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Probing Shape Coexistence in neutron-deficient ^{72}Se via Low- Energy Coulomb Excitation

D. T. Doherty[1], J. Ljungvall[2], M. Zielińska[1], W. Korten[1], P. Butler[3], F. Bello Garrote[4], E. Clément[5], J.P. Delaroche[6], H. De Witte[7], M. Djongolov[8], J. Eberth[9], G. de France[5], L. Gaffney[7], K. Gladnishki[8], M. Girod[6], A. Goasduff[2], A Görgen[4], K. Hadyńska-Klęk[4], M. Huyse[7], G. Jaworski[10], D. Jenkins[11], M. Klintefjord[4], M. Komorowska[12], J. Libert[4], B. Melon[13], A. Nannini[13], P. Napiorkowski[12], D. R. Napoli[10], A. Perego[13], G. Rainovski[8], E. Rapisarda[14], F. Recchia[15], P. Reiter[9], M. Rocchini[13], D. Rosiak[9], E. Sahin[4], M. Seidlitz[9], B. Siebeck[9], S. Siem[4], J. Srebrny[12], J. J. Valiente Dobon[10], P. Van Duppen[7], N. Warr[9], K. Wrzosek-Lipska[12]

[1] CEA, Saclay, France. [2] CSNSM, Orsay, France
[3] University of Liverpool, Liverpool, UK. [4] University of Oslo, Norway
[5] GANIL, Caen, France. [6] CEA/DAM, Bruyères-le-Châtel, France. [7] K.U Leuven, Belgium
[8] University of Sofia, Bulgaria. [9] IKP, University of Cologne, Germany. [10] LNL, INFN, Legnaro, Italy [11] University of York, York, UK. [12] HIL Warsaw, Poland. [13] INFN Sezione di Firenze, Italy. [14] CERN-ISOLDE, Switzerland. [15] Dipartimento di Fisica, Universita' di Padova, Padova, Italy

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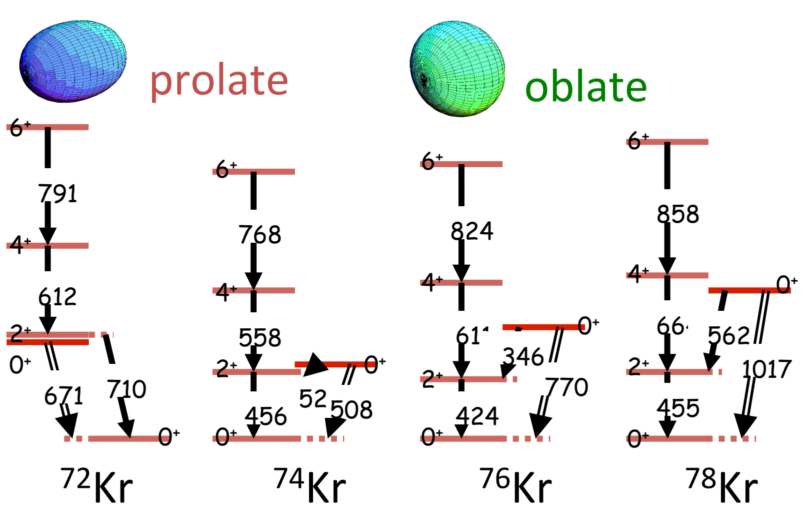
Motivation: Shape Coexistence

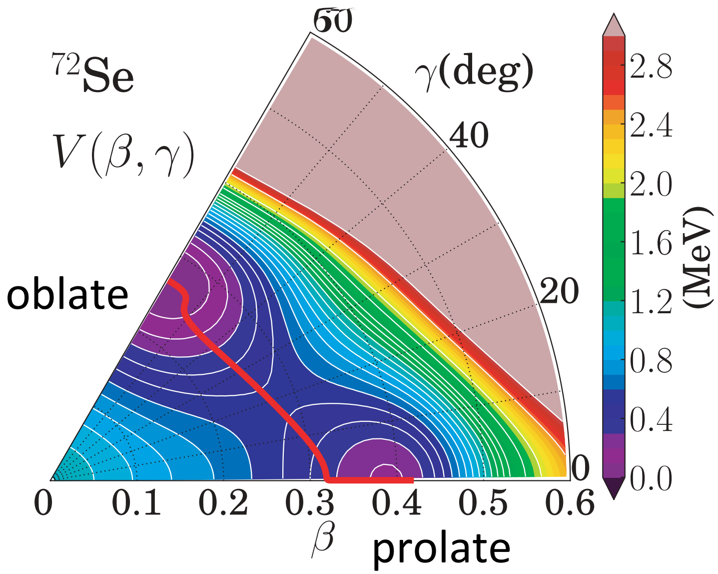
- States of different deformation observed within a very small energy range (typically a few hundred keV).

