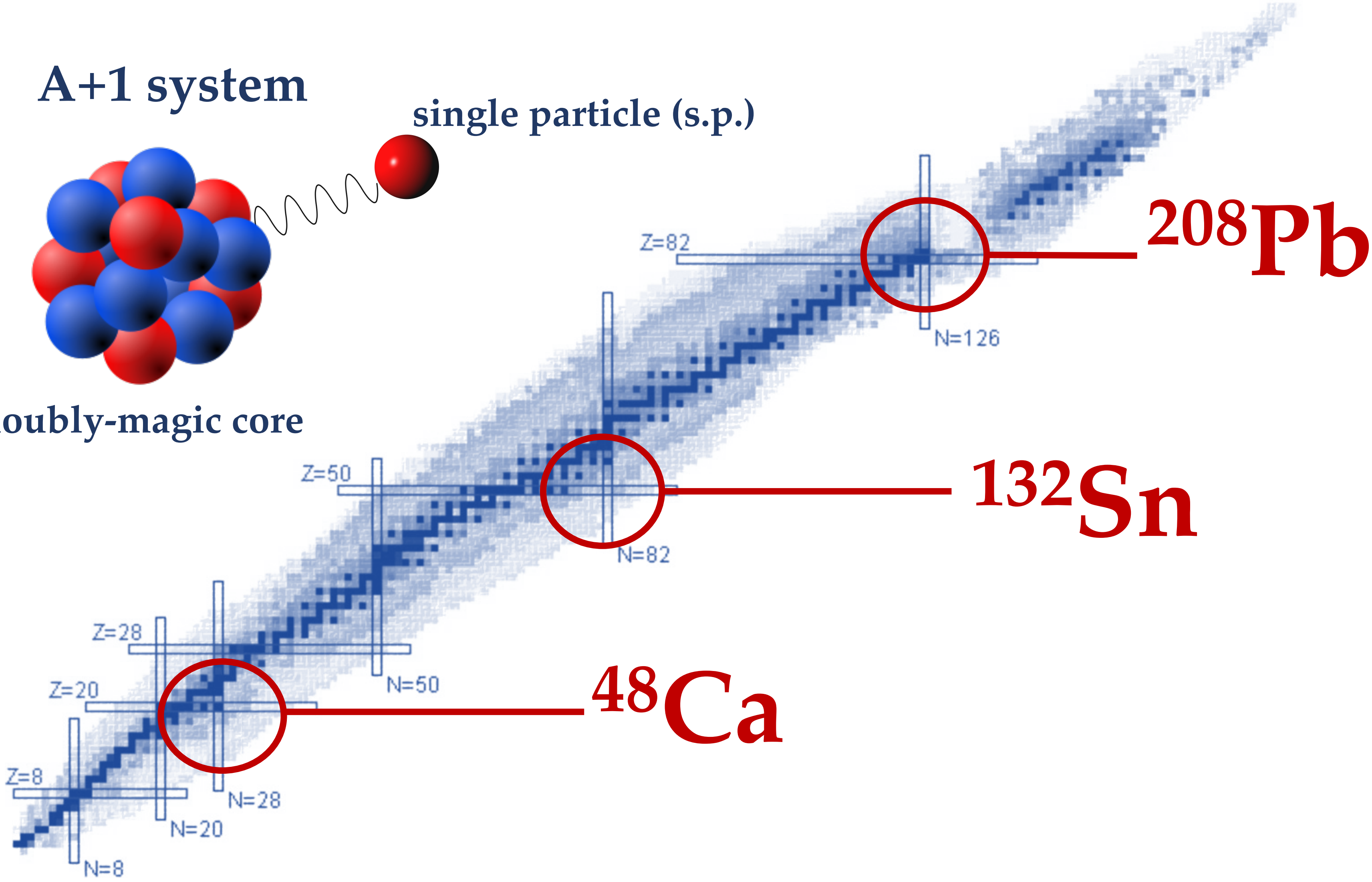
Istituto Nazionale di Fisica Nucleare

A+1 system



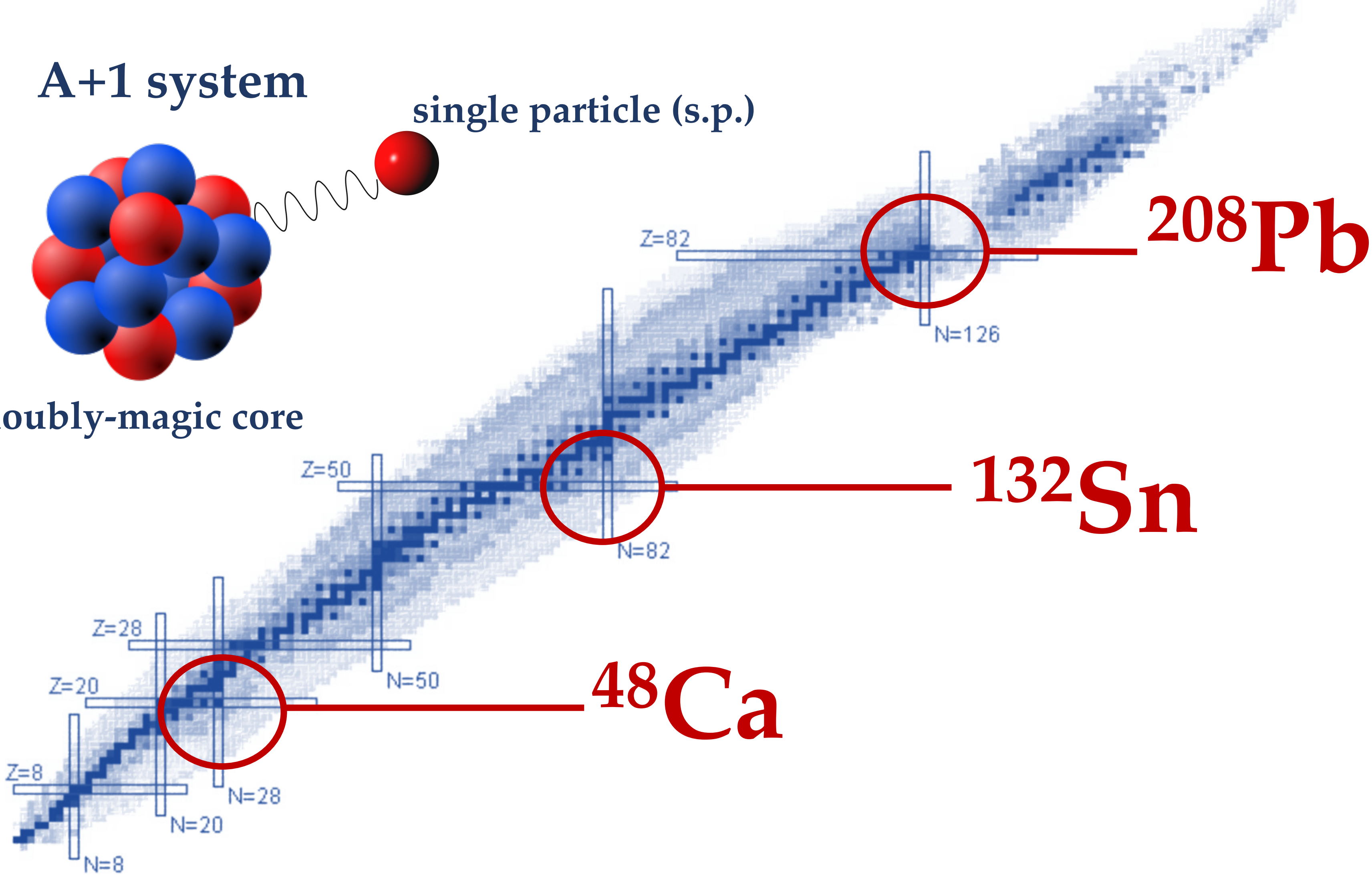
A+1 system

single particle (s.p.)



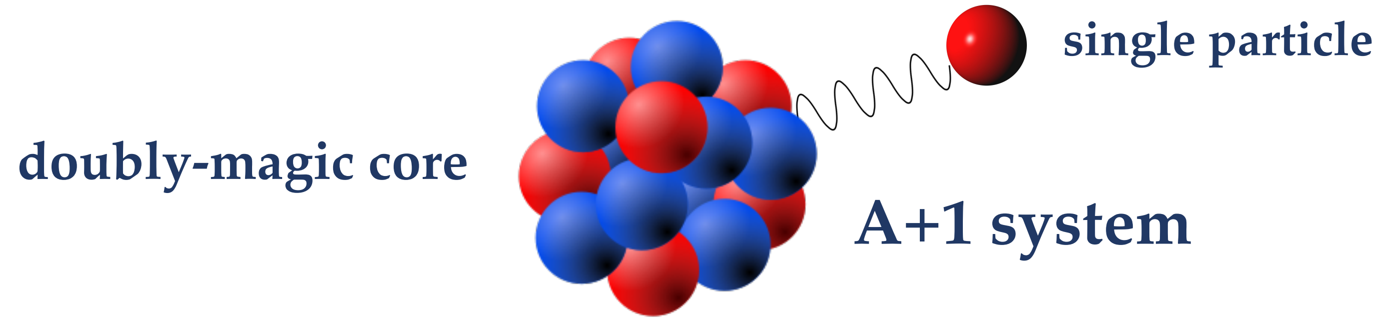
doubly-magic core

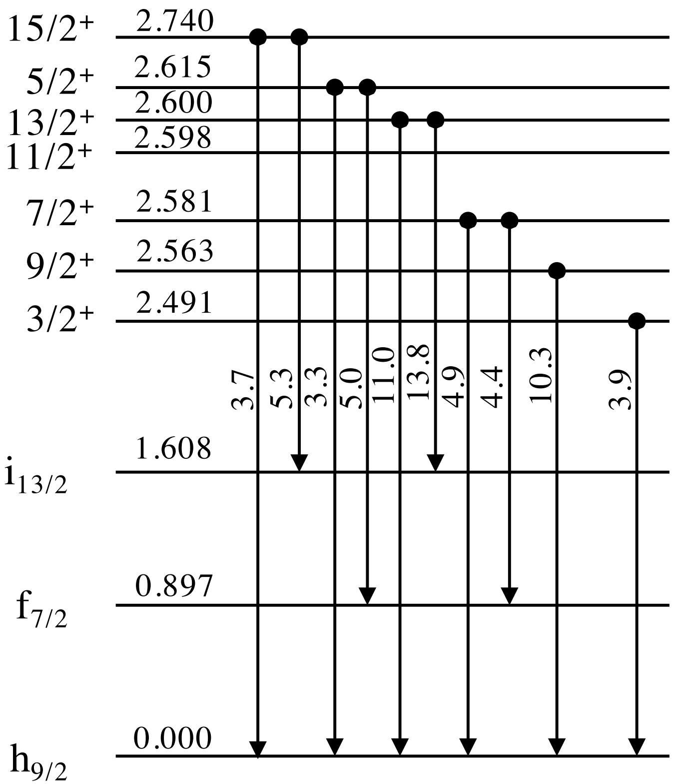
One-valence-nucleon systems around doubly-magic nuclei



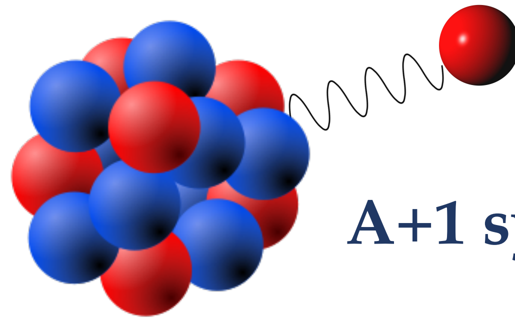
A+1 system: pure s.p. states and couplings with core excitations

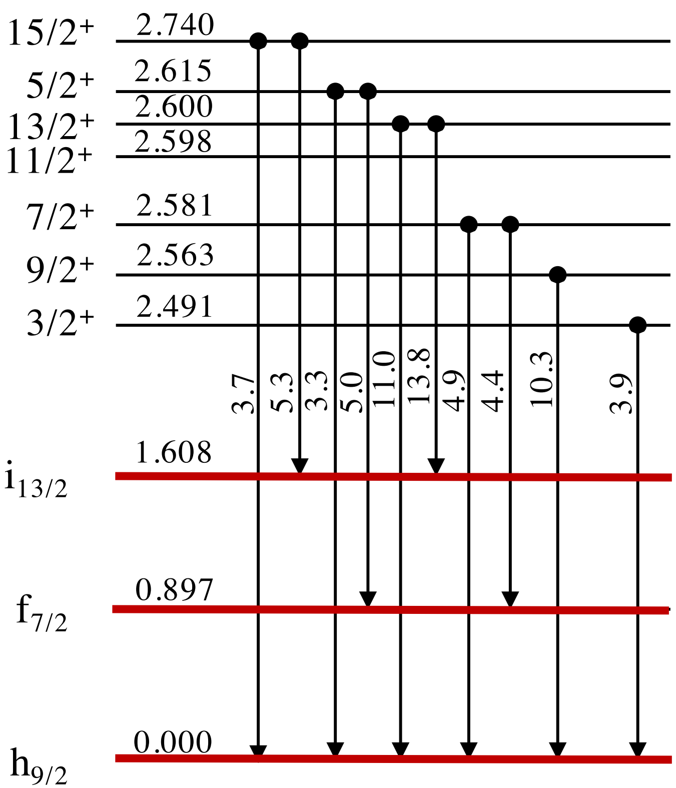
One-valence-nucleon systems around doubly-magic nuclei





$^{209}Bi = ^{208}Pb + 1\pi$





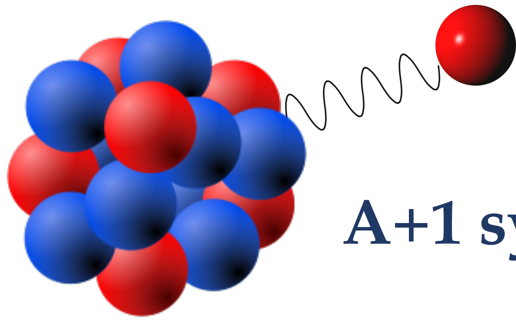
$^{209}Bi = {}^{208}Pb + 1\pi$

Single-particle states

large spectroscopic factor
small B(Eλ)

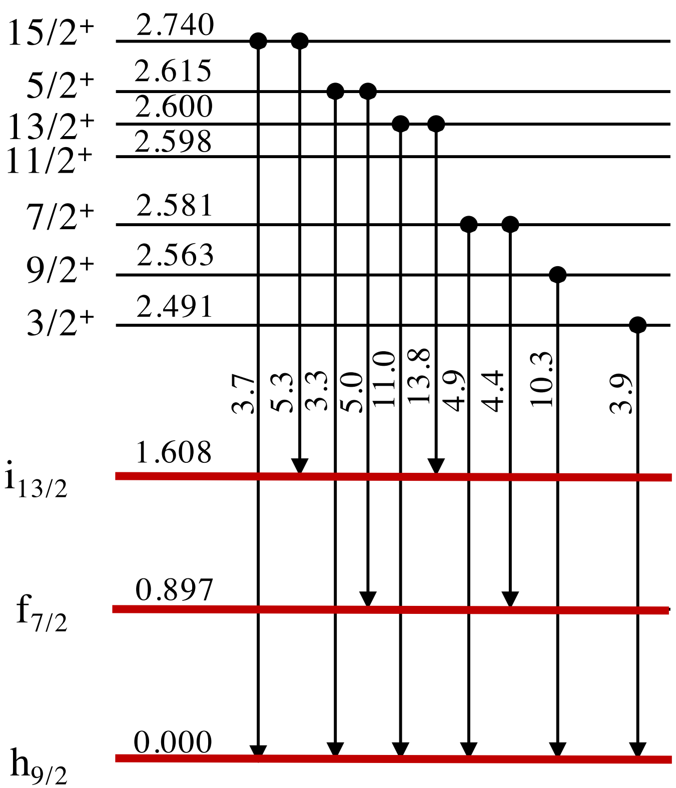
One-valence-nucleon systems around doubly-magic nuclei

doubly-magic core



single particle

A+1 system



^{209}Bi = ^{208}Pb + 1π

Particle-phonon coupled states

$|\lambda \otimes j'\rangle_j$ e.g. $|3^- \otimes \pi h_{9/2}\rangle_{3/2+,5/2+\ldots}$

