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

## Status Report

Daniel Doherty on behalf of the IS597 collaboration

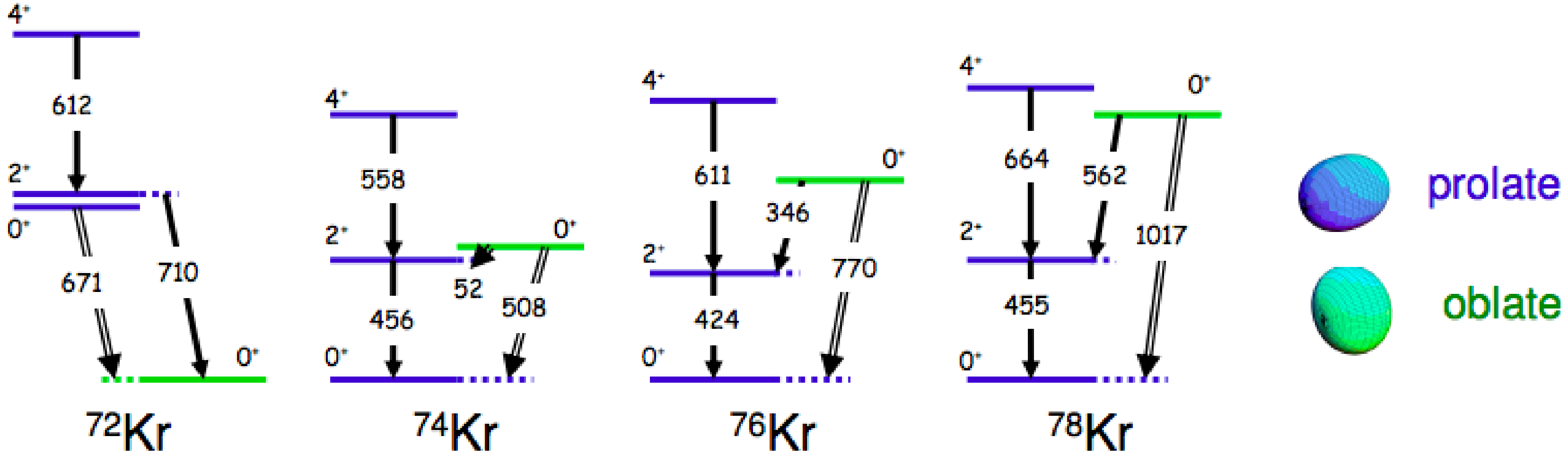
61st Meeting on the INTC
(2nd July 2019)

UNIVERSITY OF SURREY

# Coexisting Shapes in the A = 70 Region

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

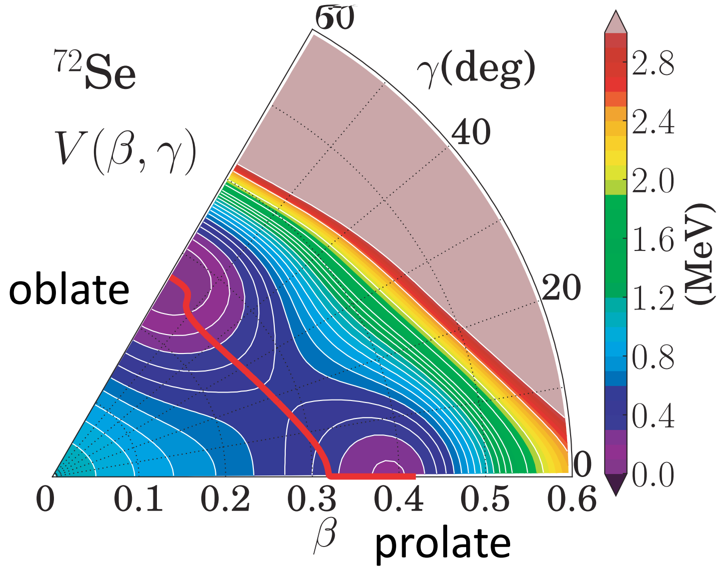
- In the A ≈ 70 region, the neutron-deficient Kr isotopes are a good example (see below, direct and indirect information).

