Neutron-rich Ti isotopes and possible N = 32 and N = 34 shell gaps

- Level structure of ^{56}Ti and the possible shell gap at N=34
- Reduced transition probabilities to the first 2^+ states in ^{52,54,56}Ti

- N=32 shell gap? What about N=34?
- Deep-inelastic studies at Argonne National Laboratory (ANL)
- Coulomb excitations at National Superconducting Cyclotron Laboratory (NSCL)

Presented by Dan-Cristian Dinca
NSCL / Michigan State University

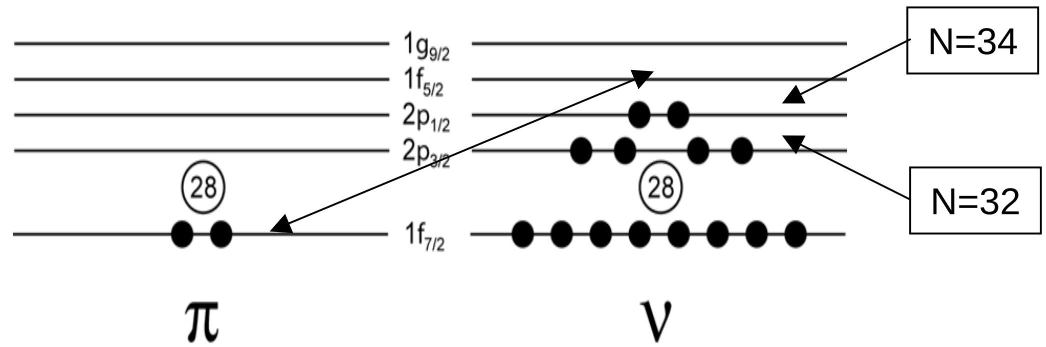
Motivation

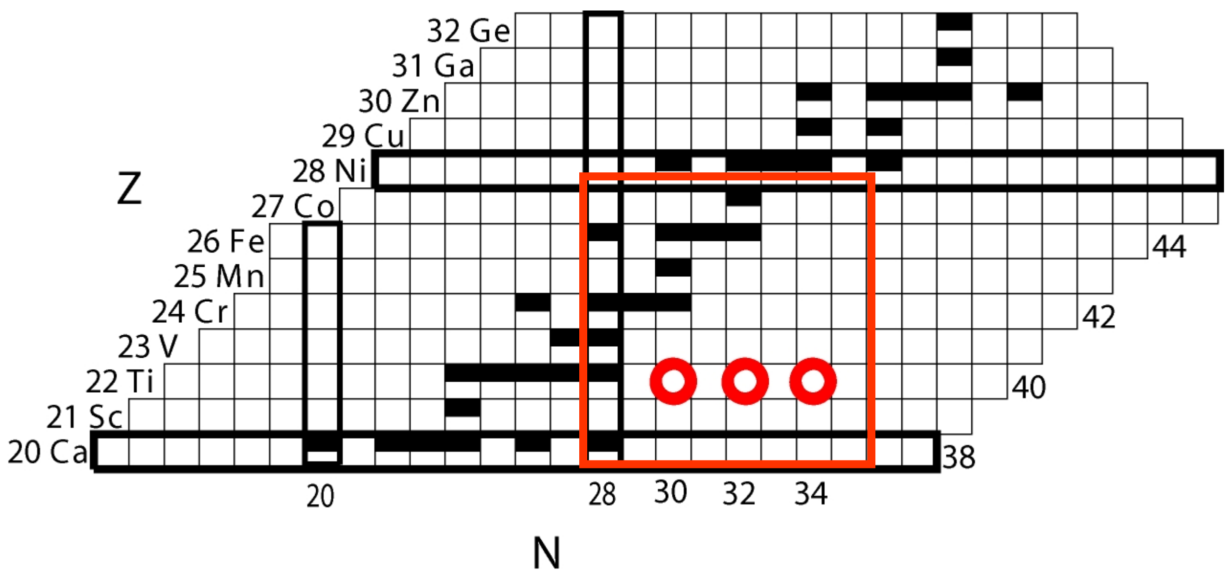
Protons are removed from the $\pi f_{7/2}$ shell

→ $\pi f_{7/2}$ –$\nu f_{5/2}$ monopole pairing interaction strength weakens[1)]