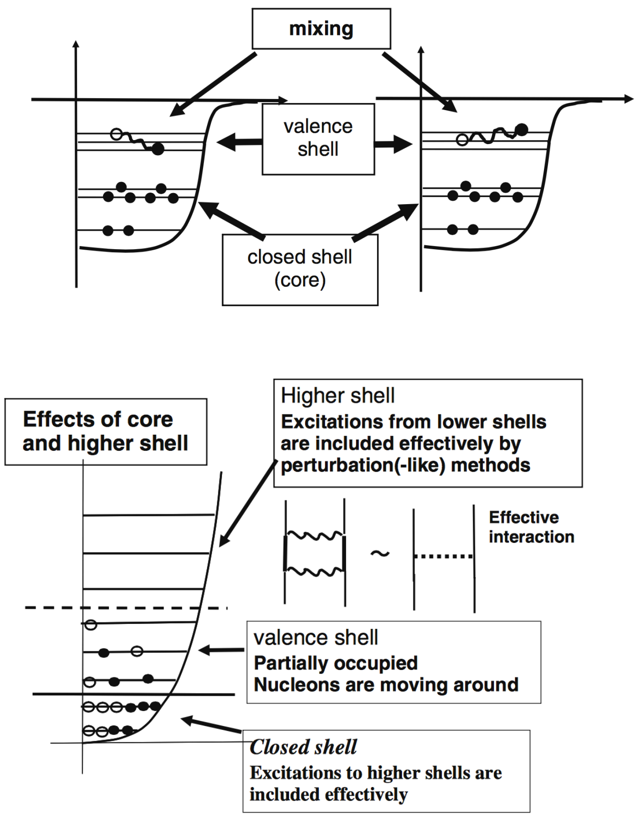
$$B(E\lambda, [j' \otimes \lambda]_j \rightarrow j') = B(E\lambda, \lambda \rightarrow 0)$$

Single-particle states

large spectroscopic factor
small B(Eλ)

Two extreme approaches

Shell model

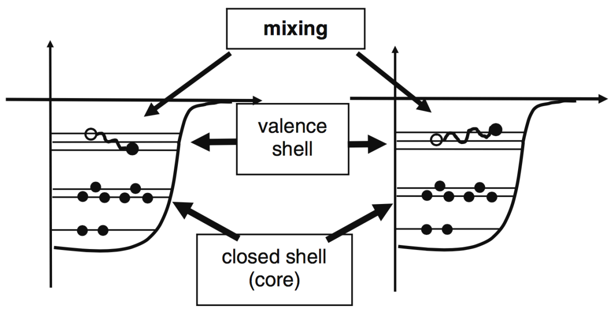


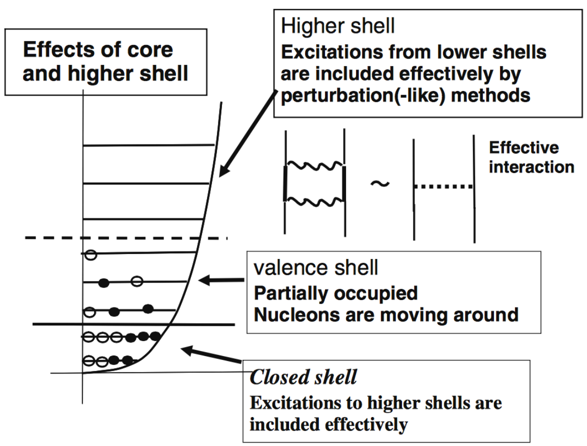
from T. Otsuka

- **No collective excitations of the core**
- **Limitations of the valence space**

Two extreme approaches

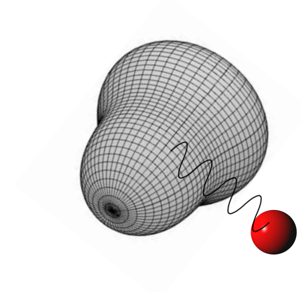
Shell model



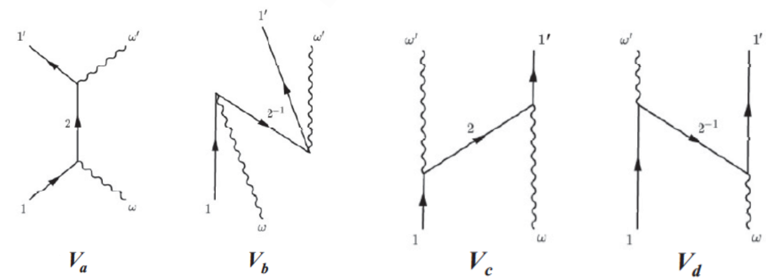


from T. Otsuka

Perturbative Particle-Vibration Coupling



PVC



$$\langle [j'\otimes J]_j \,|V_a + V_b|\, [j'\otimes J]_j\rangle = \sum_{j_1} \frac{1}{2j_1+1}\,\frac{\langle j_1||V||j',J\rangle^2}{\varepsilon(j')-\varepsilon(j_1)+\hbar\omega_J}$$

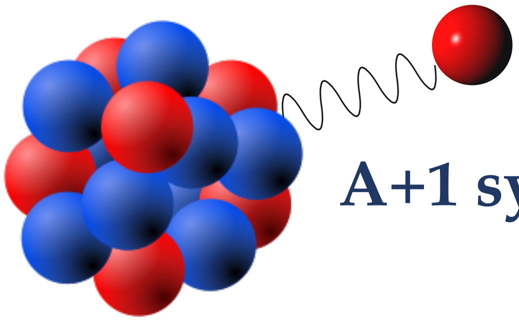
$$\langle [j'\otimes J]_j \,|V_c + V_d|\, [j'\otimes J]_j\rangle = \sum_{j_1} \frac{2j'+1}{2j_1+1}\begin{Bmatrix} J & j' & j_1 \\ J & j' & j \end{Bmatrix}\frac{\langle j_1||V||j',J\rangle^2}{\varepsilon(j_1)-\varepsilon(j')+\hbar\omega_J}$$

from A. Bohr and B. Mottelson

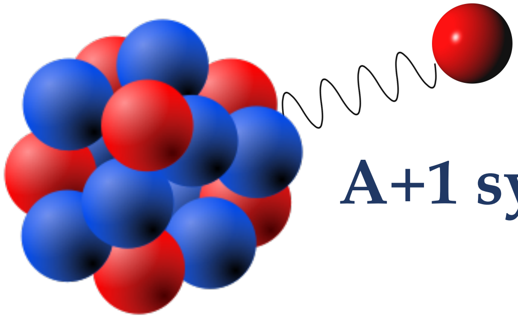
- No collective excitations of the core
- Limitations of the valence space

- Phenomenological approach
- Weak coupling approximation

Is it possible to go towards a more realistic microscopic description of one-valence nucleon systems?



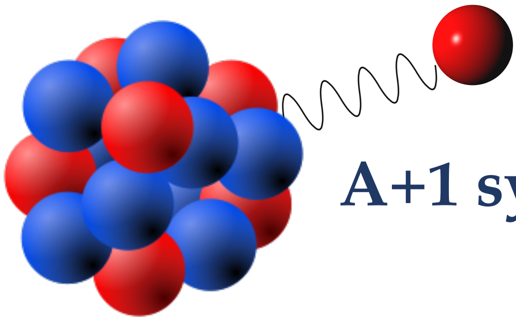
A+1 system



A+1 system

Single-particle states

$$|jm\rangle = a^{\dagger}_{jm}|0\rangle$$

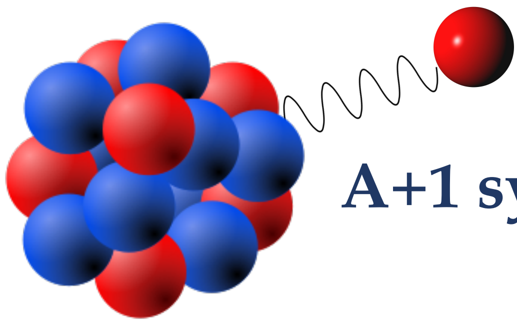


A+1 system

Single-particle states

$|jm\rangle = a^{\dagger}_{jm}|0\rangle$

HF calculations (Skyrme)



A+1 system

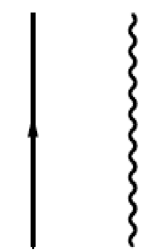
Single-particle states

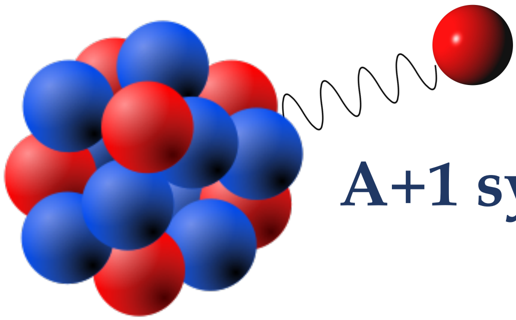
$$|jm\rangle = a^{\dagger}_{jm}|0\rangle$$

HF calculations (Skyrme)

Coupled states

$$|\,[j' \otimes NJ]_{jm}\rangle = \Bigg\{ \sum_{ph} \sum_{m'Mm_pm_h} \langle j'm'JM|jm\rangle X^{(NJ)}_{ph} (-1)^{j_h-m_h} \langle j_pm_pj_h-m_h|JM\rangle a^{\dagger}_{j'm'} a^{\dagger}_{j_pm_p} a_{j_hm_h}|0\rangle + \\ - \sum_{ph} \sum_{m'Mm_pm_h} \langle j'm'JM|jm\rangle Y^{(NJ)}_{ph} (-1)^{j_h-m_h+J+M} \langle j_pm_pj_h-m_h|J-M\rangle a^{\dagger}_{j'm'} a^{\dagger}_{j_hm_h} a_{j_pm_p}|0\rangle \Bigg\}$$





Single-particle states

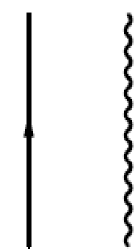
$$|jm\rangle = a^\dagger_{jm}|0\rangle$$

HF calculations (Skyrme)

Coupled states

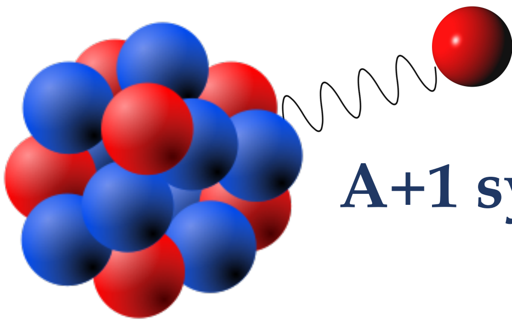
$$|[j' \otimes NJ]_{jm}\rangle = \Big\{ \sum_{ph} \sum_{m'Mm_pm_h} \langle j'm'JM|jm\rangle X^{(NJ)}_{ph} (-1)^{j_h-m_h} \langle j_pm_pj_h-m_h|JM\rangle a^\dagger_{j'm'} a^\dagger_{j_pm_p} a_{j_hm_h}|0\rangle +$$

$$- \sum_{ph} \sum_{m'Mm_pm_h} \langle j'm'JM|jm\rangle Y^{(NJ)}_{ph} (-1)^{j_h-m_h+J+M} \langle j_pm_pj_h-m_h|J-M\rangle a^\dagger_{j'm'} a^\dagger_{j_hm_h} a_{j_pm_p}|0\rangle \Big\}$$



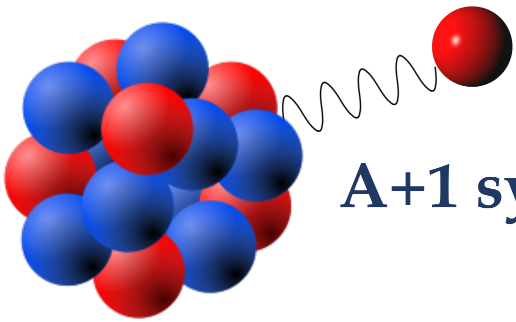
RPA calculations (Skyrme)

- **Collective phonons**
- **Non-collective 1p – 1h excitations**



A+1 system

$$H|\alpha\rangle = E_\alpha|\alpha\rangle,$$
$$|\alpha\rangle = \sum_i \xi_i^{(\alpha)}|i\rangle$$



wave function

j
(single particle)

j ⊗ λ
(PVC-like)

2p – 1h
(shell-model-like)

$$H|\alpha\rangle = E_\alpha|\alpha\rangle,$$
$$|\alpha\rangle = \sum_i \xi_i^{(\alpha)} |i\rangle$$

Hamiltonian

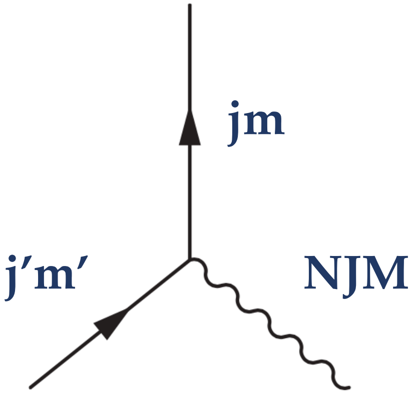
$$
\begin{aligned}
H &= H_0 + V, \\
H_0 &= \sum_{jm} \varepsilon_j a^\dagger_{jm} a_{jm} + \sum_{NJM} \hbar\omega_{NJ} \Gamma^\dagger_{NJM} \Gamma_{NJM}, \\
V &= \sum_{jmj'm'} \sum_{NJM} h(jm; j'm', NJM) a_{jm} \left[a^\dagger_{j'} \otimes \Gamma^\dagger_{NJ} \right]_{jm}
\end{aligned}
$$

Hamiltonian

$$
\begin{aligned}
H &= H_0 + V, \\
H_0 &= \sum_{jm} \varepsilon_j a^\dagger_{jm} a_{jm} + \sum_{NJM} \hbar\omega_{NJ} \Gamma^\dagger_{NJM} \Gamma_{NJM}, \\
V &= \sum_{jmj'm'} \sum_{NJM} h(jm; j'm', NJM) a_{jm} \left[a^\dagger_{j'} \otimes \Gamma^\dagger_{NJ} \right]_{jm}
\end{aligned}
$$

"PVC" vertex

(Skyrme)



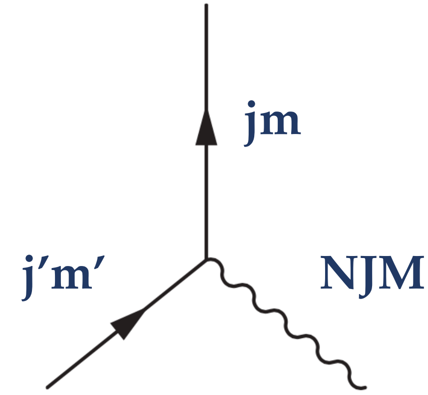
G. Colò, H. Sagawa and P.F. Bortignon
Phys. Rev. C **82**, 054307 (2017)