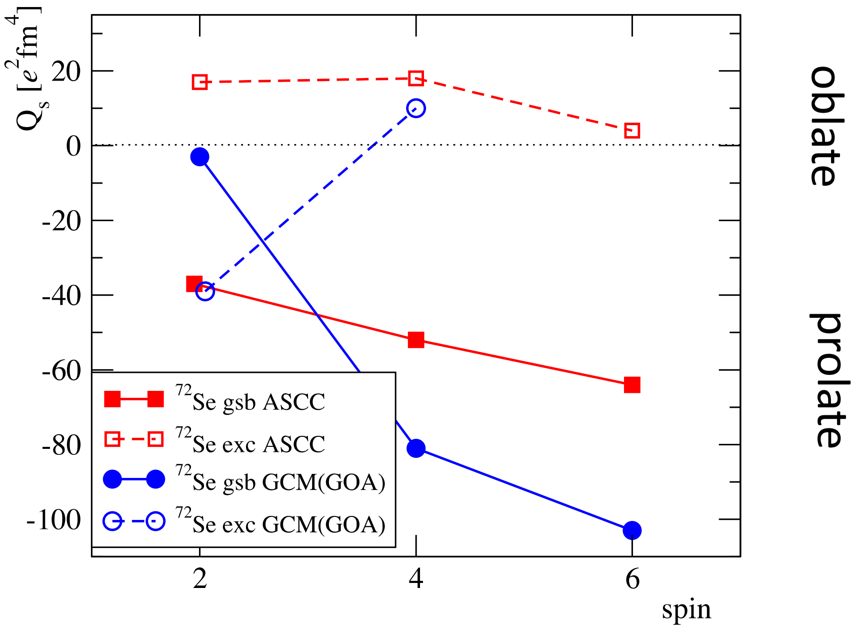



- Situation **even less well understood** and likely more complex for Se isotopes.