→ $\nu f_{5/2}$ pushes up in energy

→ possible shell gaps at N=32 and N=34



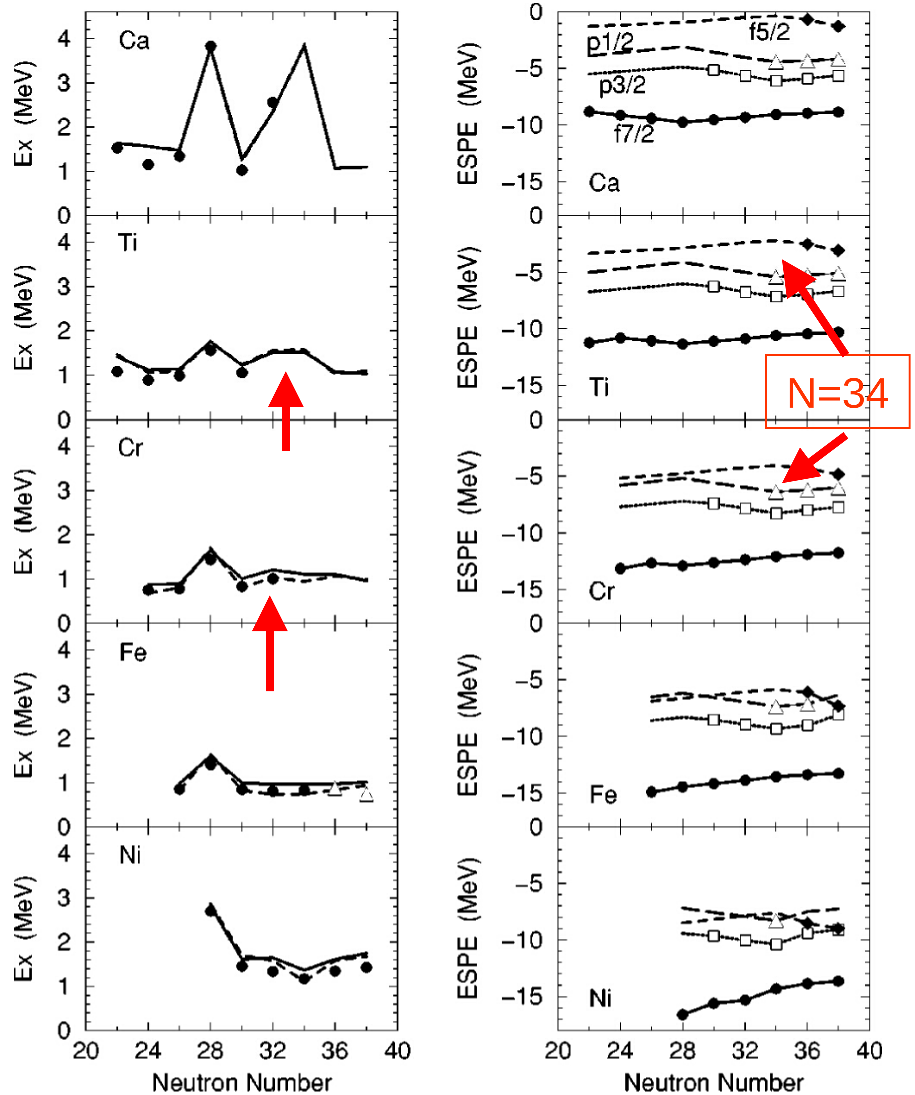


1) T. Otsuka et al., Phys. Rev. Lett. **87** (2001), 082502.

Predicted energy levels

Shell model calculations using one of the newest interactions, GXPF1[1] predict shell gaps at :

- N=32 for Z≤ 24 (Cr)
- N=32 and N=34 for Z≤22 (Ti).;



Observables:
- Energy levels
- Transition matrix elements

1) M. Honma et al., Phys. Rev. C 65 (2002), 061301

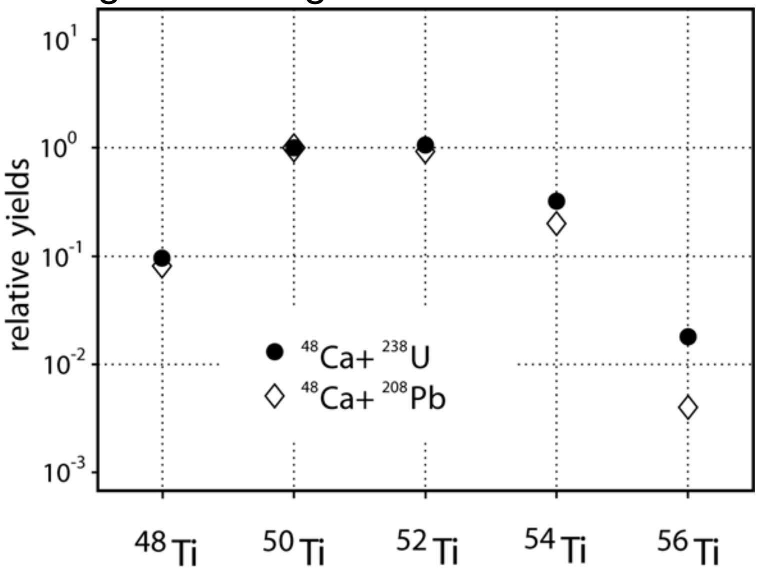
Experimental methods

- Gamma-ray spectroscopy following deep-inelastic reactions
- Coulomb excitation of fast fragments or reaccelerated beams
- β-decay
- Transfer reactions
- …

ANL experimental setup for deep inelastic reaction $^{48}Ca + ^{238}U$

- Gammasphere at ATLAS (ANL), 101 Compton-suppressed Germanium detectors
- ^{48}Ca beam at 330MeV, pulsed at ~420ns to allow separation of the prompt and isomeric decays
- ^{238}U target (50mg/cm^2)
- Trigger condition: 3 or more detectors firing in prompt coincidence