Hamiltonian

$$
\begin{aligned}
H &= H_0 + V, \\
H_0 &= \sum_{jm} \varepsilon_j a^\dagger_{jm} a_{jm} + \sum_{NJM} \hbar\omega_{NJ} \Gamma^\dagger_{NJM} \Gamma_{NJM}, \\
V &= \sum_{jmj'm'} \sum_{NJM} h(jm; j'm', NJM) a_{jm} \left[a^\dagger_{j'} \otimes \Gamma^\dagger_{NJ} \right]_{jm}
\end{aligned}
$$

"PVC" vertex

(Skyrme)



G. Colò, H. Sagawa and P.F. Bortignon
Phys. Rev. C **82**, 054307 (2017)

Pauli principle: corrections for non-orthonormality and over completeness of the basis are taken into account through the **NORM** matrix

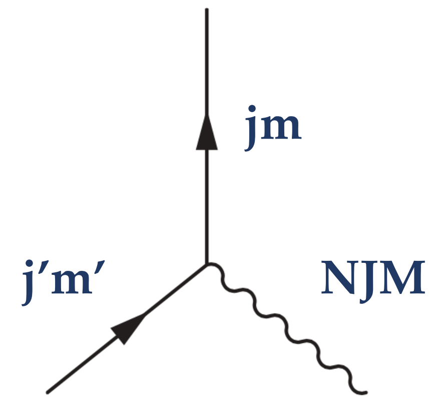
$$(H - NE)\psi = 0$$

J. Rowe, J. Math. Phys. **10**, 1774 (1969)

Hamiltonian

$$H = H_0 + V,$$
$$H_0 = \sum_{jm} \varepsilon_j a^\dagger_{jm} a_{jm} + \sum_{NJM} \hbar\omega_{NJ} \Gamma^\dagger_{NJM} \Gamma_{NJM},$$
$$V = \sum_{jmj'm'} \sum_{NJM} h(jm; j'm', NJM) a_{jm} \left[a^\dagger_{j'} \otimes \Gamma^\dagger_{NJ} \right]_{jm}$$

"PVC" vertex
(Skyrme)



G. Colò, H. Sagawa and P.F. Bortignon
Phys. Rev. C **82**, 054307 (2017)

Pauli principle: corrections for non-orthonormality and over completeness of the basis are taken into account through the **NORM** matrix

$$(H-NE)\psi=0$$

J. Rowe, J. Math. Phys. **10**, 1774 (1969)

Reduced transition probability:

$$B(X\lambda) \equiv \frac{1}{2j_i+1} |\langle \alpha_f j_f || \hat{O}(X\lambda) || \alpha_i j_i \rangle|^2$$

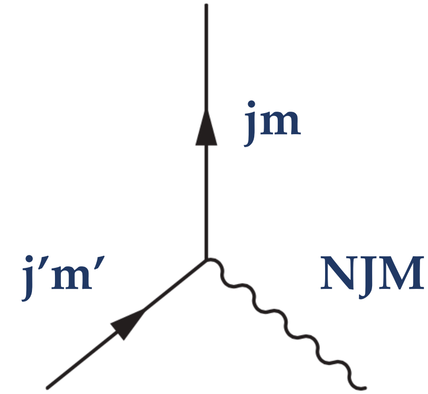
The Hybrid Configuration Mixing Model

Hamiltonian

$$H = H_0 + V,$$
$$H_0 = \sum_{jm} \varepsilon_j a^\dagger_{jm} a_{jm} + \sum_{NJM} \hbar\omega_{NJ} \Gamma^\dagger_{NJM} \Gamma_{NJM},$$
$$V = \sum_{jmj'm'} \sum_{NJM} h(jm; j'm', NJM) a_{jm} \left[a^\dagger_{j'} \otimes \Gamma^\dagger_{NJ}\right]_{jm}$$

"PVC" vertex

(Skyrme)



G. Colò, H. Sagawa and P.F. Bortignon
Phys. Rev. C **82**, 054307 (2017)

Pauli principle: corrections for non-orthonormality and over completeness of the basis are taken into account through the **NORM** matrix

$$(H\text{-}NE)\psi=0$$

J. Rowe, J. Math. Phys. **10**, 1774 (1969)

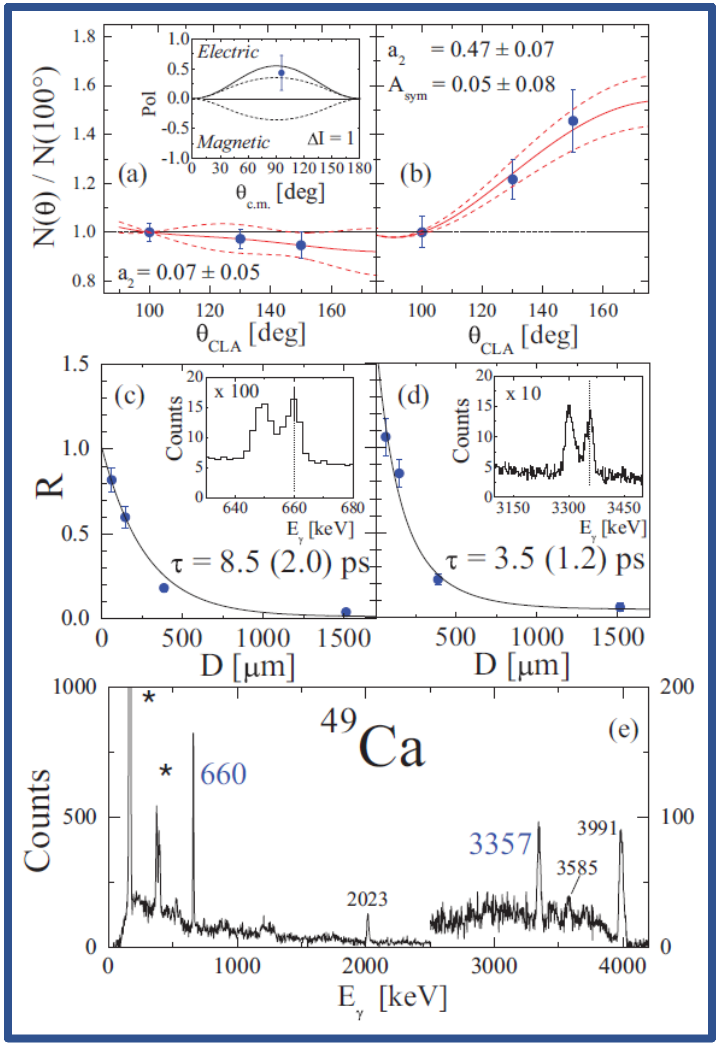
Reduced transition probability:

$$B(X\lambda) \equiv \frac{1}{2j_i+1} |\langle \alpha_f j_f || \hat{O}(X\lambda) || \alpha_i j_i \rangle|^2$$

G. Colò, P.F. Bortignon and G. Bocchi, Phys. Rev. C 95, 034303 (2017)

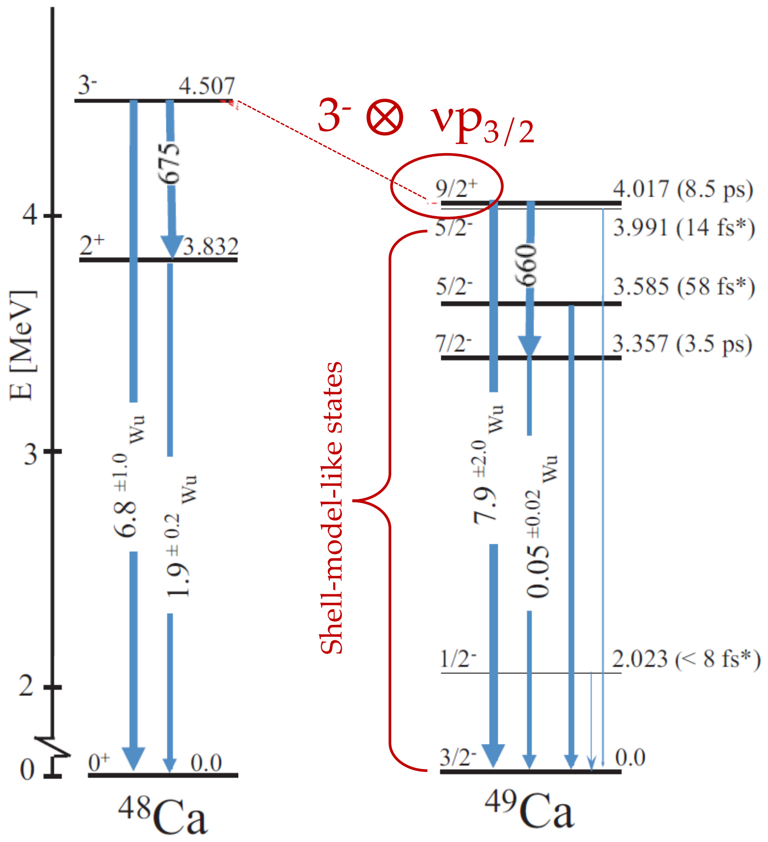
Let's test the model!

From the PRISMA-CLARA campaign @ LNL



^{48}Ca+^{64}Ni/^{208}Pb (MNT)

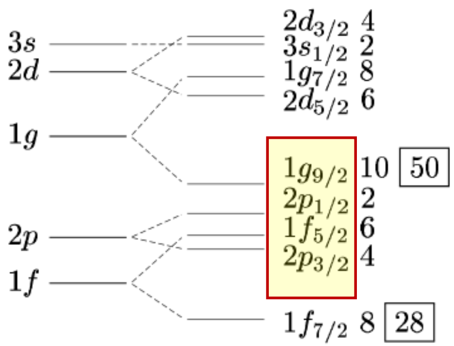
$$^{49}\text{Ca} = {}^{48}\text{Ca} + 1\nu$$

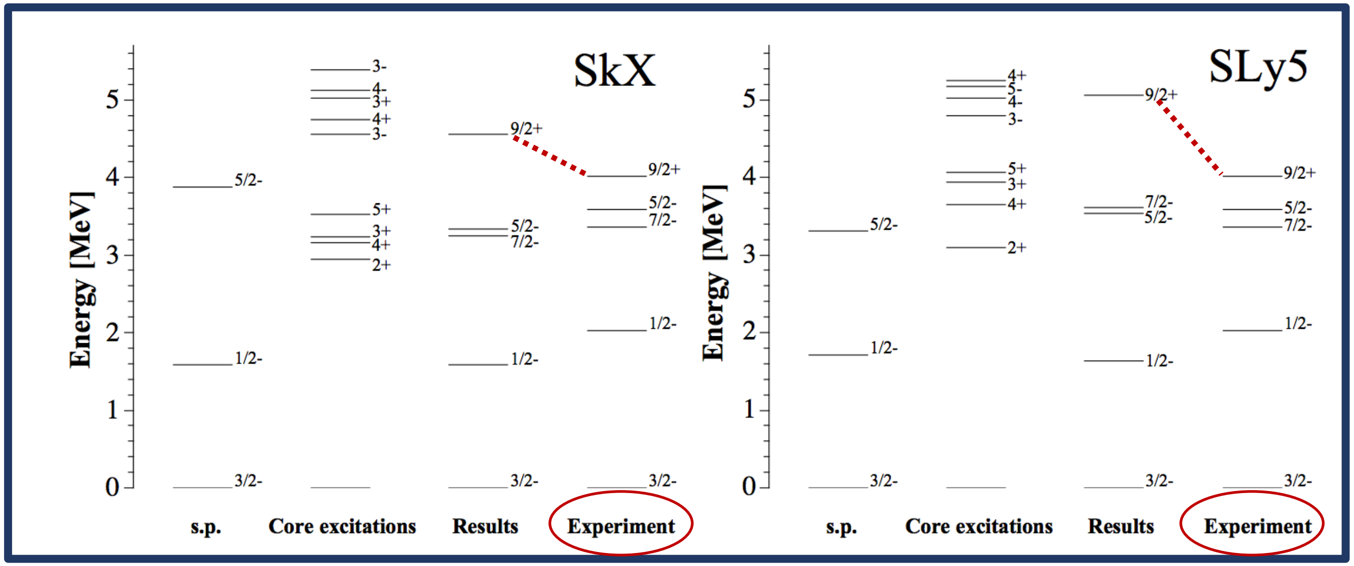


D. Montanari et al. Phys. Lett B, **697**, 288 (2011)

The case of ^{49}Ca - theoretical interpretation (Hybrid Model)

ν model space

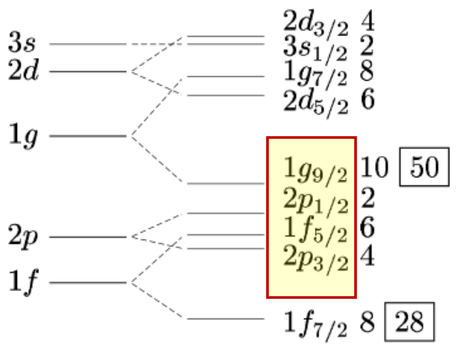


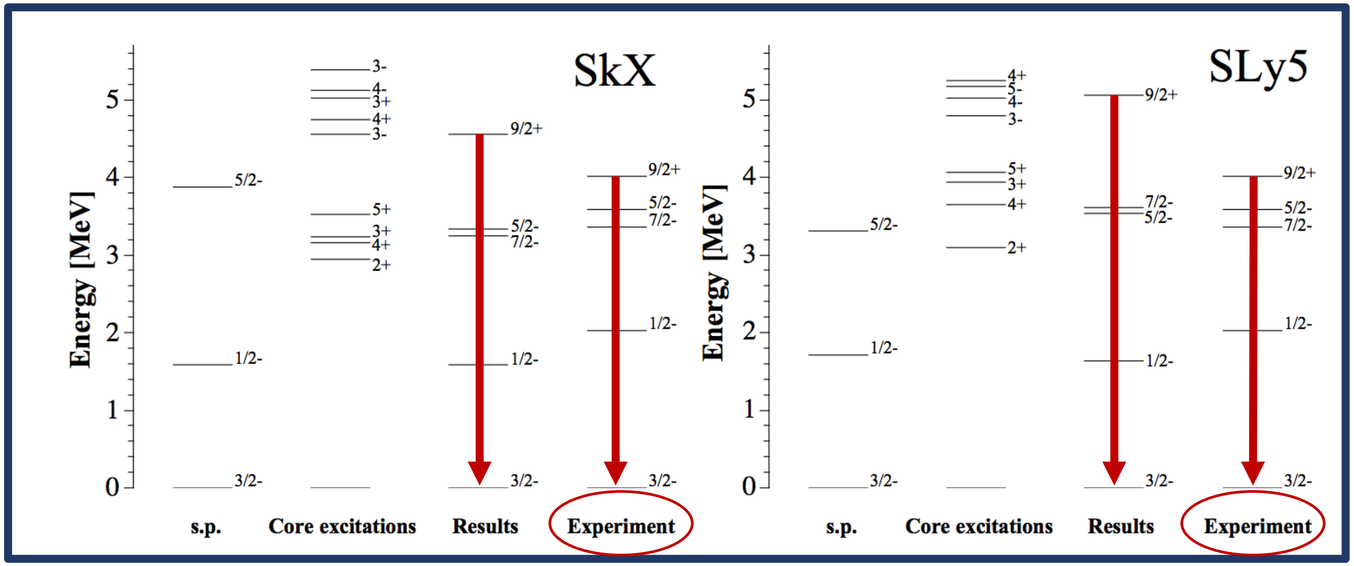


^{49}Ca

The case of ^{49}Ca - theoretical interpretation (Hybrid Model)