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

# Motivation for $^{72}$Se (1) - Shapes



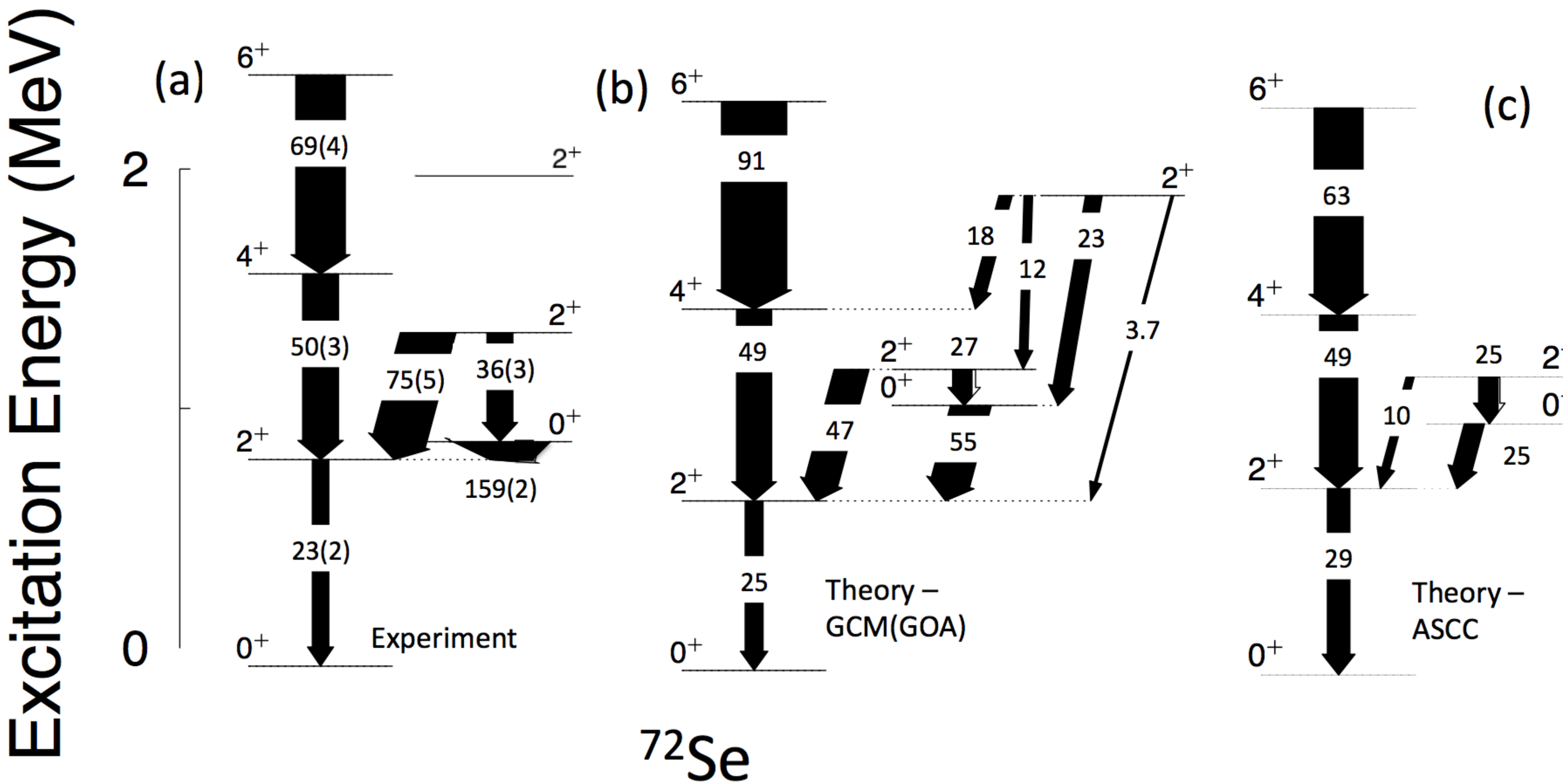




- Potential energy map for $^{72}$Se, calculated with ASCC calculations.
- Ground state predicted to have a maximum at oblate deformation but extends to prolate region.
- Similar predictions for GCM(GOA) calculations

- 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.


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

# Motivation for $^{72}$Se (2) – Transitional MEs




B(E2) values in Weisskopf units (W.u), experimental information from McCutchan *et al*

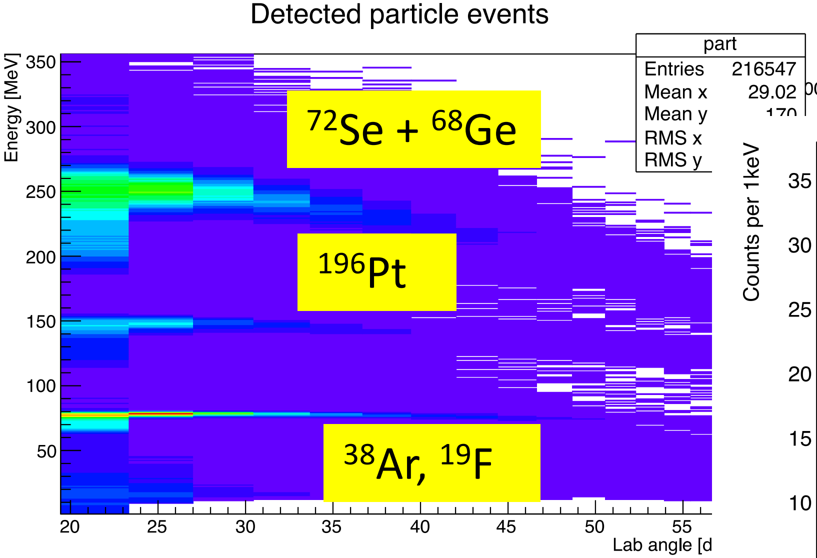
E. A. Mc Cutchan *et al.,* Phys. Rev. C. **83,** 024310 (2011).

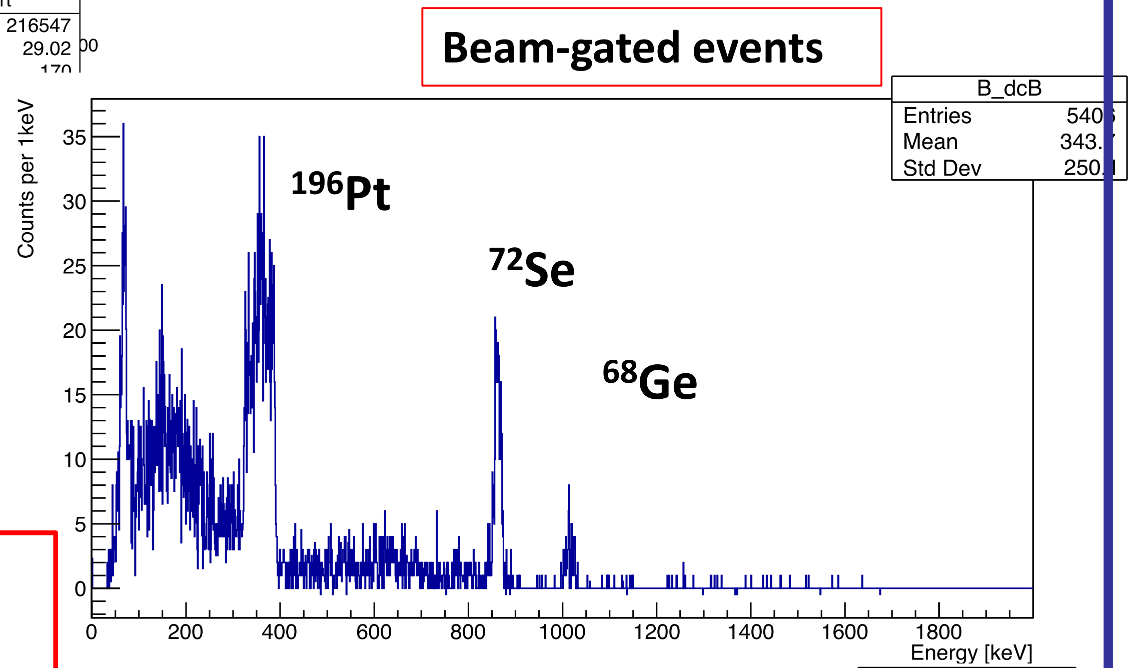
# Motivation for $^{72}$Se (3) – Summary