Advantages of using $^{48}Ca + ^{238}U$ over $^{48}Ca + ^{208}Pb$



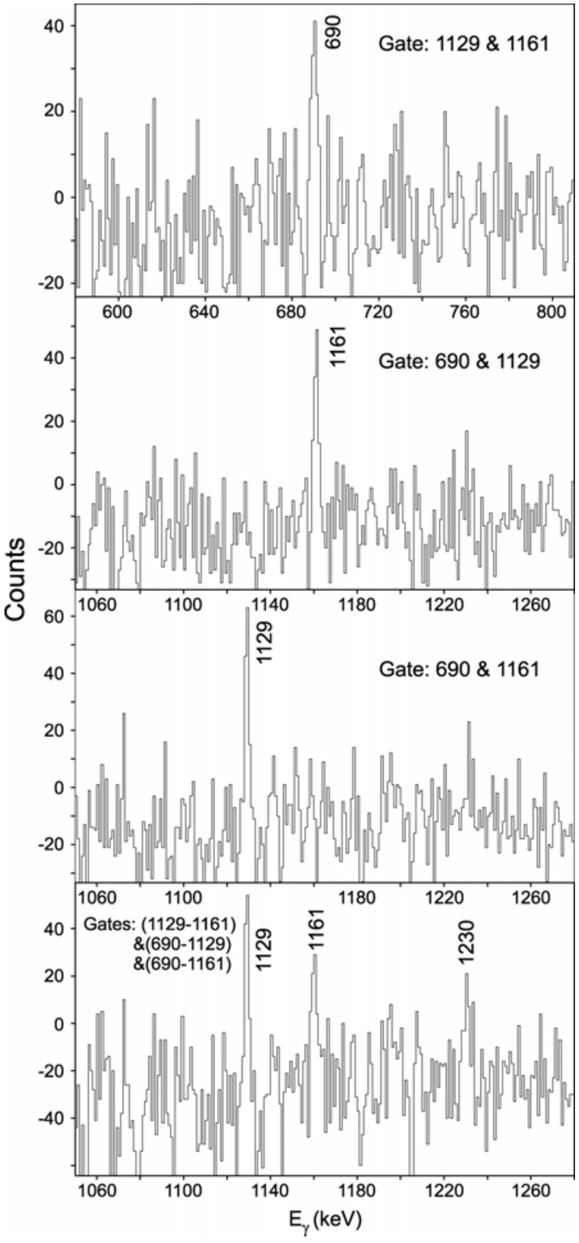
Target-like products of ^{238}U fission

➔ Identification based on cross-coincidence between gamma rays from reaction partners almost impossible.

relative 6+ state feeding yields, normalized to ^{50}Ti

Observations

- Use the recently identified via β-decay $2^+ \rightarrow 0^+$ transition in ^{56}Ti as a starting point (E_γ = 1127 keV)[1];
- γ-ray at 1161.0(5) keV found in coincidence;
- By using double coincidence a transition at 690.2(7) keV was found;
- Double gating on different combinations confirmed their mutual coincidence relationships.



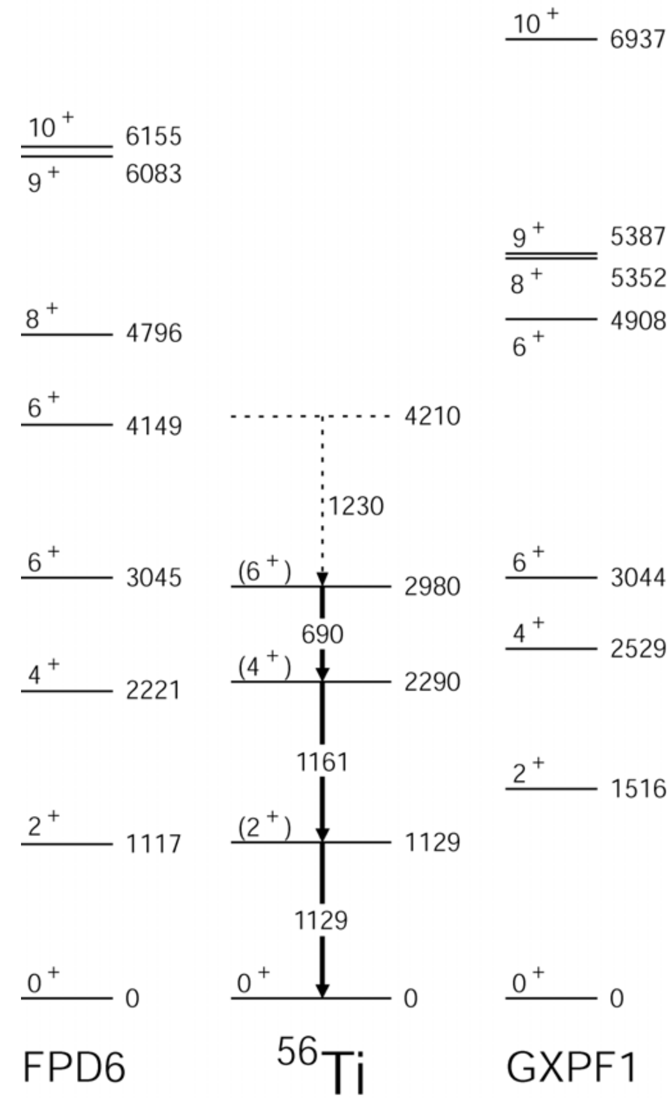
1) S. N. Liddick et al, Phys. Rev. Lett. **92** (2004), 072502.