ν model space





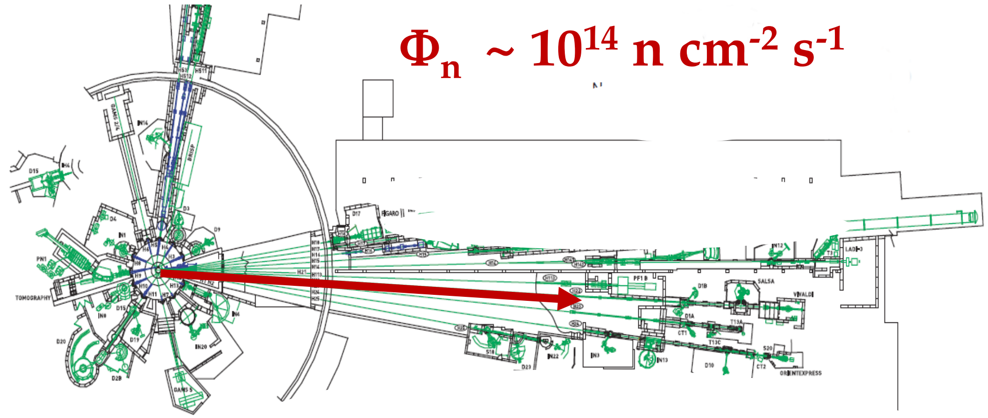
^{49}Ca

J^π	SkX	SLy5
$3/2^-$	$\vert 2p_{3/2}\rangle$	$\vert 2p_{3/2}\rangle$
$1/2^-$	$\vert 2p_{1/2}\rangle$	$\vert 2p_{1/2}\rangle$
$5/2^-$	$\vert 2p_{3/2} \otimes 2^+\rangle$	$\vert 2p_{3/2} \otimes 2^+\rangle + 1f_{5/2}$
$7/2^-$	$\vert 2p_{3/2} \otimes 2^+\rangle$	$\vert 2p_{3/2} \otimes 2^+\rangle$
$9/2^+$	$\vert 2p_{3/2} \otimes 3^-\rangle$	$\vert 2p_{3/2} \otimes 3^-\rangle$

Main components (> 30%)

	Theory SkX	Theory SLy5	Exp.
$B(E3, 9/2^+ \to 3/2^-)$	6.4	5.7	7.9 ± 2.0 W.u.
$B(E2, 7/2^- \to 3/2^-)$	1.4	1.0	0.05 ± 0.02 W.u.

The EXILL - FATIMA experimental campaign (2012 – 2013)

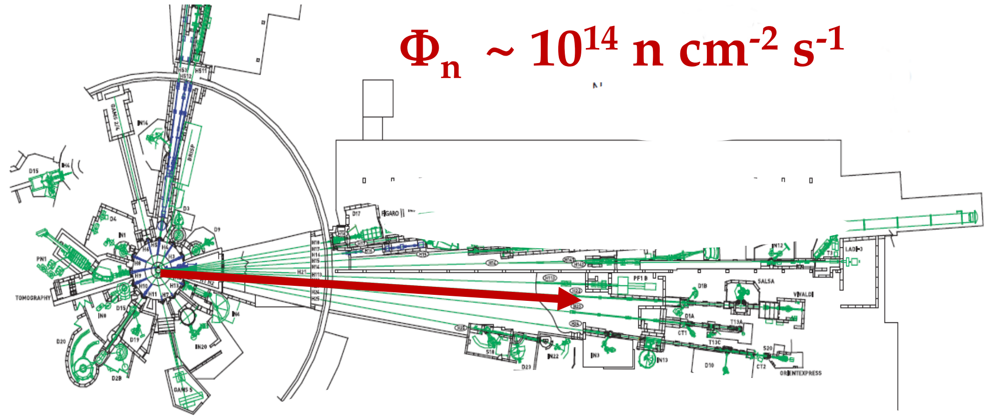


$\Phi_n \sim 10^{14}$ n cm^{-2} s^{-1}

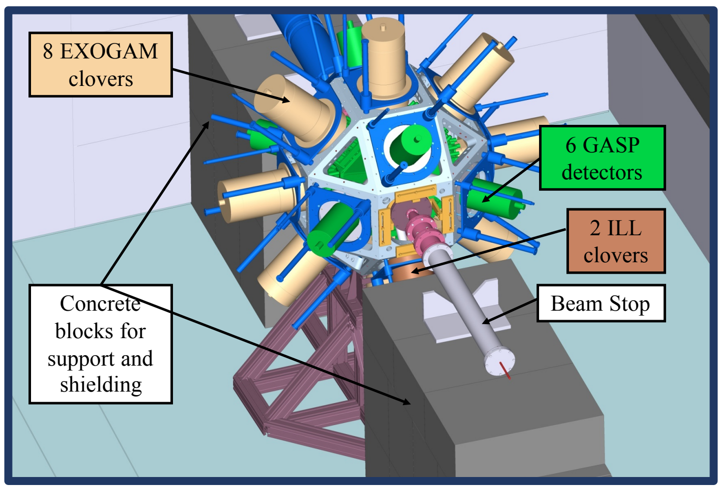
Cold neutrons: E_n < 25 meV

The EXILL - FATIMA experimental campaign (2012 – 2013)

$\Phi_n \sim 10^{14}$ n cm^{-2} s^{-1}

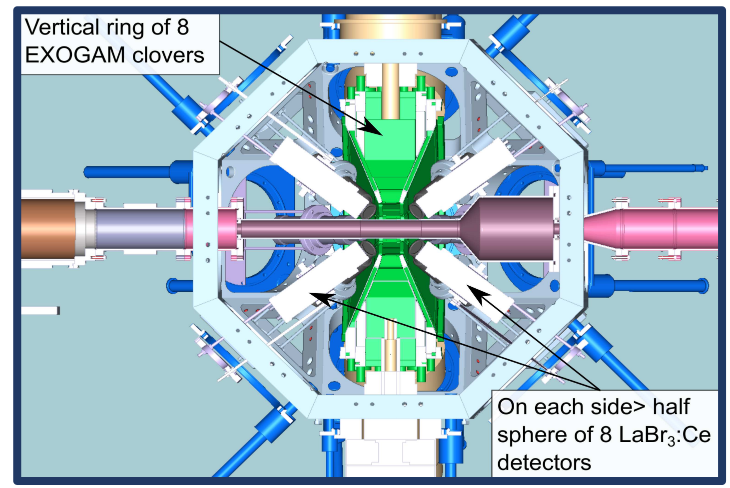


Cold neutrons: $E_n < 25$ meV



γ spectroscopy: Ge detectors

Trigger-less digital system



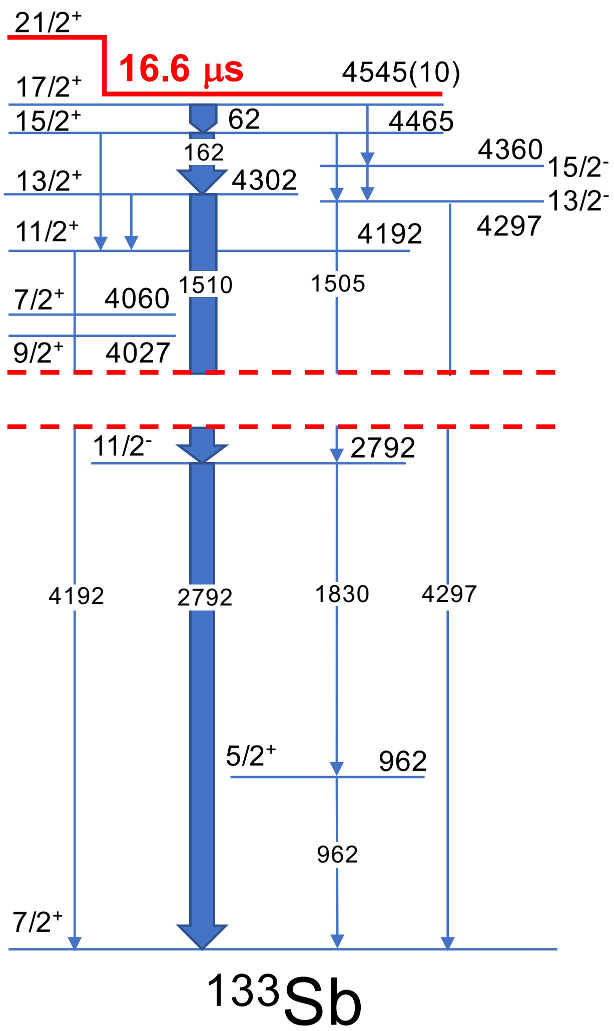
Lifetime measurements: Ge +$LaBr_3$ detectors

The case of ^{133}Sb – experimental results

From the EXILL - FATIMA campaign: ^{235}U(n,fγ) and ^{241}Pu(n,fγ)

NEUTRONS FOR SOCIETY
Institut Laue-Langevin

^{133}Sb = ^{132}Sn + 1π

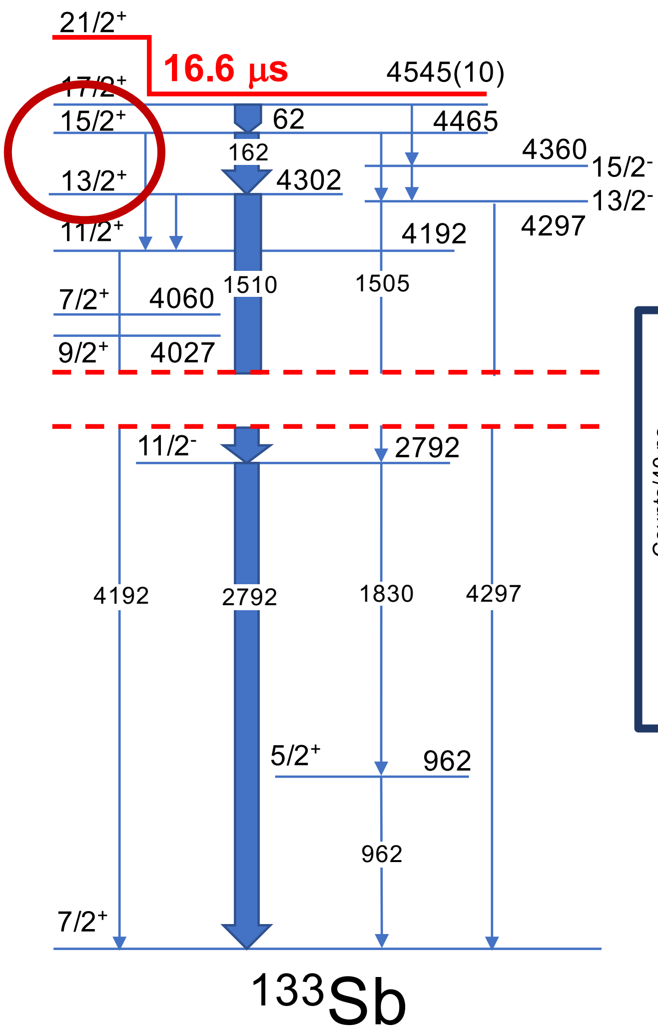


G. Bocchi et al., Phys. Lett. B, **760,** 273 (2016)

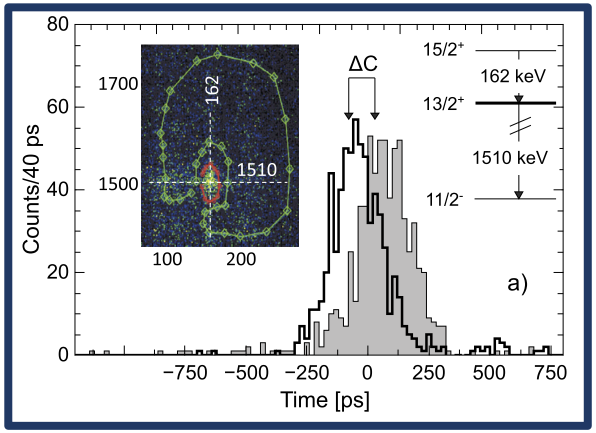
From the EXILL - FATIMA campaign: **^{235}U(n,fγ) and ^{241}Pu(n,fγ)**

NEUTRONS FOR SOCIETY
Institut Laue-Langevin

$^{133}Sb = {}^{132}Sn + 1\pi$

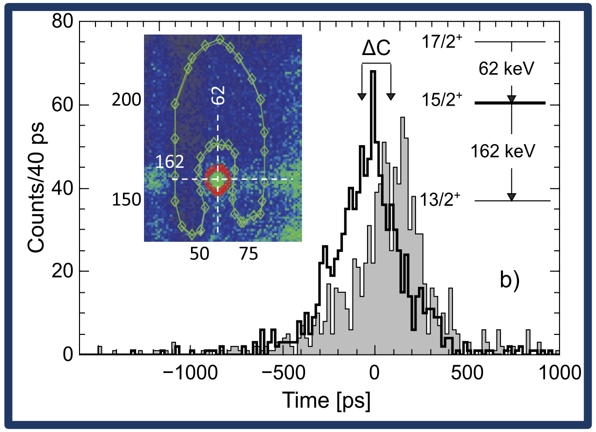


13/2+



τ = 31(8) ps

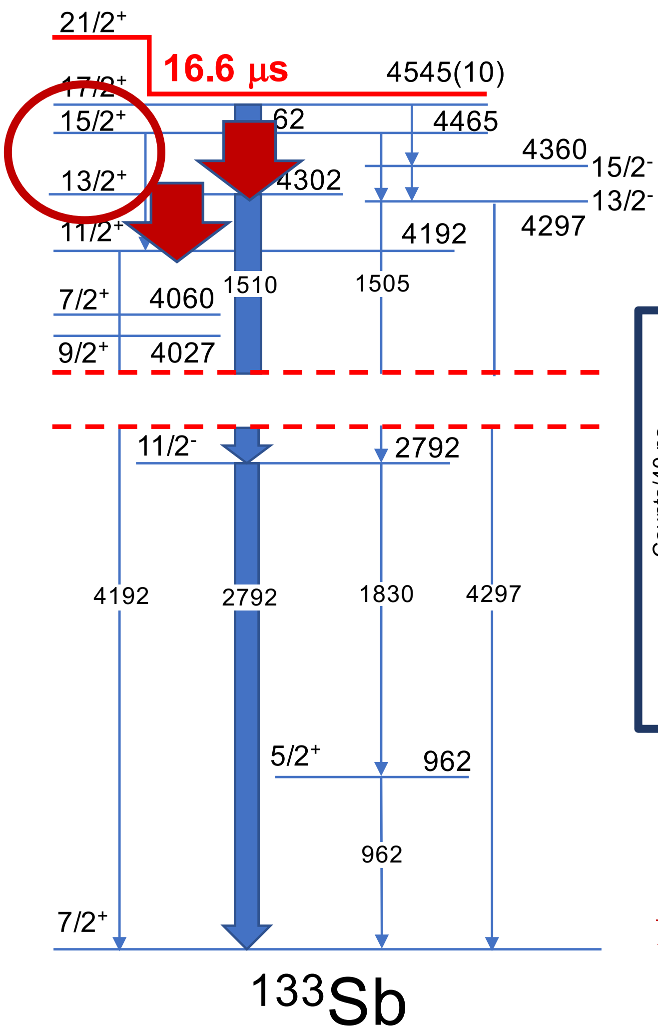
15/2+



τ < 20 ps

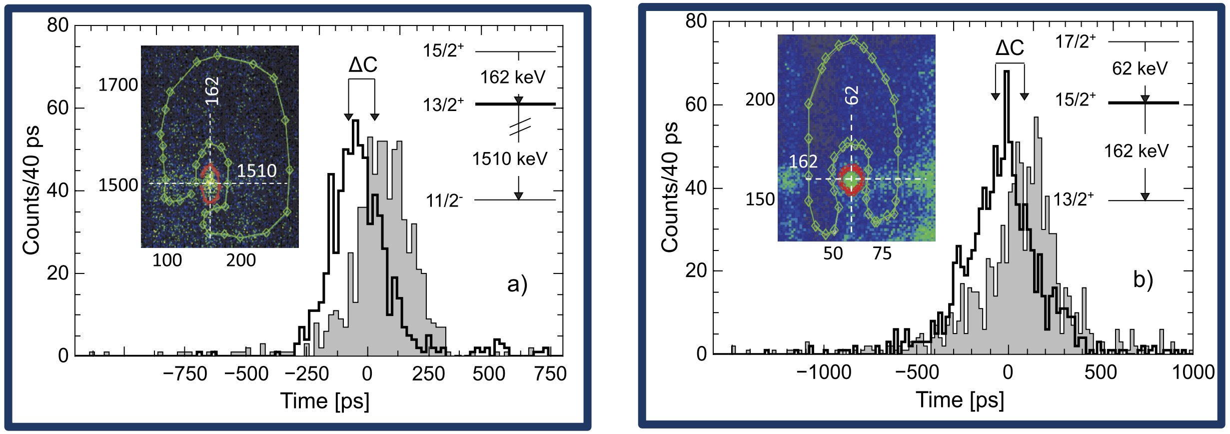
G. Bocchi et al., Phys. Lett. B, **760,** 273 (2016)