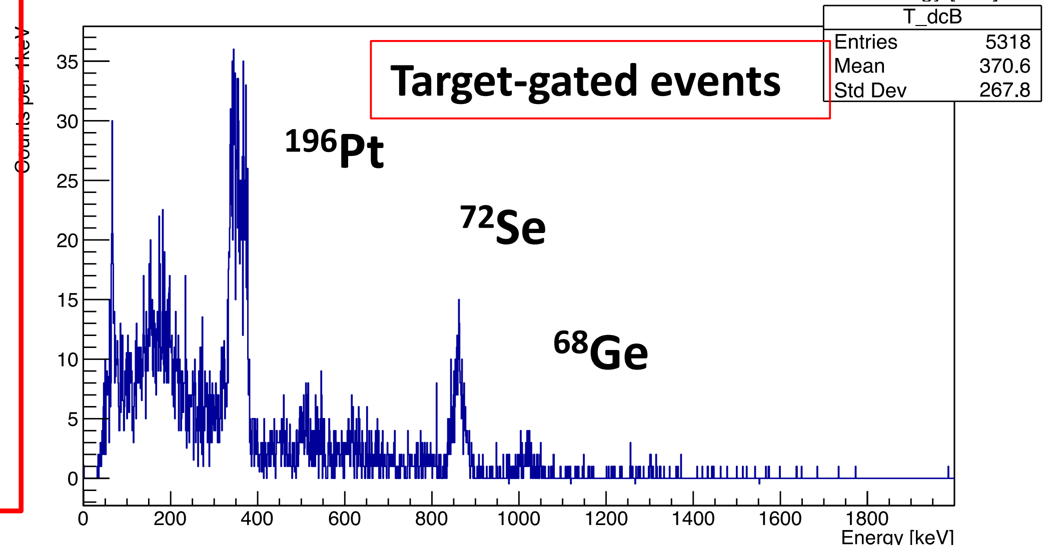
- Previous slides focussed on beyond-mean-field and ASCC calculations but, in addition, interesting and conflicting results from **shell model** (K. Kaneko *et al*., Phys. Rev. C **92**, 044331 (2015).) and **IBM** (E. A. McCutchan et al., Phys. Rev. C **83**, 024310 (2011)).

- Key information from Coulomb excitation required to test and **benchmark** calculations in this key and challenging region in order to shed light on, e.g.
  - Location of prolate-oblate shape transition and role of non-axial degree of freedom
  - Shape coexistence and mixing between structures