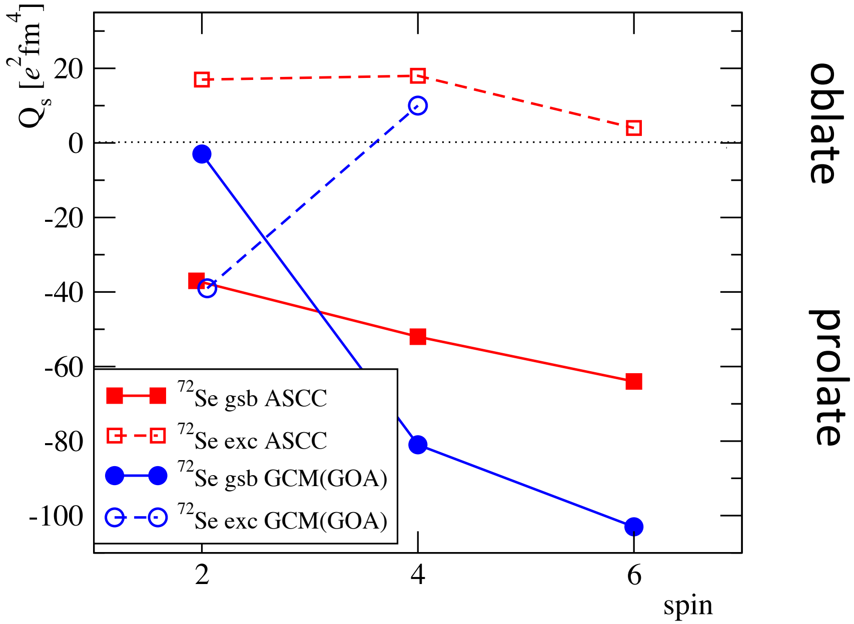
- In the A ≈ 70 region, the neutron-deficient krypton isotopes are a good example.
  - Intrinsic shapes of several low-lying states have been determined in Coulomb excitation measurements on ^{74}Kr, ^{76}Kr providing firm evidence for a prolate ground state band coexisting with an excited oblate band built on 0^+_2 level [1].
  - Inversion of the shapes in ^{72}Kr [2].
  - Situation well-described by Hartree-Fock-Bogoliubov (HFB) calculations using the Gogny D1S interaction and the configuration-mixing method (GCM/GOA) [1].



[1] E. Clément *et al.*, Phys. Rev. C. **75**, 054313 (2007).
[2] A. Gade *et al.*, Phys. Rev. Lett. **95,** 022502 (2005).