From the EXILL - FATIMA campaign: $^{235}U(n,f\gamma)$ **and** $^{241}Pu(n,f\gamma)$



$^{133}Sb = {}^{132}Sn + 1\pi$

13/2+ **15/2+**



τ = 31(8) ps **τ < 20 ps**

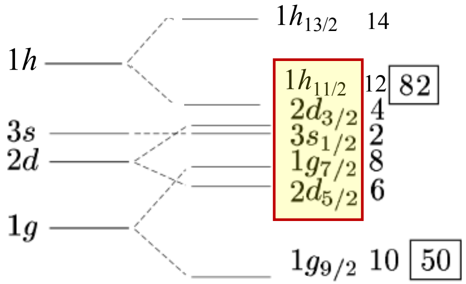
B(M1; 13/2+ → 11/2+) = 0.004 W.u. **B(M1; 15/2+ → 13/2+) > 0.24 W.u.**

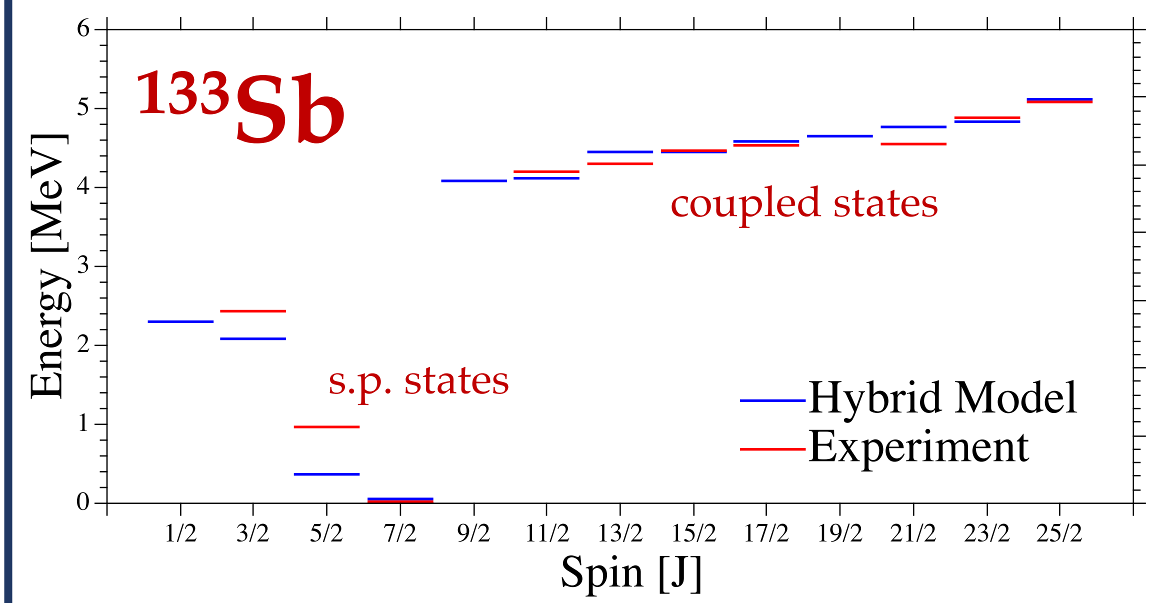
FACTOR OF 60!!

G. Bocchi et al., Phys. Lett. B, **760,** 273 (2016)

The case of ^{133}Sb – theoretical interpretation (Hybrid Model)

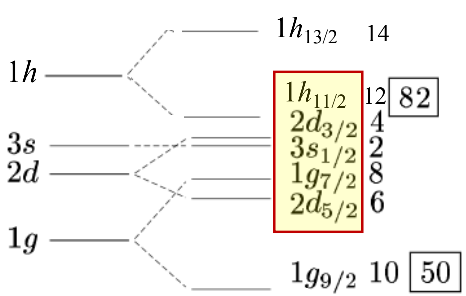
π model space

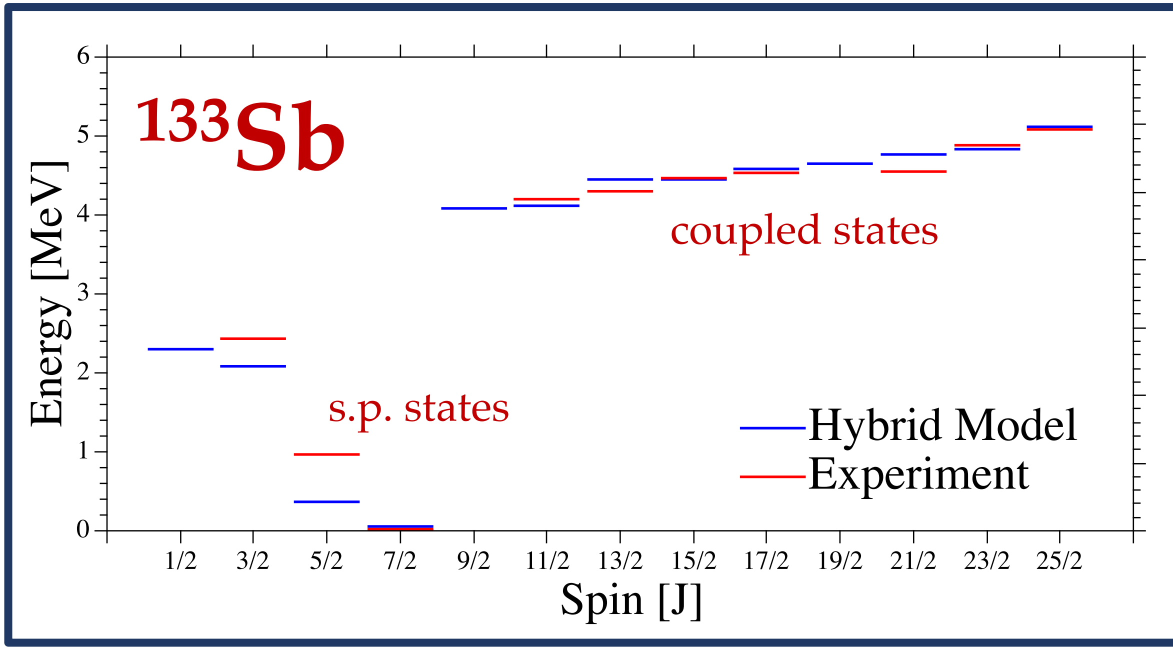




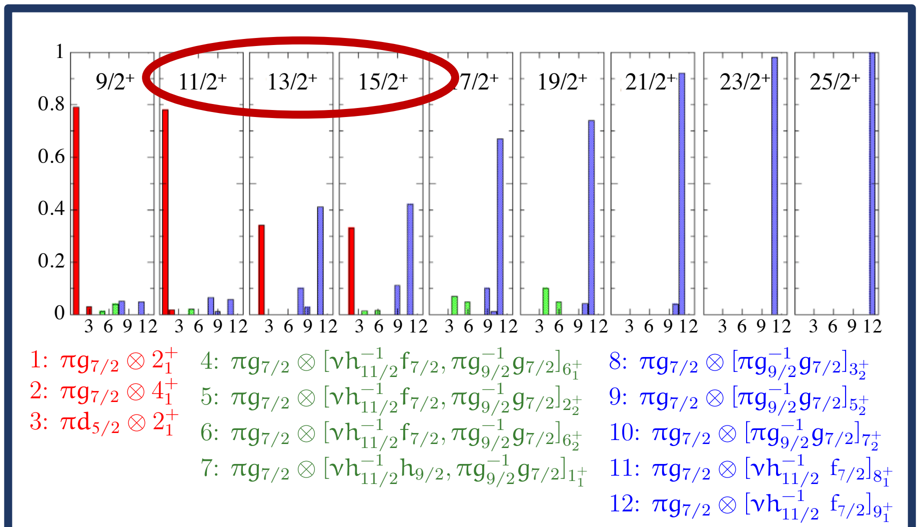
The case of ^{133}Sb – theoretical interpretation (Hybrid Model)

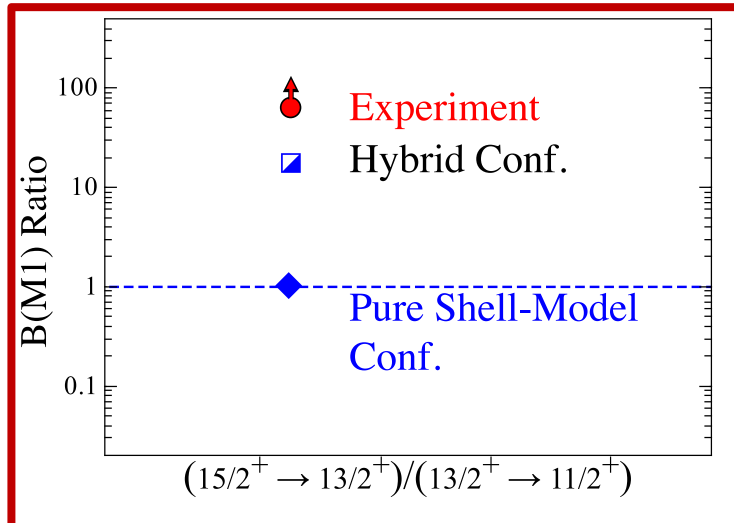
π model space





positive-parity states





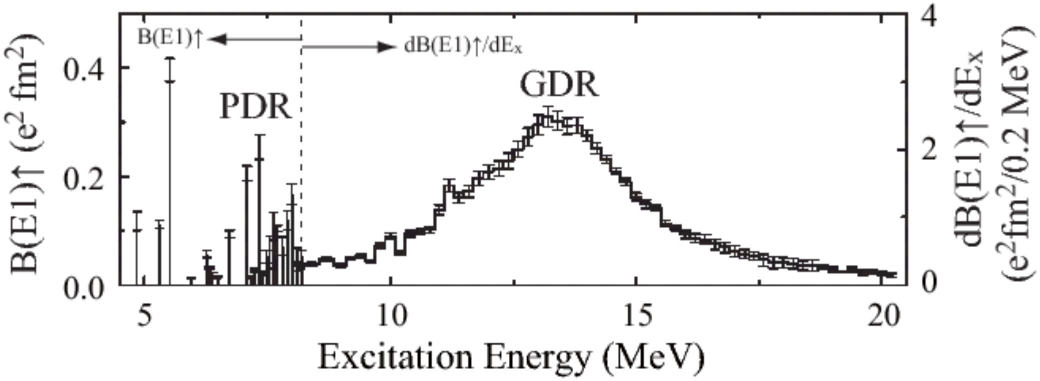
Conclusions

- **Microscopic many-body model for odd-A nuclei**
- **Mean-field approach based on the Skyrme effective interaction**
- **Particle-phonon states and 1p-1h non-collective excitations of the core**
- **Good agreement with spectroscopic results in different mass regions**

Conclusions

- **Microscopic many-body model for odd-A nuclei**
- **Mean-field approach based on the Skyrme effective interaction**
- **Particle-phonon states and 1p-1h non-collective excitations of the core**
- **Good agreement with spectroscopic results in different mass regions**

Low-lying and high-lying (e.g. GDR) excitations could be treated in the same framework



Future perspectives

Theory

Couplings with holes (e.g. ^{47}Ca)

Particles and holes together

Extension to open-shell systems

(quasiparticle basis)

Add more complicated configurations

Convergence of the model space (e.g. ^{209}Bi)

…

Experiment

Negative-parity states in ^{133}Sb

(cluster-transfer reaction @ISOLDE)

Complete spectroscopy of all Ca isotopes
((n,γ) reactions on rare and radioactive Ca @ ILL)

Cu isotopic chain
(Ni ⊗ p)

…

Collaboration

S. Bottoni , G. Bocchi, S. Leoni, G. Benzoni, A. Bracco, F.C.L. Crespi

G. Colò, P. F. Bortignon

Università degli Studi di Milano and INFN, Milano, Italy

B.Fornal, N. Cieplicka-Oryńczak, L. iskra, B. Szpak

Institute of Nuclear Physics, Kraków, Poland

&

the EXILL - FATIMA collaboration
and
the PRISMA– CLARA collaboration

Thank you!