# Summary of IS597 running period in 2017

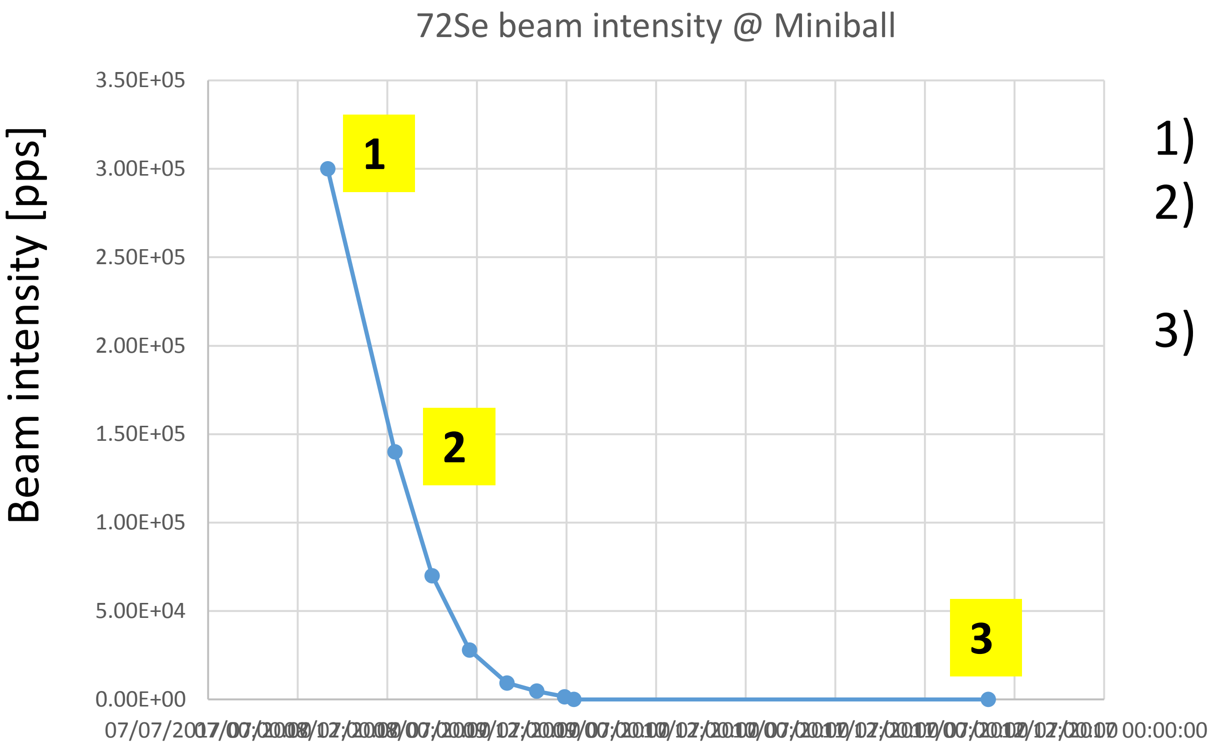



- **Promising data** but only ~5% of requested $^{72}$Se delivered to Miniball
- Extraction of $^{72}$SeCO molecule **extremely problematic**
- Unexpected $^{68}$Ge contamination