Motivation



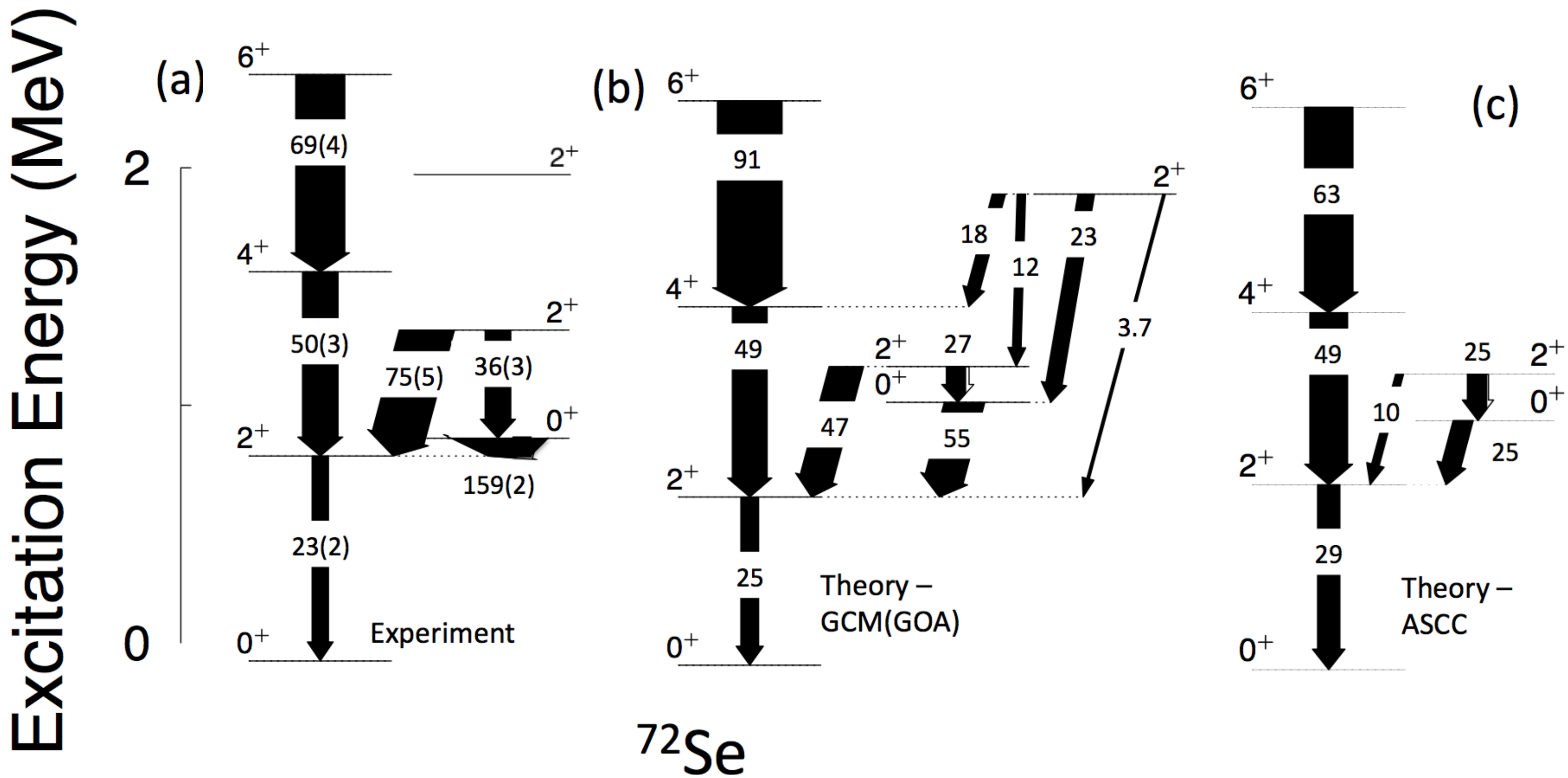


- Potential energy map for ^{72}Se, calculated with ASCC calculations [3].
- Ground state predicted to have a maximum at oblate deformation but extends to prolate region.
- Similar predictions for GCM(GOA) calculations [4].

- Theoretical quadrupole moments (QM) for states in the ground-state and excited bands in ^{72}Se.
- Both ASCC and GCM(GOA) approaches predict increasing prolate deformation moving up the GSB.
- Calculations in disagreement for band built on 0^+_2 level.

[3] N. Hinohara *et al.* Phys. Rev. C **80**, 014305 (2009) and N. Hinohara *et al.* Phys. Rev. C **82**, 064313 (2010).
[4] J. P. Delaroche, Private Communication (2014).

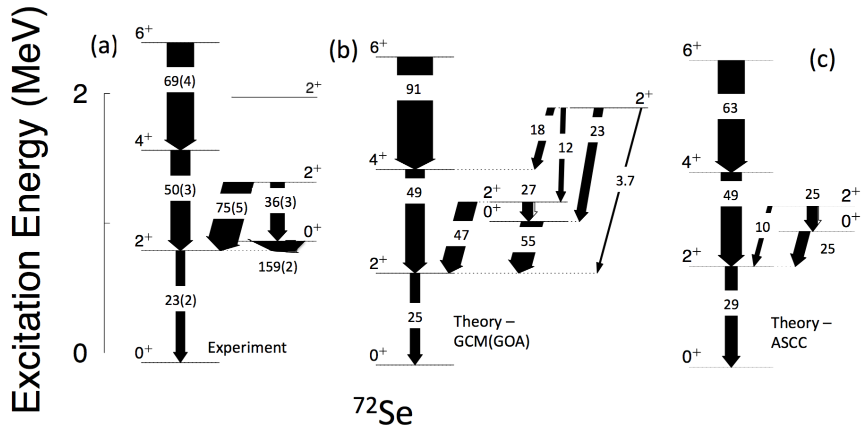
Motivation: Comparison between experiment and theory