Simone Bottoni

Università degli Studi di Milano and INFN

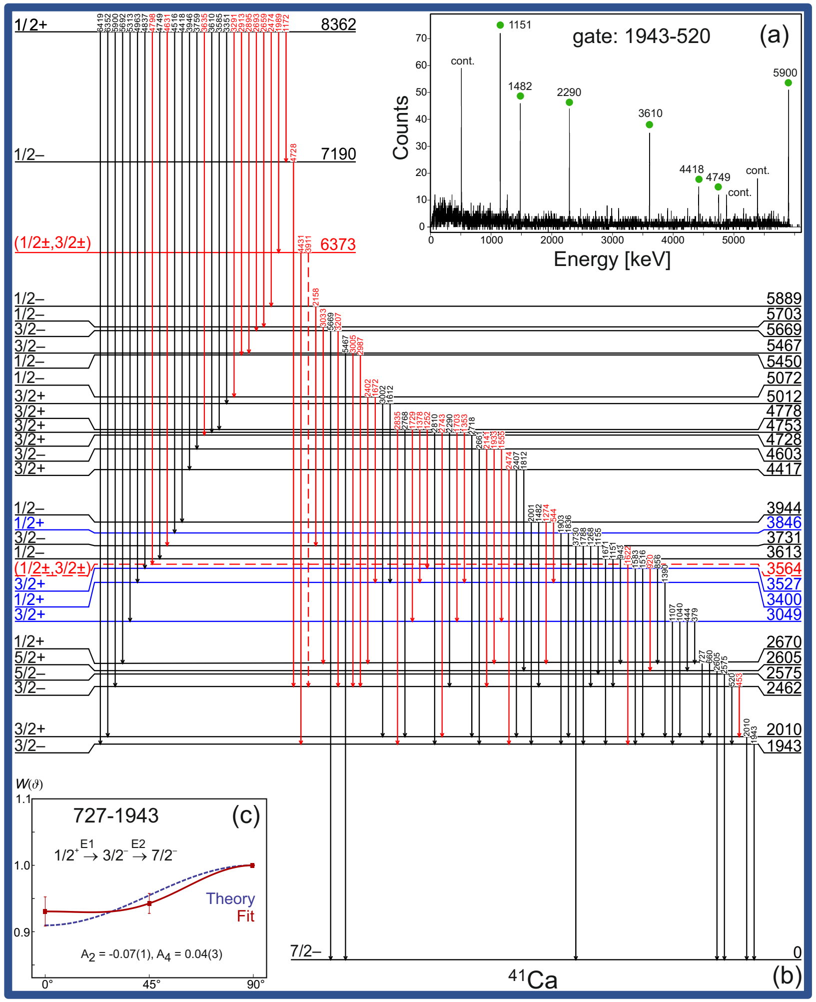
6^{th} Workshop on Nuclear Level Density and Gamma Strength

Oslo, May 8-12, 2017

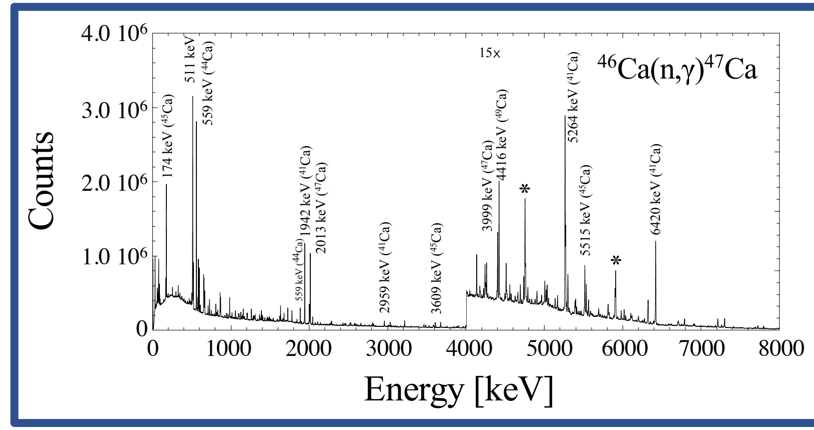
Extra slides

The case of Ca isotopes @ EXILL

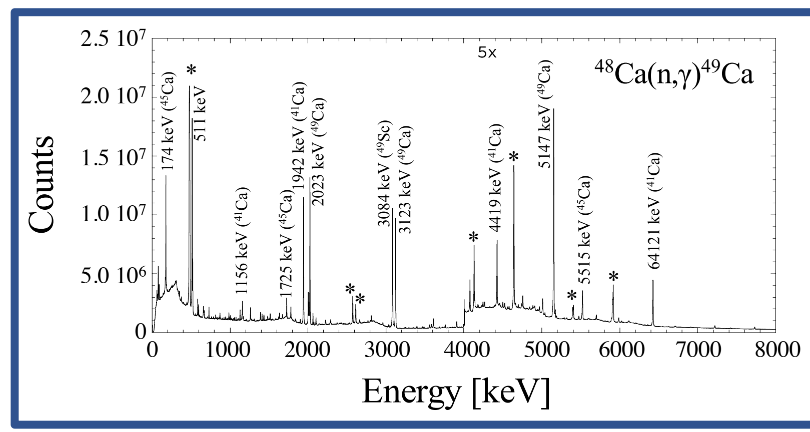
^{41}Ca



^{47}Ca

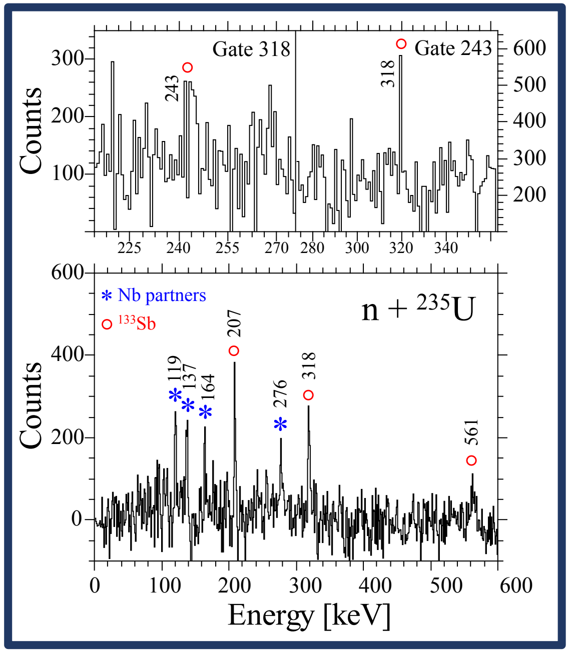


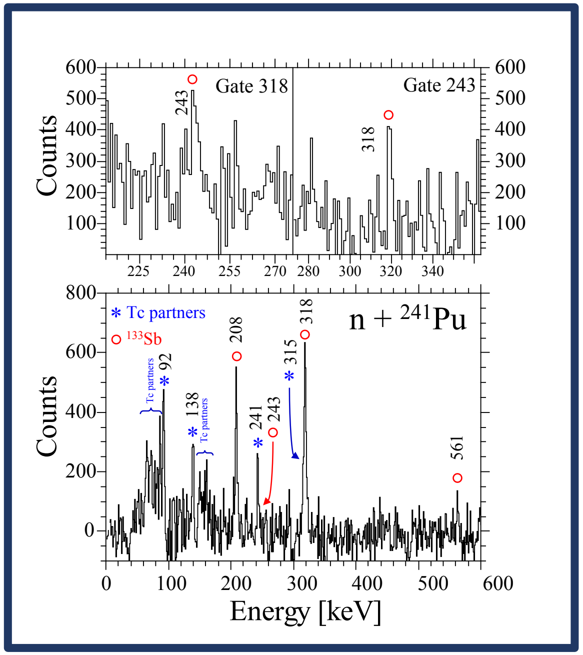
^{49}Ca

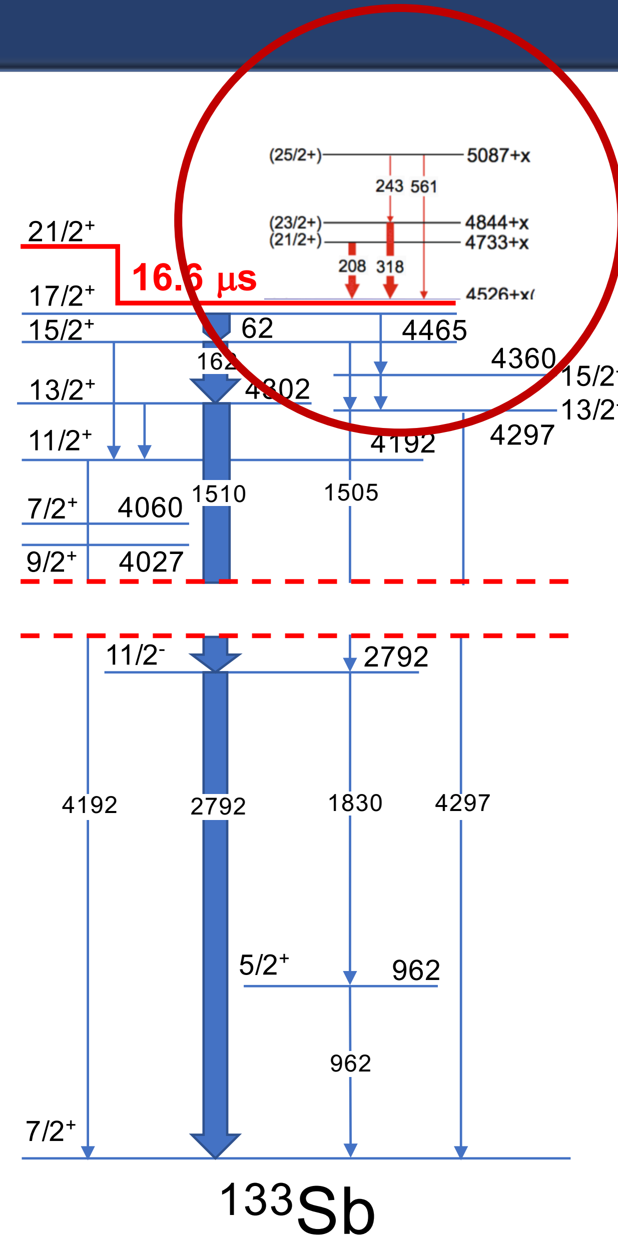


Analysis still ongoing

$^{133}Sb = ^{132}Sn + 1\pi$



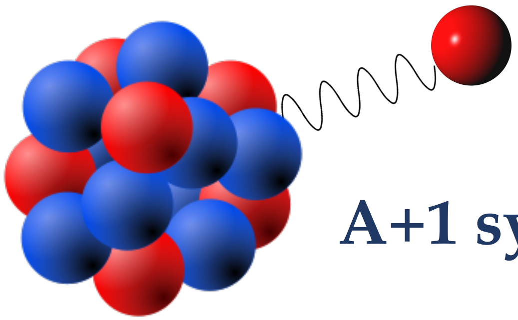




PROMPT – DELAYED γ–γ–γ coincidences

G. Bocchi et al., PLB, 760(2016)273

even-even core



A+1 system

Microscopic mean field description of the interplay and coupling between single-particle states and collective and non collective excitations of the core, using a Skyrme effective interaction and no adjustable parameters.

G. Colò, P.F. Bortignon and G. Bocchi, Phys. Rev. C **95**, 034303 (2017)

Reduced transition probability

$$B(X\lambda) \equiv \frac{1}{2j_i+1} \left|\langle \alpha_f j_f || \hat{O}(X\lambda) || \alpha_i j_i \rangle\right|^2$$

Reduced matrix element

$$\begin{aligned}
\langle \alpha_f j_f || \hat{O}(X\lambda) || \alpha_i j_i \rangle = & \sum_{if} \xi_i^{\alpha_i} \xi_f^{\alpha_f} \langle j_f || \hat{O}(X\lambda) || j_i \rangle + \quad \text{single particle} \\
& + \sum_{if} \xi_i^{\alpha_i} \xi_f^{\alpha_f} \delta(J'_f, \lambda) \delta(j'_f, j_i) \frac{\hat{j}_f}{\hat{\lambda}} \langle J'_f || \hat{O}_{\rm ph} || 0 \rangle + \\
& + \sum_{if} \xi_i^{\alpha_i} \xi_f^{\alpha_f} \delta(J'_i, \lambda) \delta(j'_i, j_f) \frac{\hat{j}_i}{\hat{\lambda}} \langle J'_i || \hat{O}_{\rm ph} || 0 \rangle (-)^{j_i - j_f + \lambda + \left(\begin{smallmatrix} +1 & \text{for M} \\ +0 & \text{for E} \end{smallmatrix} \right)} + \quad \text{phonon} \\
& + \sum_{if} \xi_i^{\alpha_i} \xi_f^{\alpha_f} \hat{j}_f \hat{j}_i \Bigg\{ (-)^{j_f + J'_i + \lambda + j'_i} \begin{Bmatrix} j_i & j_f & \lambda \\ J'_f & J'_i & j'_f \end{Bmatrix} \delta(j'_f, j'_i) \times \\
& \times \sum_{ph,p'h'} \left[X^f_{ph} X^i_{p'h'} + (-)^{J'_f - J'_i + \lambda} Y^f_{ph} Y^i_{p'h'} \right] \times \\
& \quad \times \Bigg(\delta(h,h') \hat{J}'_f \hat{J}'_i (-)^{j_h + j_p + J'_i + \lambda} \begin{Bmatrix} j_h & J'_i & j_{p'} \\ \lambda & j_p & J'_f \end{Bmatrix} \langle j_p || \hat{O}_{sp} || j_{p'} \rangle + \\
& \quad - \delta(p,p') \hat{J}'_f \hat{J}'_i (-)^{j_h + j_p + J'_f} \begin{Bmatrix} j_p & J'_i & j_{h'} \\ \lambda & j_h & J'_f \end{Bmatrix} \langle j_{h'} || \hat{O}_{sp} || j_h \rangle \Bigg) + \\
& + (-)^{j_i + j'_f + \lambda + J'_f} \begin{Bmatrix} j_f & j_i & \lambda \\ j'_i & j'_f & J'_f \end{Bmatrix} \delta(J'_f, J'_i) \langle j'_f || \hat{O}_{sp} || j'_i \rangle \Bigg\} . \quad \text{mixed}
\end{aligned}$$

Diagonalization $(H-NE)\psi=0$

$$\mathcal{H}=\begin{pmatrix} \varepsilon_{n_1lj} & 0 & \frac{\langle n_1lj||V||n_1'l_1'j_1'N_1J_1\rangle}{\hat{j}} & \frac{\langle n_1lj||V||n_2'l_2'j_2'N_2J_2\rangle}{\hat{j}} \\ 0 & \varepsilon_{n_2lj} & \frac{\langle n_2lj||V||n_1'l_1'j_1'N_1J_1\rangle}{\hat{j}} & \frac{\langle n_2lj||V||n_2'l_2'j_2'N_2J_2\rangle}{\hat{j}} \\ \frac{\langle n_1lj||V||n_1'l'j_1'N_1J_1\rangle}{\hat{j}} & \frac{\langle n_2lj||V||n_1'l'j_1'N_1J_1\rangle}{\hat{j}} & \varepsilon_{n_1'l_1'j_1'}+\hbar\omega_{N_1J_1} & 0 \\ \frac{\langle n_1lj||V||n_2'j_2'N_2J_2\rangle}{\hat{j}} & \frac{\langle n_2lj||V||n_2'l'j_2'N_2J_2\rangle}{\hat{j}} & 0 & \varepsilon_{n_2'l_2'j_2'}+\hbar\omega_{N_2J_2} \end{pmatrix}.$$

$$n(j_1'n_1J_1,j_2'n_2J_2)=\delta(j_1',j_2')\delta(n_1,n_2)\delta(J_1,J_2)-\sum_{h_1}(-)^{J_1+J_2+j_1'+j_2'}\hat{J}_1\hat{J}_2\begin{Bmatrix} j_2' & j_{h_1} & J_1 \\ j_1' & j & J_2 \end{Bmatrix}X^{(n_1J_1)}_{j_2'h_1}X^{(n_2J_2)}_{j_1'h_1}$$

$$\mathcal{N}=\begin{pmatrix} 1 & 0 & \dots & 0 & 0 & \dots \\ 0 & 1 & \dots & 0 & 0 & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & n(j_1'n_1J_1,j_1'n_1J_1) & n(j_1'n_1J_1,j_2'n_2J_2) & \dots \\ 0 & 0 & \dots & n(j_2'n_2J_2,j_1'n_1J_1) & n(j_2'n_2J_2,j_1'n_1J_1) & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots \end{pmatrix}.$$