Results

- Deep inelastic reactions preferentially populate yrast states
- The 4^+ and 6^+ levels in ^{56}Ti expected to correspond to proton excitations of $\pi(f_{7/2})^2$ character, energy spacing $E(4^+ \rightarrow 2^+) > E(6^+ \rightarrow 4^+)$
- ➔ 1161 keV assigned to $4^+ \rightarrow 2^+$
- ➔ 690 keV assigned to $6^+ \rightarrow 4^+$

- Good agreement with shell model with FPD6 interaction

  (however, not so good for ^{52,54}Ti)
- There is significant disagreement with GXPF1 interaction for the first 2^+ state.



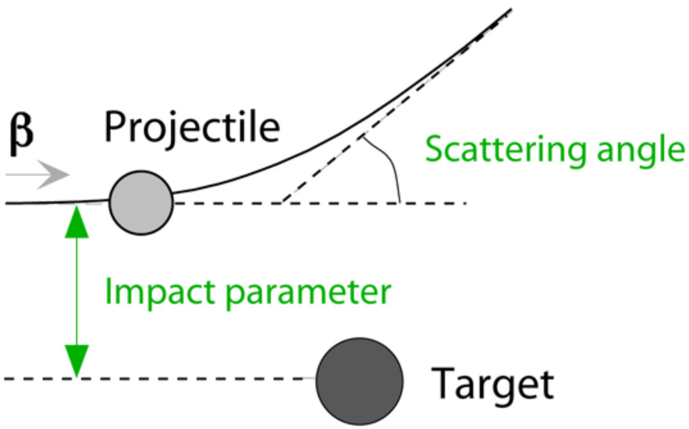
Intermediate-energy Coulomb excitation to measure B(E2) values

Observables

- Number of gamma rays detected (N_γ)
- Number of beam particles detected (N_{beam})
- Energy of de-excitation gamma ray (E_γ)

Experimental results

- Coulomb excitation cross section (σ)
- Reduced transition probability B(E2,↑)
- Energy of excited state



$$\sigma = \frac{N_\gamma}{\varepsilon} \frac{1}{N_{\text{target}} N_{\text{beam}}}$$

$$\sigma_{0\to 2} \approx \left(\frac{Z_{\text{target}} e^2}{\hbar c} \right)^2 \frac{\pi}{e^2 b_{\text{min}}^2} \mathrm{B}(\mathrm{E}2, 0^+ \to 2^+)$$

Details in: Winther and Alder, Nucl. Phys. A **319** 518 (1979).

NSCL experimental setup

- MSU Segmented Germanium Detector Array (SeGA) in conjunction with the S800 spectrograph
- ^{76}Ge at 130MeV/nucl as primary beam
- ^{9}Be production (fragmentation) target
- Particle-γ or d/s particle as trigger conditions

Observations for ^{76}Ge and ^{197}Au, the test cases

Primary beam: ^{76}Ge @ 130 MeV/nucl.
Secondary beam: ^{76}Ge @ 81 MeV/nucl.
$\beta = 0.392$
^{197}Au target thickness: 257.67 mg/cm^2
$\Theta_{max} = 3.06°$ (CM)
Number of ^{76}Ge particles detected: 26.1E6