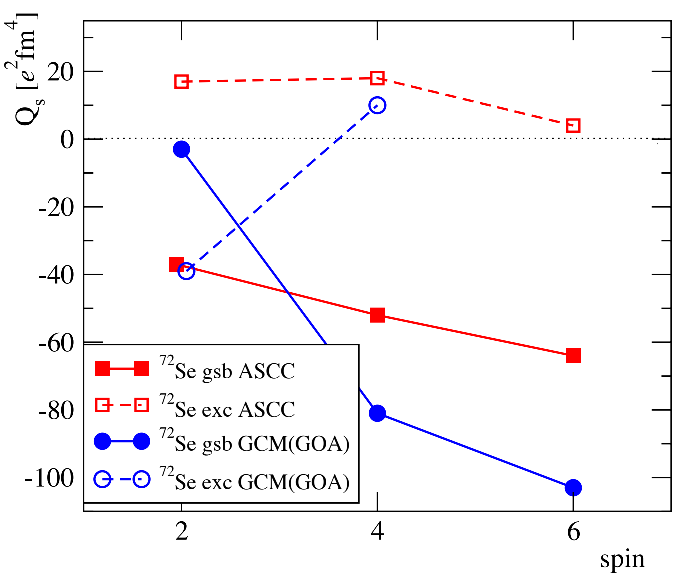
B(E2) values in Weisskopf units (W.u), experimental information from [5]

[5] E. A. Mc Cutchan *et al.,* Phys. Rev. C. **83,** 024310 (2011).

Motivation: Comparison



B(E2) values in Weisskopf units (W.u)



Both theoretical approaches well describe the **ground-state band**.

For excited band approaches are in disagreement.

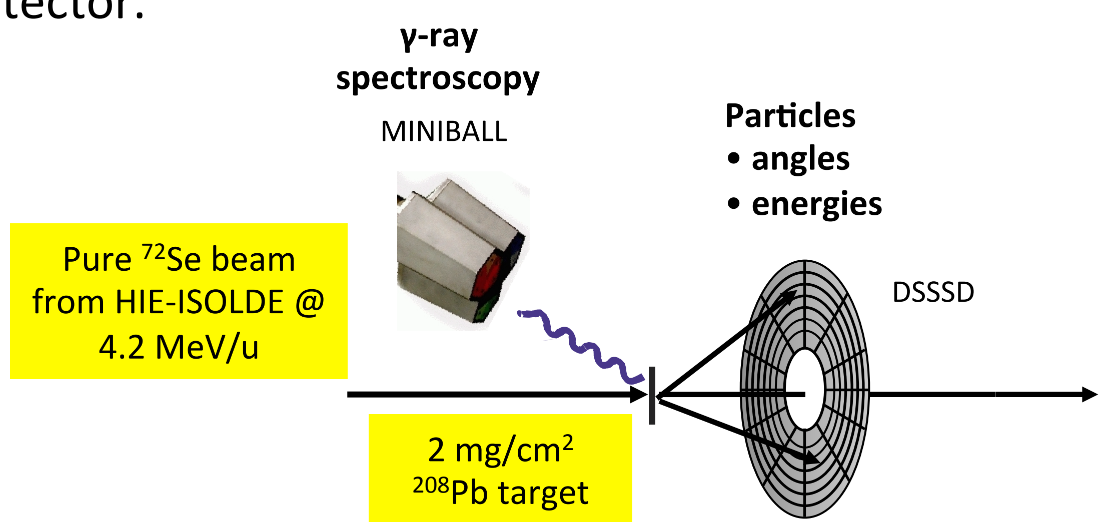
- ASCC calculations predict a weakly deformed, oblate excited band.
- GCM(GOA) calculations predict mixed 0^+_2 and 2^+_2 levels with purer configurations at larger excitation energy.

Both approaches underestimate the inter-band transitions and, therefore, the mixing between these two structures.

Goals of the measurement

- Perform a low-energy Coulomb excitation measurement which will enable
  - Determination of a number of transitional matrix elements.
  - Quadrupole moments of 2^+_1, 2^+_2 and 4^+_1 states to be determined.
  - Shapes of the ground state and 0^+_2 state to be determined via the Quadruple Sum Rules method.
  - Verify the lifetimes of the 0^+_2 and 2^+_2 states through their B(E2) values.