Zero-range momentum-dependent effective nucleon-nucleon interaction

$$V(\mathbf{r}_1,\mathbf{r}_2) = t_0(1+x_0P_\sigma)\delta(\mathbf{r}) + \frac{1}{2}t_1(1+x_1P_\sigma)[\mathbf{P}'^2\delta(\mathbf{r})+\delta(\mathbf{r})\mathbf{P}^2] + t_2(1+x_2P_\sigma)\mathbf{P}'\cdot\delta(\mathbf{r})\mathbf{P} + \frac{1}{6}t_3(1+x_3P_\sigma)\rho^\alpha(\mathbf{R})\delta(\mathbf{r}) + iW_0(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)\cdot[\mathbf{P}'\times\delta(\mathbf{r})\mathbf{P}]$$

$$\mathbf{r} = \mathbf{r}_1 - \mathbf{r}_2$$

$$\mathbf{R} = \frac{1}{2}(\mathbf{r}_1+\mathbf{r}_2)$$

$$P_\sigma = \frac{1}{2}(1+\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)$$

$$\mathbf{P} = \frac{1}{2i}(\nabla_1-\nabla_2)$$

$$\rho = \rho_n + \rho_p$$

SkX Skyrme: fit of binding energies, rms charge radii and single-particle energies

^{16}O, ^{24}O, ^{34}Si, ^{40}Ca, ^{48}Ca, ^{48}Ni, ^{68}Ni, ^{88}Sr, ^{100}Sn, ^{132}Sn, ^{208}Pb

B. A. Brown, Phys. Rev. C, **58**, 220 (1998)

Single-particle wave function

$$\varphi_\alpha^q(\mathbf{r},\sigma) = \frac{u_\alpha^q(r)}{r}[Y_l(\hat{r}) \otimes \chi_{1/2}(\sigma)]_{jm}\chi_q(\tau),$$

HF – Skyrme Schrödinger equation

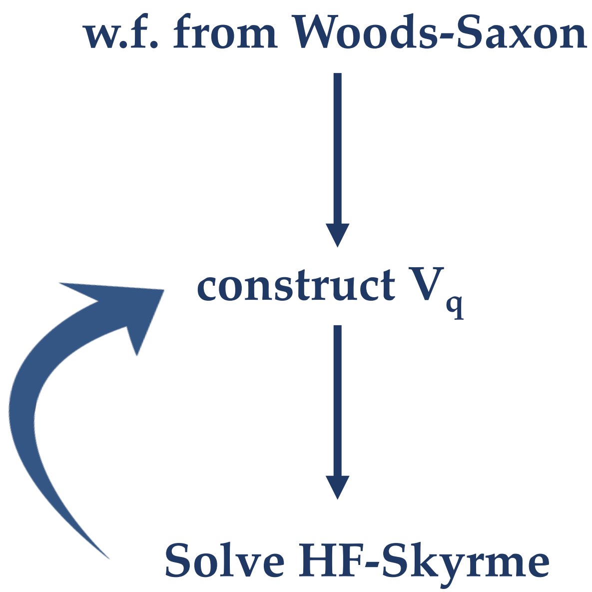
$$\left[-\nabla \cdot \frac{\hbar^2}{2m_q^*(\mathbf{r})}\nabla + U_q(\mathbf{r}) + qV_C(\mathbf{r}) - i\mathbf{W}_q(\mathbf{r}) \cdot (\nabla \times \boldsymbol{\sigma})\right]\varphi_\alpha^q = \epsilon_\alpha \varphi_\alpha^q,$$

Radial equation

$$\frac{\hbar^2}{2m_q^*(r)}\left[-u_\alpha'' + \frac{l(l+1)}{r^2}u_\alpha\right] + V_q(r)u_\alpha - \left(\frac{\hbar^2}{2m_q^*}\right)' u_\alpha' = \epsilon_\alpha u_\alpha.$$

Interaction

$$V_q(r) = V_q^{cent}(r) + \delta_{q,1}V_C(r) + V_q^{s.o.}(r)\langle \mathbf{l} \cdot \sigma \rangle.$$



Random Phase Approximation

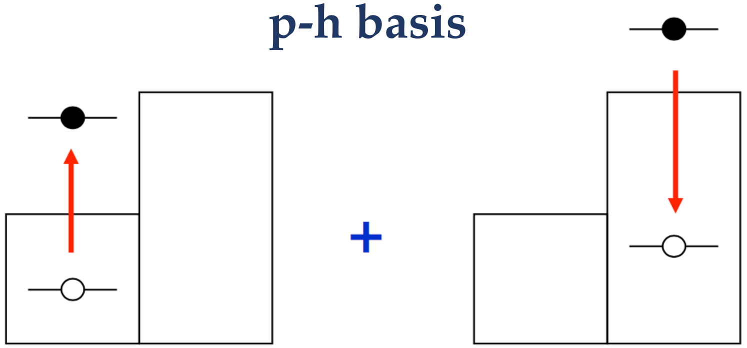
Creation operator of a p-h

$$Q^{+}_{mi}(JM) = \sum_{m_m, m_i} (j_m j_i m_m - m_i | JM) c^{+}_{j_m m_m} (-1)^{j_i - m_i} c_{j_i m_i}$$

RPA creation operator

$$O^{+}_{\nu} = \sum_{mi} X^{(\nu)}_{mi} Q^{+}_{mi}(JM) - Y^{(\nu)}_{mi} Q_{mi}(\widetilde{JM})$$

p-h basis



RPA state

$$|\nu\rangle = O^{+}_{\nu} |\tilde{0}\rangle$$

RPA secular matrix

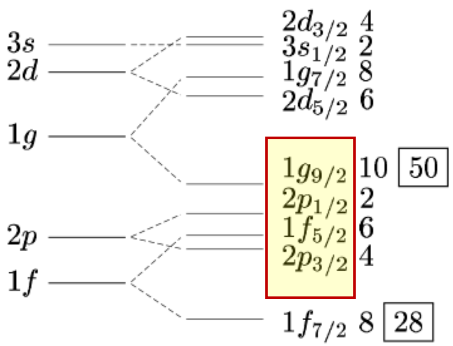
$$\begin{pmatrix} A & B \\ -B & -A \end{pmatrix} \begin{pmatrix} X^{(\nu)} \\ Y^{(\nu)} \end{pmatrix} = E_{\nu} \begin{pmatrix} X^{(\nu)} \\ Y^{(\nu)} \end{pmatrix}$$

$$A_{mi,nj} = (\epsilon_m - \epsilon_i)\, \delta_{mn} \delta_{ij} + \langle \overbrace{mj | V_{res} | i}^{J} n \rangle_{\underbrace{\qquad}_{J}}$$

$$B_{mi,nj} = \langle \overbrace{mn | V_{res} | i}^{J} j \rangle_{\underbrace{\qquad}_{J}}.$$

^{48}Ca – RPA

ν model space

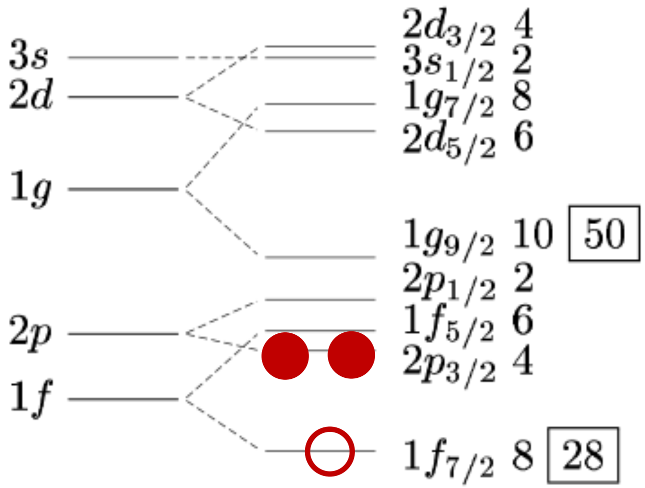


J^π	Energy [MeV]			$B(E/M\lambda)$ [W.u.]		
	Exp.	Theory (SkX)	Theory (SLy5)	Exp.	Theory (SkX)	Theory (SLy5)
2_1^+	3.83	2.87	3.02	1.71	1.31	1.12
4_1^+	4.50	3.12	3.60		0.43	0.70
3_1^-	4.51	4.43	4.75	5.0	6.77	6.12
3_1^+	4.61	3.22	3.92		6.6×10^{-4}	6.6×10^{-3}
4_1^-	5.26	5.11	5.01		0.07	1.80
3_2^-	5.37	5.37			0.05	
3_2^+		5.02			7.6×10^{-4}	
4_2^+		4.70	5.20		1.02	0.86
5_1^+		3.51	3.90		5.0×10^{-3}	0.01

RPA calculations for the ^{48}Ca core

^{49}Ca – particle or hole?

neutrons



$$|7/2^-\rangle_{^{49}Ca} = |1f^{-1}_{7/2} 2p^2_{3/2}\rangle_{7/2^-}$$

Coupling with particles

$$|^{49}Ca\rangle = |^{48}Ca \otimes n\rangle$$

$$|7/2^-\rangle_{^{49}Ca} = |(1f^{-1}_{7/2} 2p_{3/2})_{2^+} \otimes 2p_{3/2}\rangle_{7/2^-}$$

Coupling with holes

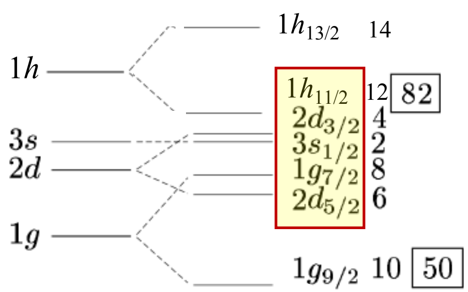
$$|^{49}Ca\rangle = |^{50}Ca \otimes n^{-1}\rangle$$

$$|7/2^-\rangle_{^{49}Ca} = |(2p^2_{3/2})_{0^+} \otimes 1f^{-1}_{7/2}\rangle_{7/2^-}$$

same final configuration
but
different couplings!

^{132}Sn – RPA

π model space



collective

non collective (1p – 1h)

J^π	Energy [MeV] Exp.	Energy [MeV] Theory	B(E/Mλ) [W.u.] Exp.	B(E/Mλ) [W.u.] Theory	Main components Theory
2_1^+	4.041	3.87	7	4.75	$\nu h_{11/2}^{-1} f_{7/2}$ (0.56), $\pi g_{9/2}^{-1} d_{5/2}$ (0.19), $\pi g_{9/2}^{-1} g_{7/2}$ (0.14)
3_1^-	4.352	5.02	> 7.1	9.91	$\nu s_{1/2}^{-1} f_{7/2}$ (0.40), $\nu d_{3/2}^{-1} f_{7/2}$ (0.12), $\pi p_{1/2}^{-1} g_{7/2}$ (0.12)
4_1^+	4.416	4.42	4.42	5.10	$\nu h_{11/2}^{-1} f_{7/2}$ (0.63), $\pi g_{9/2}^{-1} g_{7/2}$ (0.21)
6_1^+	4.716	4.73		1.65	$\nu h_{11/2}^{-1} f_{7/2}$ (0.86), $\pi g_{9/2}^{-1} g_{7/2}$ (0.11)
8_1^+	4.848	4.80		0.28	$\nu h_{11/2}^{-1} f_{7/2}$ (0.98)
5_1^+	4.885	4.77		0.20	$\nu h_{11/2}^{-1} f_{7/2}$ (0.99)
7_1^+	4.942	4.80		0.30	$\nu h_{11/2}^{-1} f_{7/2}$ (0.98)
(9_1^+)	5.280	4.99		0.04	$\nu h_{11/2}^{-1} f_{7/2}$ (0.99)
1_1^+		4.97		7.95	$\pi g_{9/2}^{-1} g_{7/2}$ (0.76), $\nu h_{11/2}^{-1} h_{9/2}$ (0.24)
2_2^+		5.37		$< 10^{-2}$	$\pi g_{9/2}^{-1} g_{7/2}$ (0.72), $\nu h_{11/2}^{-1} f_{7/2}$ (0.18)
2_1^-		5.44		0.47	$\nu d_{3/2}^{-1} f_{7/2}$ (0.79)
3_1^+		4.79		0.13	$\nu h_{11/2}^{-1} f_{7/2}$ (0.96)
3_2^+		5.40		1.99	$\pi g_{9/2}^{-1} g_{7/2}$ (0.96)
4_2^+		5.25		1.01	$\pi g_{9/2}^{-1} d_{3/2}$ (0.56), $\nu h_{11/2}^{-1} f_{7/2}$ (0.32)
5_2^+		5.45		0.61	$\pi g_{9/2}^{-1} g_{7/2}$ (0.99)
6_2^+		5.32		2.67	$\pi g_{9/2}^{-1} g_{7/2}$ (0.74), $\nu h_{11/2}^{-1} f_{7/2}$ (0.13)
7_2^+		5.42		0.50	$\pi g_{9/2}^{-1} g_{7/2}$ (0.99)

RPA calculations for the ^{132}Sn core

Angular correlations

$$\overline{W(\theta)} = \sum_{\text{even } k}^{k_{\max}} A_{kk} P_k(\cos\theta) Q_k(1) Q_k(2)$$

$$A_{kk} = A_k(L_1 L_1' I_i I) A_k(L_2 L_2' I_f I)$$

$$A_k(L_1 L_1' I_i I) = \frac{F_k(L_1 L_1' I_i I) + 2\delta_1(\gamma_1) F_k(L_1 L_1' I_i I) + \delta_1^2(\gamma_1) F_k(L_1 L_1' I_i I)}{1 + \delta_1^2(\gamma_1)}$$

$$F_k(LL' I_i I) = (-)^{I_i + I - 1} [(2L+1)(2L'+1)(2I+1)(2k+1)]^{\frac{1}{2}} \begin{pmatrix} L & L' & k \\ 1 & 1 & 0 \end{pmatrix} \begin{Bmatrix} L & L' & k \\ I & I & I_i \end{Bmatrix}$$

$$Q_k = J_k / J_0$$

$$J_k(1) = \int_0^{\beta_1^{\max}} d\beta_1 \sin(\beta_1) P_k(\cos\beta_1) \varepsilon_1(\beta_1)$$

$$J_k(2) = \int_0^{\beta_2^{\max}} d\beta_2 \sin(\beta_2) P_k(\cos\beta_2) \varepsilon_2(\beta_2)$$

Transition rates

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

$$\begin{aligned} T(E1) &= 1.59 \cdot 10^15 E_\gamma^3 B(E1) \\ T(E2) &= 1.22 \cdot 10^9 E_\gamma^5 B(E2) \\ T(E3) &= 5.67 \cdot 10^2 E_\gamma^7 B(E3) \\ T(E4) &= 1.69 \cdot 10^{-4} E_\gamma^9 B(E4) \end{aligned}$$

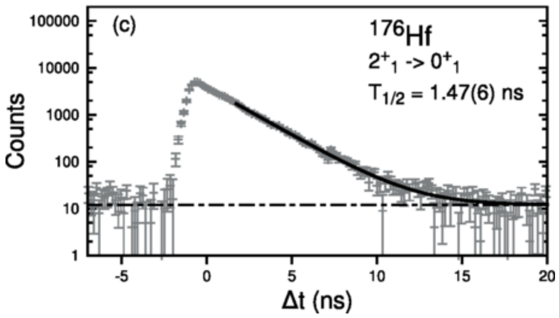
$$\begin{aligned} T(B1) &= 1.76 \cdot 10^13 E_\gamma^3 B(M1) \\ T(B2) &= 1.35 \cdot 10^7 E_\gamma^5 B(M2) \\ T(B3) &= 6.28 \cdot 10^0 E_\gamma^7 B(M3) \\ T(B4) &= 1.87 \cdot 10^{-6} E_\gamma^9 B(M4) \end{aligned}$$