Measured for ^{76}Ge

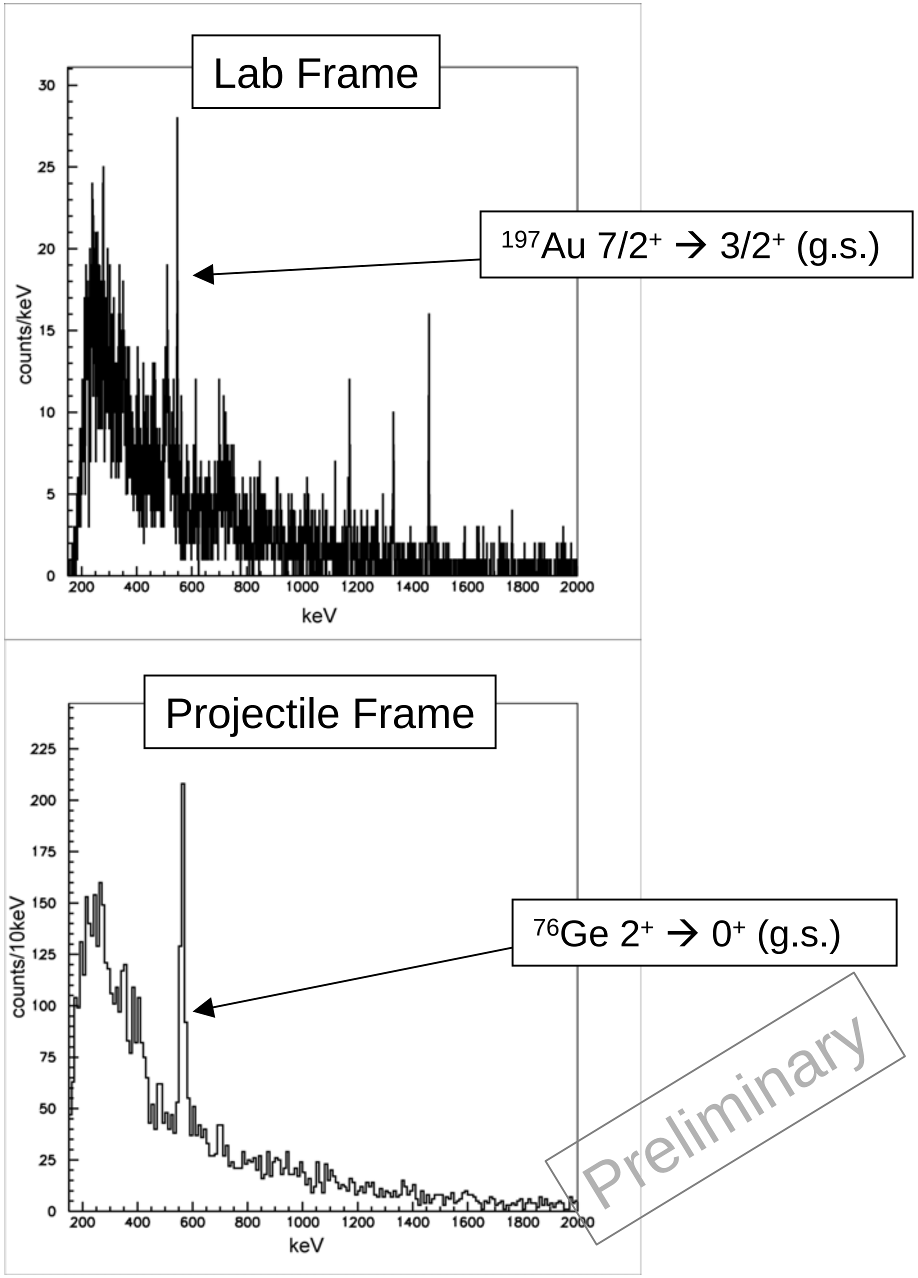
- $E_\gamma = 562.6(6)$keV
- $\sigma(\theta<\Theta_{max}) = 394(47)$ mb
- B(E2, ↑) = 2923(346) e^{2}fm^4

- Adopted values:
  - $E_\gamma = 562.93(3)$keV
  - B(E2, ↑) = 2780(30) e^{2}fm^4

Measured for ^{197}Au

- $E_\gamma = 547.03(24)$ keV
- $\sigma(\theta<\Theta_{max}) = 94(20)$ mb
- B(E2, ↑) = 4223(898) e^{2}fm^4

- Adopted values:
  - $E_\gamma = 547.5(3)$ keV
  - B(E2, ↑) = 4494(409) e^{2}fm^4