- Utilise standard Coulex setup. MINIBALL in conjunction with CD silicon detector.



Beam Delivery

- Numerous *A* = 72 isobaric contaminants expected. As, Ge, Ga ….
- Instead make use of selenium carbonyl molecules, $^{72}Se^{12}C^{16}O$

  => 100 a.m.u
- Break apart $^{72}SeCO$ inside EBIS and charge breed (up to $q = 19^{+}$) to remove *A* = 100 isobars (e.g. ^{100}Mo).
- This approach was successfully used with the more neutron-deficient isotope ^{70}Se [6]
- ^{72}Se accelerated to 305 MeV (4.2 MeV/u), such energies only possible due to HIE-ISOLDE upgrade.

- Alternative is production with RILIS after irradiation of cold ZrO_2

[6] A.M. Hurst et al., PRL 98, 072501 (2007)

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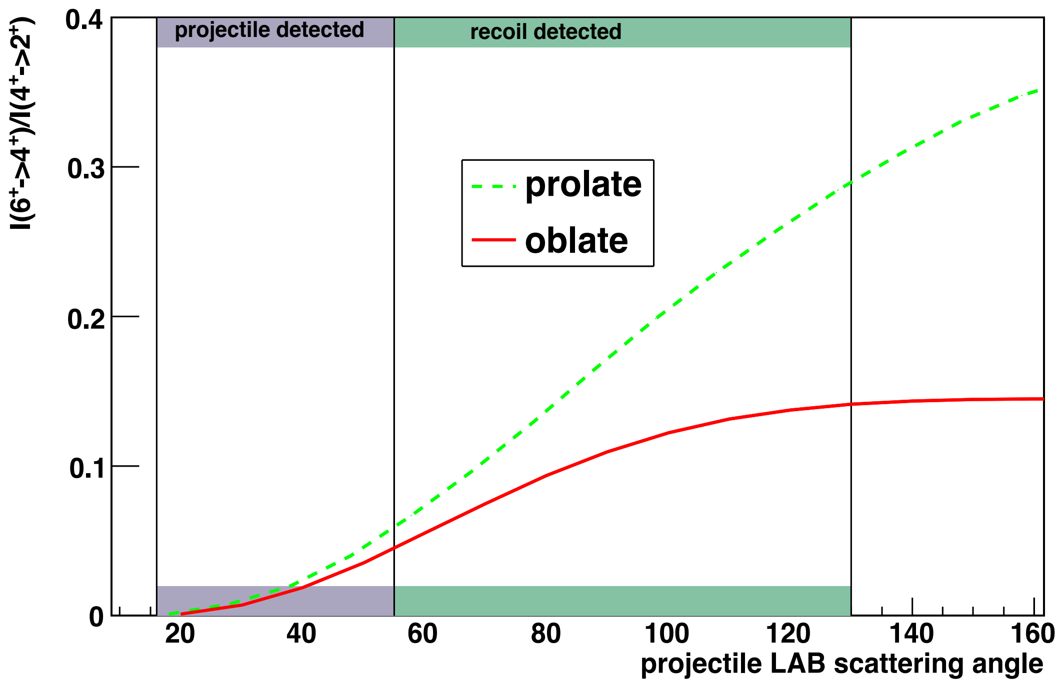
Expected Yields

- Expected yields calculated with the computer code GOSIA following the Coulomb excitation of a 305 MeV ^{72}Se beam (of average intensity 2 x 10^5 pps) incident on a 2 mg/cm^2 ^{208}Pb target.

Transition	Multipolarity	E_γ [keV]	Predicted Yield [counts/day]	Minimum Yield [counts/day]
$2^+_1 \rightarrow 0^+_1$	E2	862	17470	
$4^+_1 \rightarrow 2^+_1$	E2	775	960	
$6^+_1 \rightarrow 4^+_1$	E2	830	75	
$8^+_1 \rightarrow 6^+_1$	E2	958	6	
$0^+_2 \rightarrow 2^+_1$	E2	75	325	135
$2^+_2 \rightarrow 2^+_1$	E2/M1 $\delta = +11^{+11}_{-4}$	455	200	160
$2^+_2 \rightarrow 0^+_2$	E2	379	35	
$2^+_2 \rightarrow 0^+_1$	E2	1317	235	
$2^+_3 \rightarrow 2^+_1$	E2/M1 $\delta = -8^{+3}_{-12}$	1137	50	25
$2^+_3 \rightarrow 0^+_2$	E2	937	25	
$3^-_1 \rightarrow 2^+_2$	E1	1117	15	