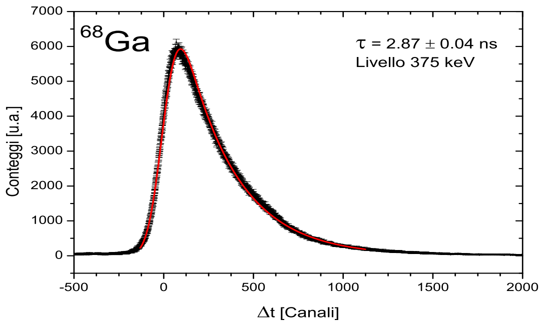
Weisskopf units:

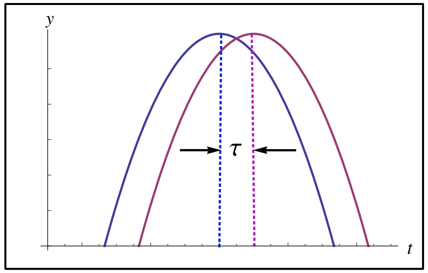
$$\begin{cases} B_W(E\lambda) = \frac{1.2^{2\lambda}}{4\pi}\left(\frac{3}{\lambda+3}\right)^2 A^{2\lambda/3} & e^2(\mathrm{fm})^{2\lambda} \\ B_W(M\lambda) = \frac{10}{\pi}1.2^{2\lambda-2}\left(\frac{3}{\lambda+3}\right)^2 A^{(2\lambda-2)\lambda/3} & \left(\frac{e\hbar}{2Mc}\right)^2(\mathrm{fm})^{2\lambda-2} \end{cases}$$

$$\tau \gg \text{FWHM} \qquad \tau \cong \text{FWHM} \qquad \tau \ll \text{FWHM}$$

Slope Method | **Convolution Method** | **Centroid Shift Method**



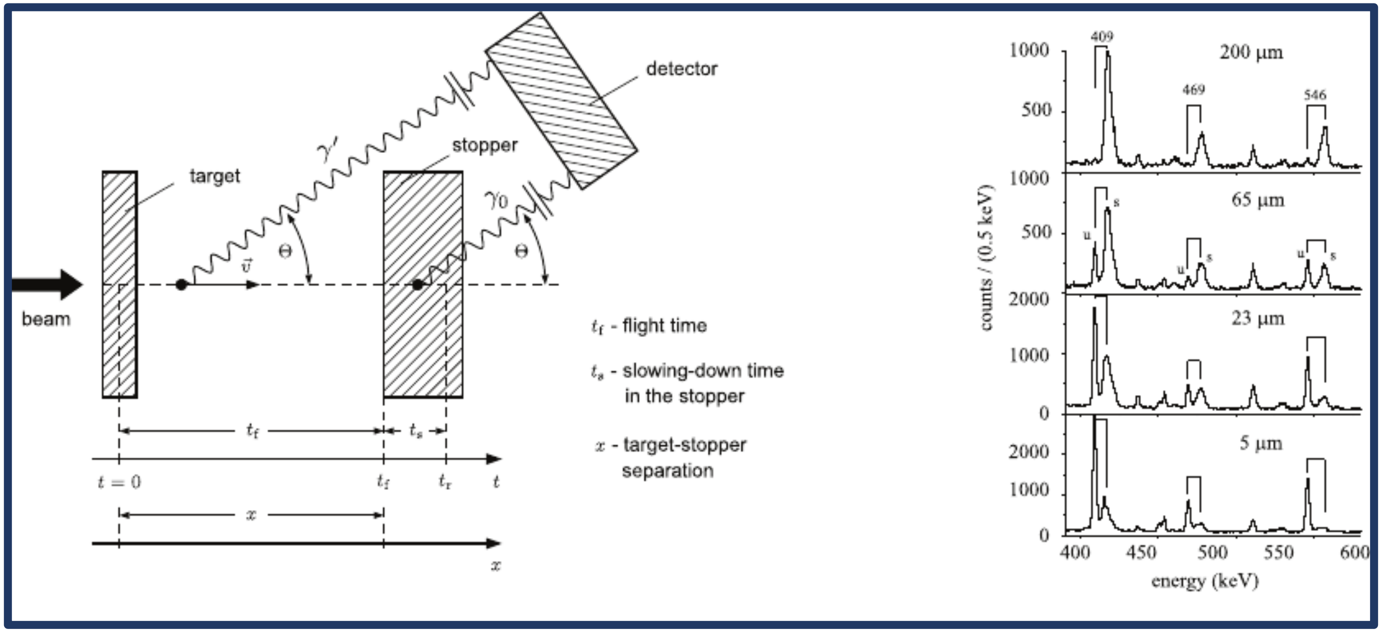


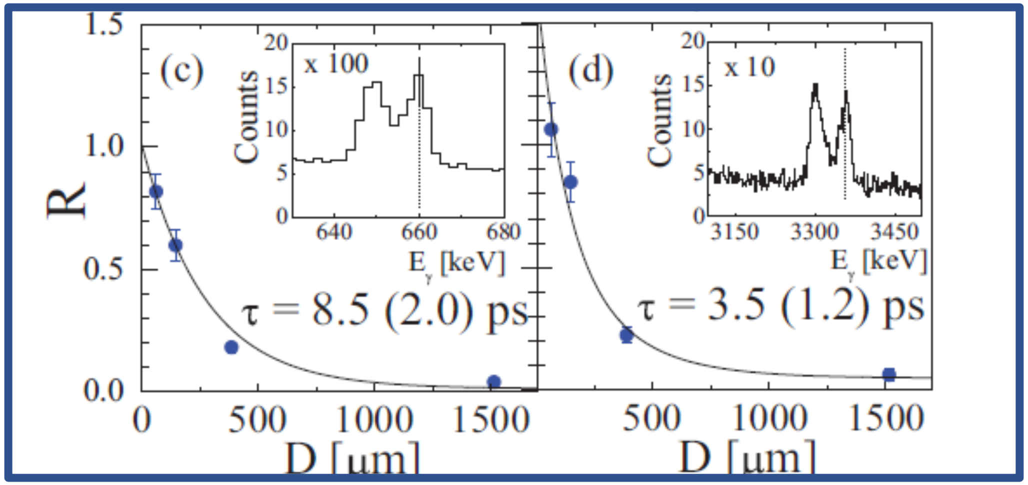


Convolution

$$D(t) = n\lambda \int_{-\infty}^{t} P(t' - t_0)\exp^{-\lambda(t-t')}\, dt' \quad \text{with} \quad \lambda = 1/\tau.$$

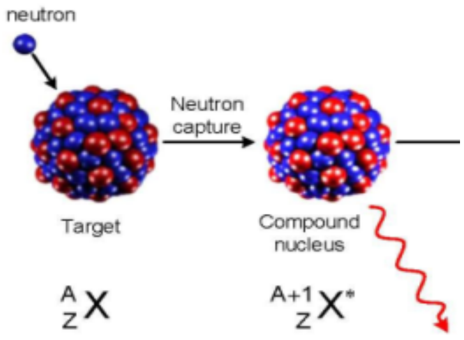
The plunger technique

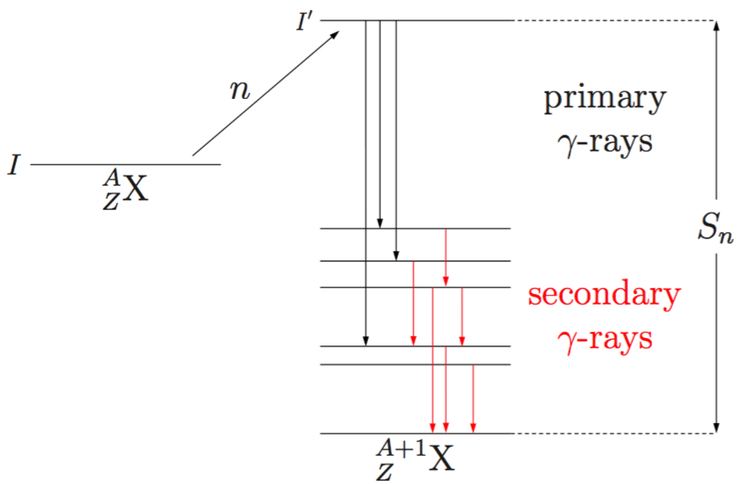




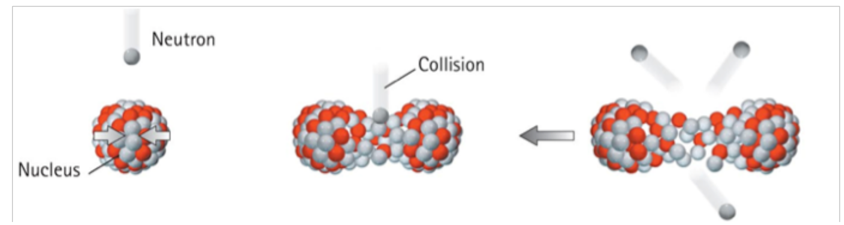
The EXILL - FATIMA campaign (2012 – 2013)

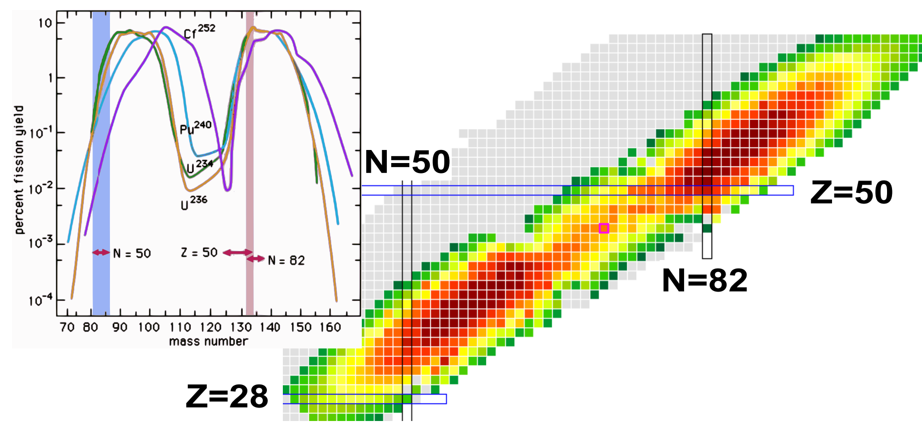
ν-capture reaction





ν-induced fission



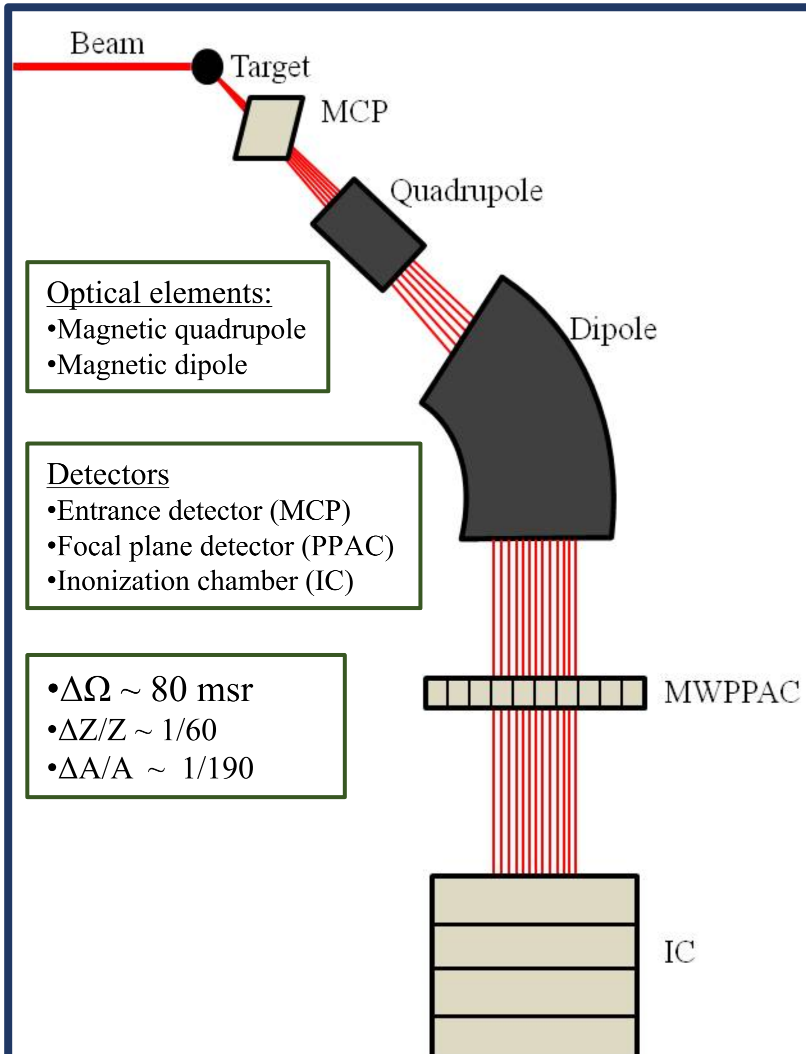


^{40}Ca(n,γ) ^{46}Ca(n,γ) ^{48}Ca(n,γ)

^{235}U(n,fγ) ^{241}Pu(n,fγ)

The PRISMA - CLARA campaign @ LNL

PRISMA



Optical elements:
- Magnetic quadrupole
- Magnetic dipole

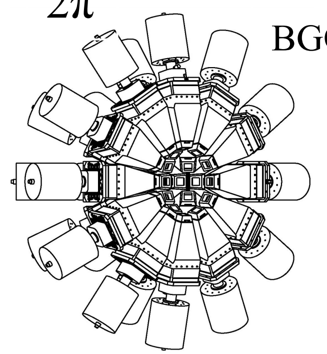
Detectors
- Entrance detector (MCP)
- Focal plane detector (PPAC)
- Inonization chamber (IC)

- $\Delta\Omega \sim 80$ msr
- $\Delta Z/Z \sim 1/60$
- $\Delta A/A \sim 1/190$

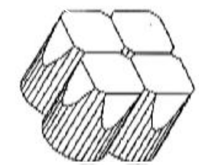
CLARA

25 HpGe Clover
$\varepsilon \sim 3$ % @ $E_\gamma = 1.3$ MeV

2π

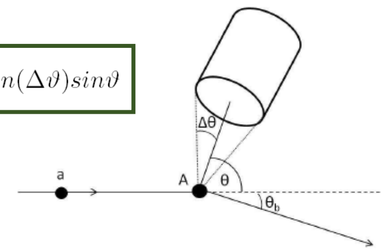


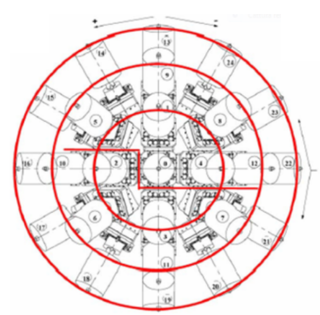
Composite Ge
50mm x 70mm



Compton polarimeter

$$\Delta FWHM = 2E_{\gamma 0}\frac{v}{c}sin(\Delta\vartheta)sin\vartheta$$





3 RINGS
$\theta \sim 100°\text{-}130°\text{-}150°$

γ angular distributions