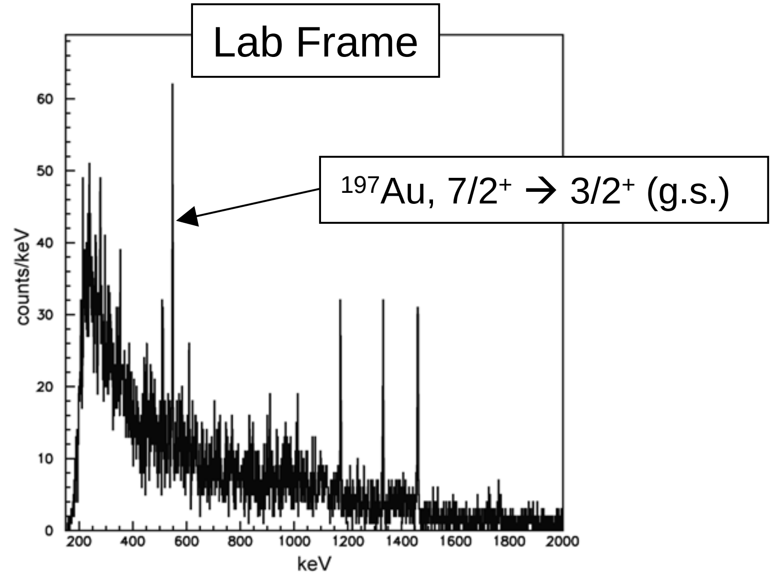


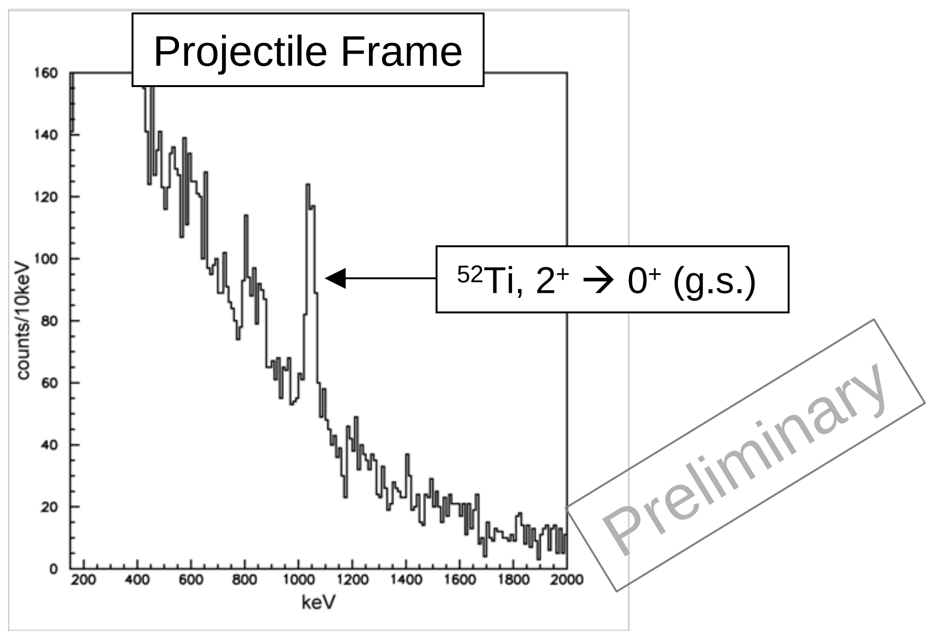
Observations for ^{52}Ti

Primary beam: ^{76}Ge @ 130 MeV/nucl.
Secondary beam: ^{52}Ti @ 89 MeV/nucl.
$\beta = 0.408$
^{197}Au target thickness: 257.67 mg/cm^2
$\Theta_{max} = 3.10°$ (CM)
Number of ^{52}Ti particles detected: 130E6

Measured for ^{52}Ti
- E_γ = 1050(2) keV
- $\sigma(\theta<\Theta_{max})$ = 119(16) mb
- B(E2, ↑) = 593(81) e^{2}fm^4

Measured for ^{197}Au
- E_γ = 547.40(15) keV
- $\sigma(\theta<\Theta_{max})$ = 59(9) mb
- B(E2, ↑) = 3885(592) e^{2}fm^4





Observations for ^{54}Ti

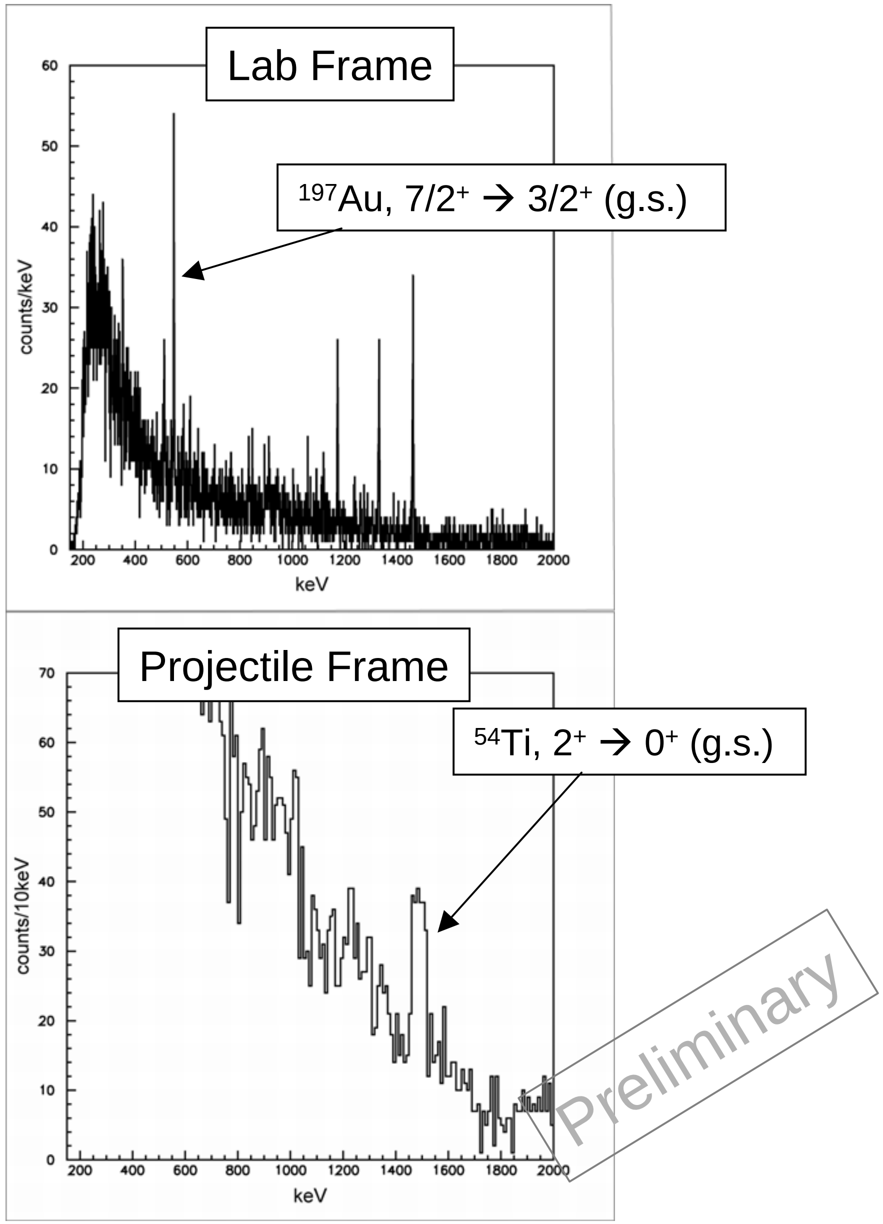
Primary beam: ^{76}Ge @ 130 MeV/nucl.
Secondary beam: ^{54}Ti @ 88 MeV/nucl.
β=0.406
^{197}Au target thickness: 257.67 mg/cm^2
Θ_{max} = 3.20° (CM)
Number of ^{54}Ti particles detected: 91.665E6