Sensitivity to Quadrupole Moments (QM)

- Figure shows the ratio of the calculated intensity of the $6^+ \rightarrow 4^+$ transition to the $4^+ \rightarrow 2^+$ transition as a function of projectile scattering angle for two choices of QM, which correspond to prolate and oblate deformations of the 4^+_1 level, respectively.
- Demonstrating the sensitivity of the method for determining QMs



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Summary of beam time request

- To study the evolution of nuclear structure in neutron-deficient ^{72}Se by performing a low-energy Coulomb excitation measurement.
- We will determine matrix elements for low-lying states allowing for a full comparison with theoretical predictions.
- Furthermore, the intrinsic shape of the ground state and second 0^+ state will be investigated using the quadrupole sum rules method.

We request a total of 12 shifts with a 305-MeV ^{72}Se beam (10 on a ^{208}Pb target and up to 2 with a ^{196}Pt target) at a minimum intensity of 2×10^5 pps in order to perform this experiment.

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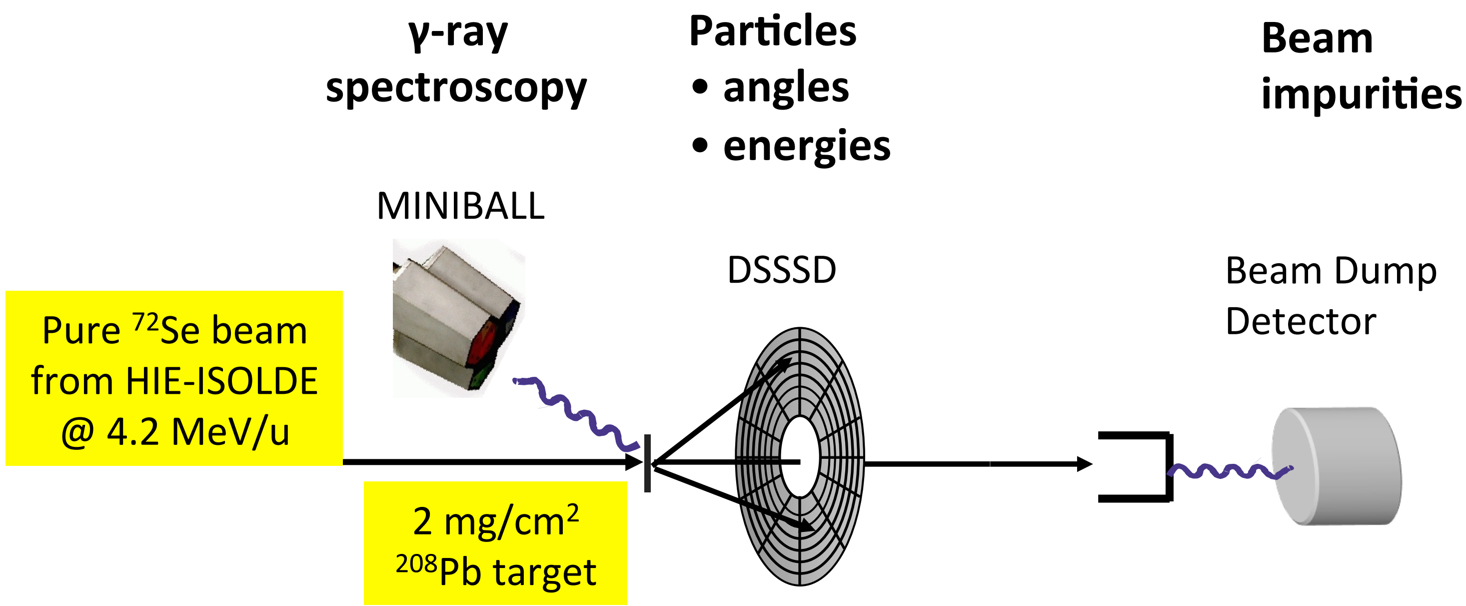
Thank you !!

Extra Slides

Experimental Setup



MINIBALL

- Purpose-built for the detection of low multiplicity γ rays with high-efficiency ($\varepsilon \approx 8\%$ for 1.3-MeV photons).
- Segmented detectors => superior Doppler correction.