# Issues with 2017 Experiment



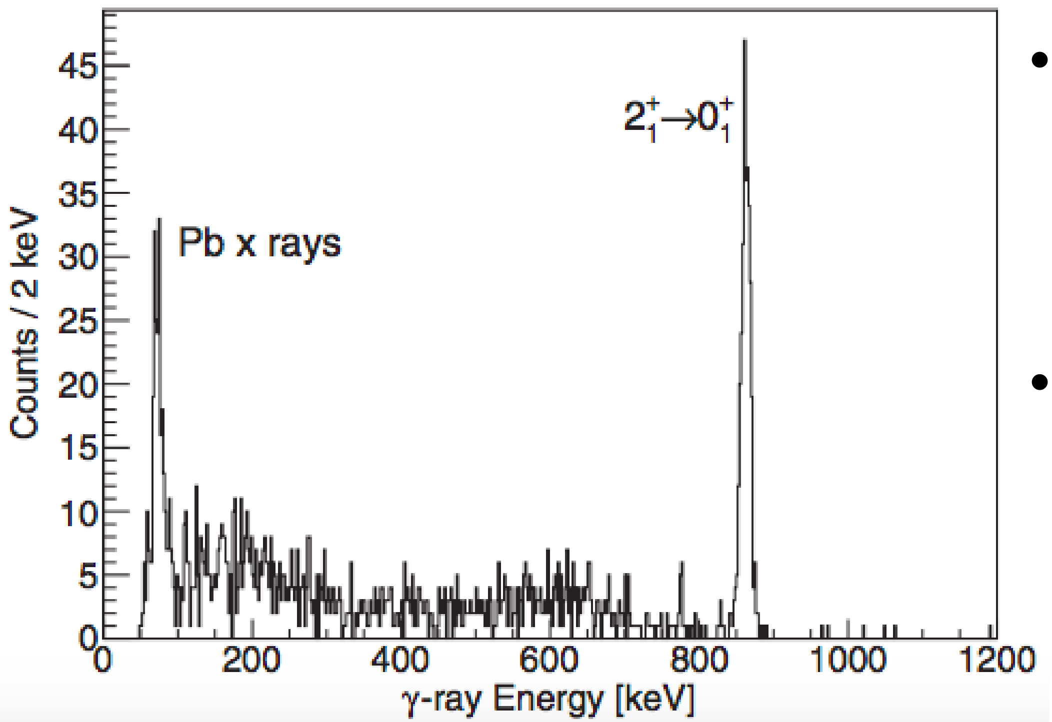

1) Prior to us taking beam
2) First ~1 hour of running
3) End of the run (Tues 8am)

- Molecular extraction of $^{72}$SeCO
- Used a VADIS ion source (molybdenum) rather than a FEBIAD (carbon) one.

# 2018 NSCL Study

- $^{72}$Se beam was produced following the **fragmentation** of a 150 MeV/u $^{78}$Kr beam at NSCL.

- Stopped in a **linear gas stopper**, thermalized, charge bred and then injected into the ReA3 accelerator chain.



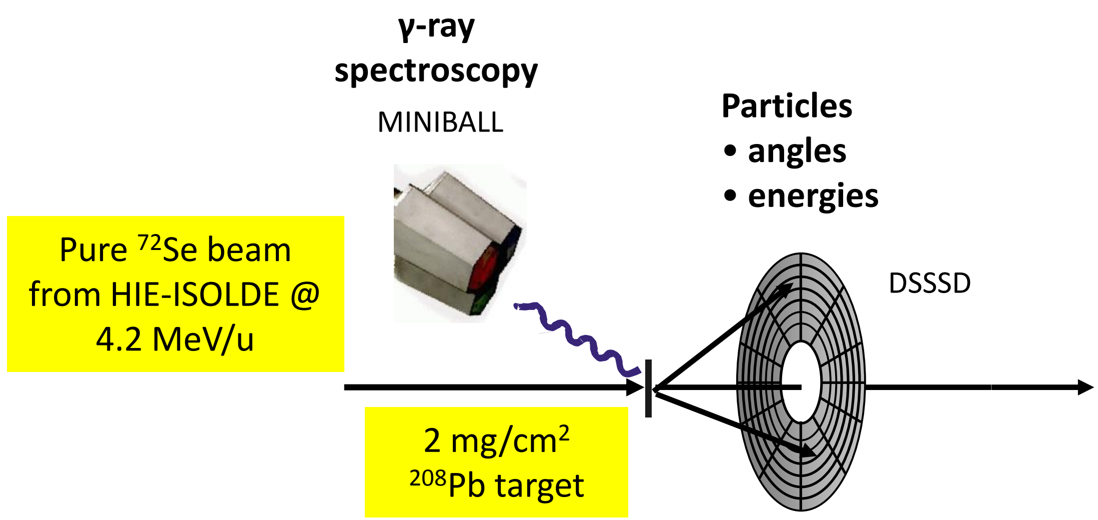

- Beam intensity ~ 4000 pps (**two orders of magnitude less** than ISOLDE)
- Negative $Q(2^+_1)$ => prolate deformation (in agreement with most theoretical calculations)

J. Henderson *et al.*, Phys. Rev. Lett. **121**. 082502 (2018)

# Goals for Remaining Shifts

- Perform a low-energy Coulomb excitation measurement which will enable
  - Determination of a number of transitional matrix elements.
  - Quadrupole moments of **$\underline{2^+_1}$**, $2^+_2$ 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.



# TAC Comments/ Questions

- **$^{72}$Se at TRIUMF**: Yield measurement in 2016 of 1.3 x $10^6$ pps at the target. Charge-breeding and post-acceleration efficiency of 0.1% => 1 x $10^3$ pps at Coulomb-excitation setup.

- Formation of $^{72}$SeCO molecules still not understood but likely related to the choice of ion source.

- **Cold irradiation** and then ionisation with either RILIS, VADIS or VADLIS suggested by TAC => seems a promising alternative as other potential A ~70 contaminants are short lived.

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**We request the remaining 9 shifts with a 305-MeV $^{72}$Se beam (using both $^{196}$Pt and $^{208}$Pb targets) at a minimum intensity of 2 x $10^5$ pps in order to perform this experiment.**

# Thank you for your attention

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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 | $E_\gamma$ [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