Measured for ^{54}Ti

- E_γ = 1497(4) keV
- $\sigma(\theta<\Theta_{max})$ = 83(15) mb
- B(E2, ↑) = 357(63) e^{2}fm^4

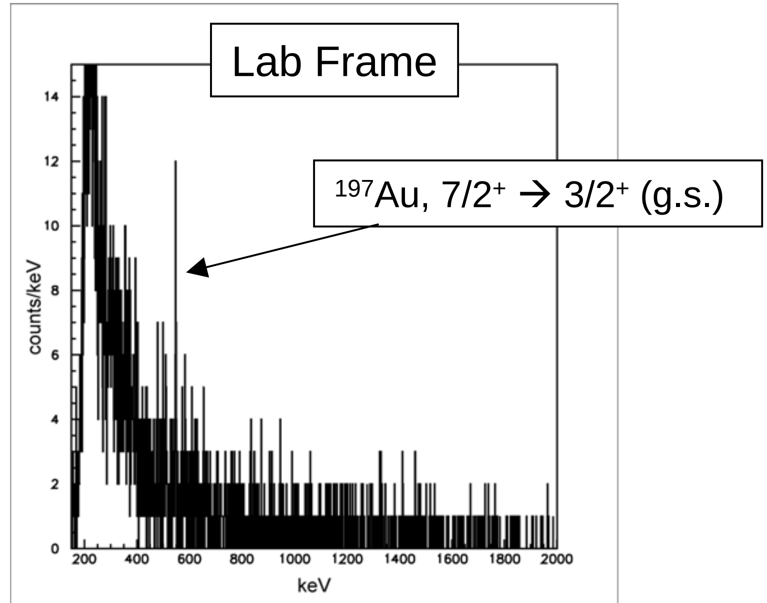
Measured for ^{197}Au

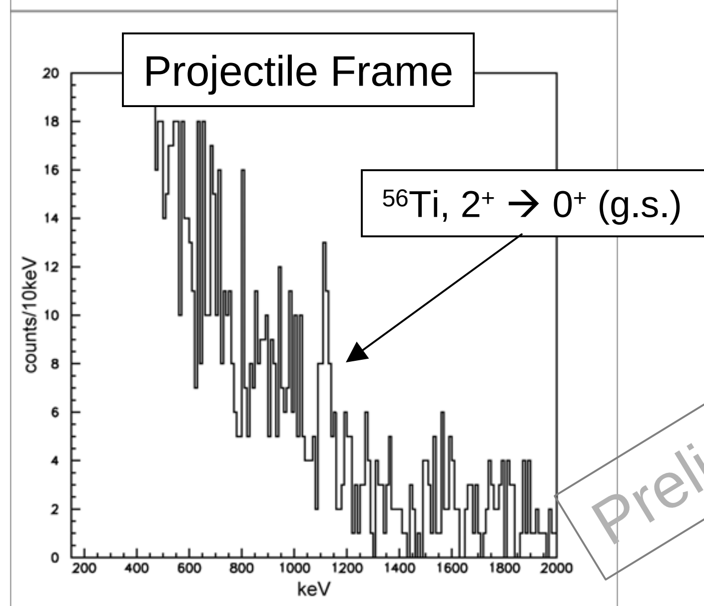
- E_γ = 547.41(17) keV
- $\sigma(\theta<\Theta_{max})$ = 70(11) mb
- B(E2, ↑) = 4041(635) e^{2}fm^4



Observations for ^{56}Ti

Primary beam: ^{76}Ge @ 130 MeV/u
Secondary beam: ^{56}Ti @ 88 MeV/u
$\beta=0.406$
^{197}Au target thickness: 518 mg/cm^2
Θ_{max} = 3.58° (CM)
Number of ^{56}Ti particles detected: 5.92E6