Particle Detection

- Scattered projectile or recoiling target nuclei detected in Si CD detector subtending LAB angles of 16°-53°.
- 16 annular p^+ strips/quadrant
- 24 sector n^+ strips/quadrant
  => large degree of segmentation.

Expected Yields (2)

- As before, but with new Coulex chamber.

Transition	Multipolarity	E_γ [keV]	Predicted Yield [counts/day] 20° - 130° in LAB	Predicted Yield [counts/day] 130° - 170° in LAB
$2^+_1 \rightarrow 0^+_1$	E2	862	17470	420
$4^+_1 \rightarrow 2^+_1$	E2	775	960	96
$6^+_1 \rightarrow 4^+_1$	E2	830	75	28
$8^+_1 \rightarrow 6^+_1$	E2	958	6	8
$0^+_2 \rightarrow 2^+_1$	E2	75	325	18
$2^+_2 \rightarrow 2^+_1$	E2/M1 $\delta = +11^{+11}_{-4}$	455	200	56
$2^+_2 \rightarrow 0^+_2$	E2	379	35	7
$2^+_2 \rightarrow 0^+_1$	E2	1317	235	50
$2^+_3 \rightarrow 2^+_1$	E2/M1 $\delta = -8^{+3}_{-12}$	1137	50	4
$2^+_3 \rightarrow 0^+_2$	E2	937	25	1
$3^-_1 \rightarrow 2^+_2$	E1	1117	15	8

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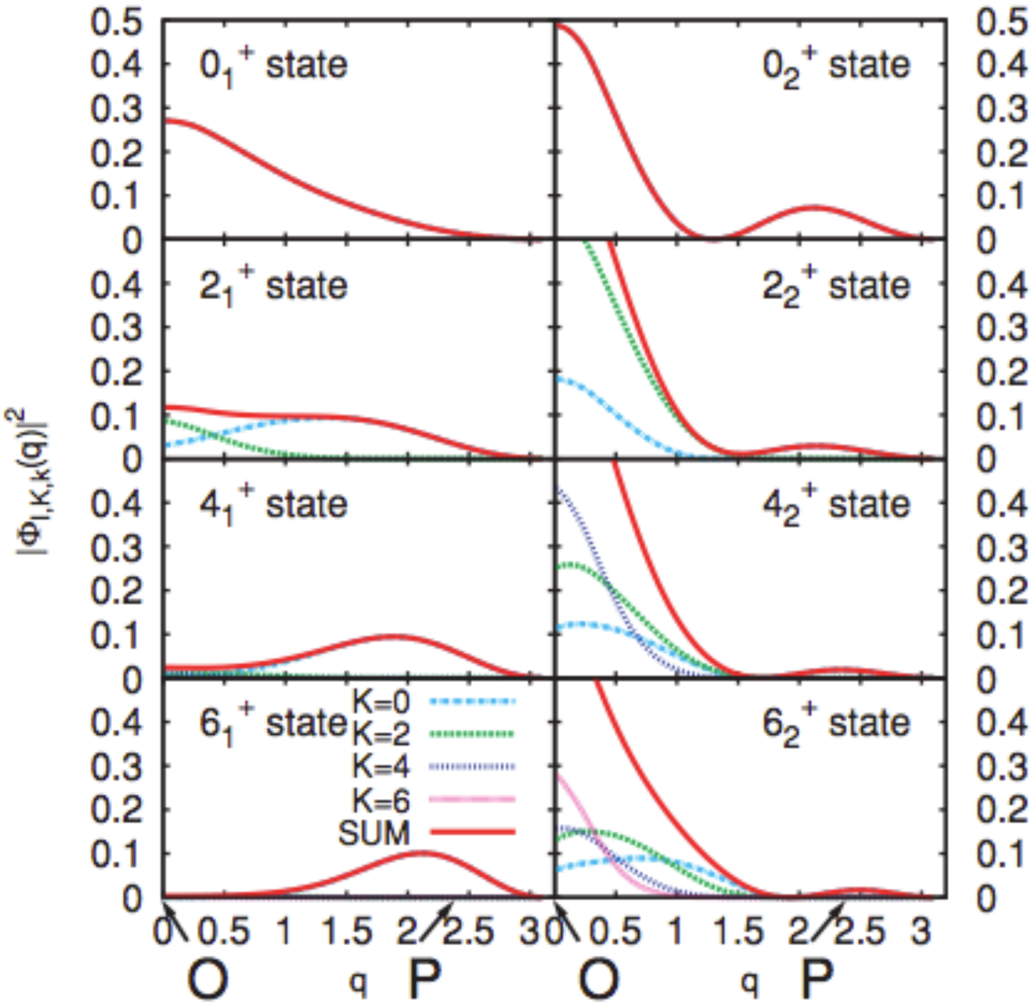
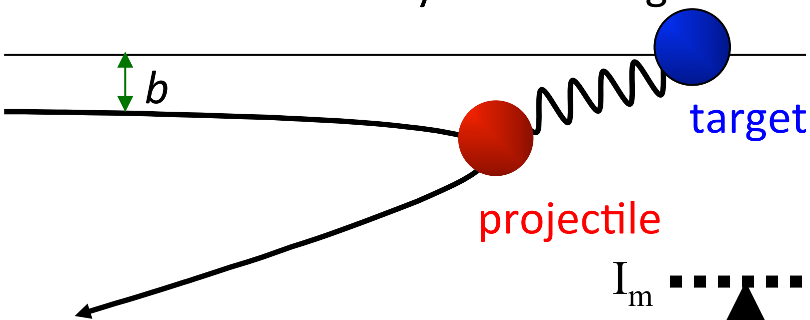
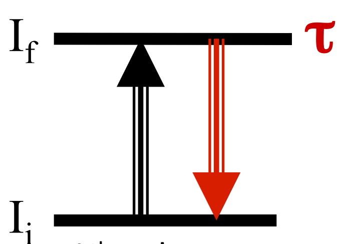
Motivation