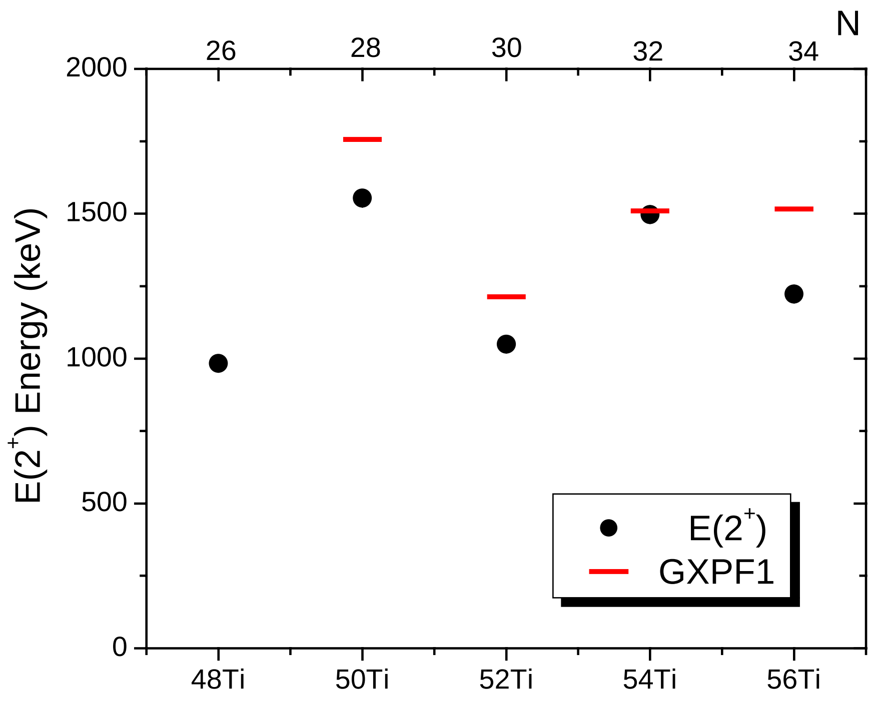
Measured for ^{56}Ti

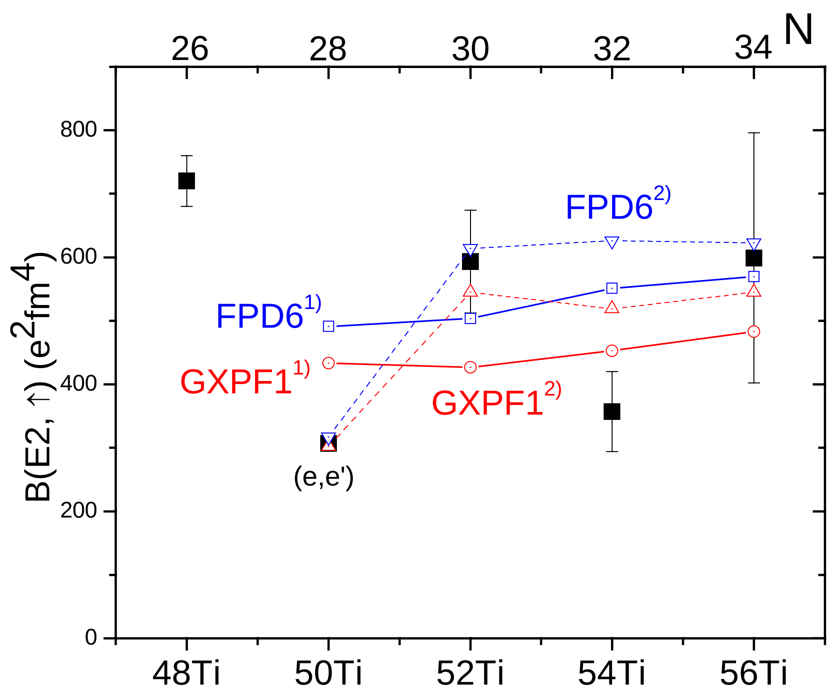
- $E\gamma$ = 1123(7) keV
- $\sigma(\theta<\Theta_{max})$ = 155(51) mb
- B(E2, ↑) = 599(197) e^{2}fm^4

Measured for ^{197}Au

- $E\gamma$ = 547.3(4) keV
- $\sigma(\theta<\Theta_{max})$ = 117(41) mb
- B(E2, ↑) = 6002(2103) e^{2}fm^4

Results and comparison with shell model





1) Full fp shell effective interaction, M. Honma and B. A. Brown, private communication
2) Truncated fp shell, B. A. Brown, private communication

Summary

- Level scheme for ^{56}Ti for spins up to 6^+ (possible 8^+).
- B(E2) values for ^{52,54,56}Ti.
- Experimentally, both E(2^+) and B(E2, $\uparrow$) indicate increased shell gap at N=32 but not at N=34.
- No conclusive agreement with shell model calculations.

Collaborators

D.-C. D.[a,b], R.V.F. Janssens[c], A. Gade[b], B. Fornal[d], S. Zhu[c], D. Bazin [b], R. Broda[d] ,C. M. Campbell[a, b], M. P. Carpenter[c], P. Chowdhury[c,e], J. M. Cook[a, b], P. J. Daly[g], A. Deacon[f], S. J. Freeman[f], T. Glasmacher[b], Z. W. Grabowski[g], N. Hammond[c], F.G. Kondev[c], W. Krolas[d], J.-L. Lecouey[b], T. Lauritsen[c],S. N. Liddick[a, b], C. J. Lister[c], P. F. Mantica[b], E. F. Moore[c], W. F. Mueller[b], H. Olliver[a, b], T. Pawlat[d], D. Seweryniak[c], K. Starosta[a, b], J. R. Terry[a, b], B. A. Tomlin[a, b], J. Wrzesinski[d] , K. Yoneda[b]

a)Department of Physics and Astronomy, Michigan State University, East Lansing, USA

b)National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, USA

c)Argonne National Laboratory, Argonne, USA

d)Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland

e)Department of Physics, University of Massachusetts, Lowell, USA

f)Schuster Laboratory, University of Manchester M13 PL, UK

g) Chemistry and Physics Department, Purdue University, West Lafayette, IN USA