Nuclear excitation by electromagnetic field acting between nuclei.

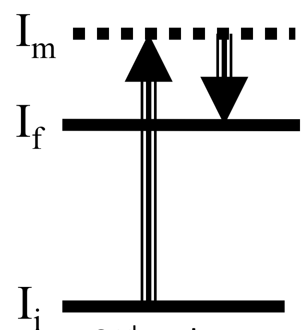


The excitation cross section is a direct measure of the $E\lambda$ matrix elements.



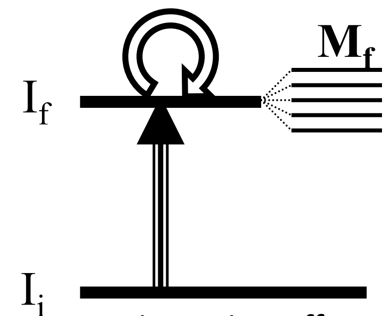
1st order:

$$a^{(1)}_{i\to f} \propto \langle I_f \| \mathbf{M}(E2) \| I_i \rangle$$



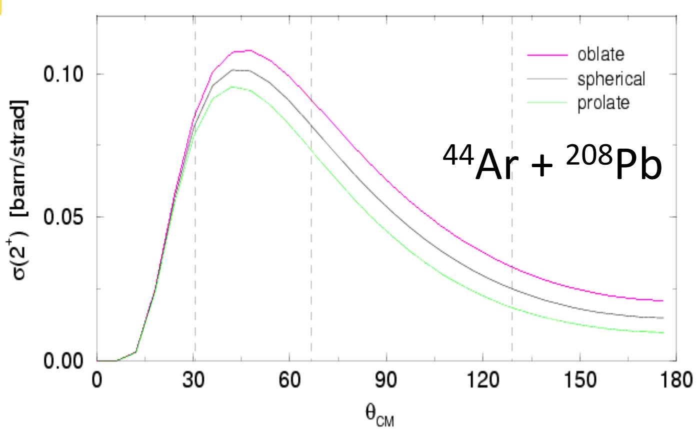
2nd order:

$$a^{(2)}_{i\to f} \propto \langle I_f \| \mathbf{M}(E2) \| I_m \rangle \langle I_m \| \mathbf{M}(E2) \| I_i \rangle$$



reorientation effect:

$$a^{(2)}_{i\to f} \propto \langle I_f \| \mathbf{M}(E2) \| I_f \rangle \langle I_f \| \mathbf{M}(E2) \| I_i \rangle$$



differential Coulomb excitation cross section

⇒ transition probability $B(E2)$

⇒ quadrupole moment Q_s

lifetime measurement

$$\lambda = \frac{1}{\tau} \propto B(E2; I_f \to I_i)\,(E_\gamma)^5$$