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

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

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

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Motivation

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

$\rightarrow \pi f_{7/2} - \nu f_{5/2}$ monopole pairing interaction strength weakens\(^1\)

$\rightarrow \nu f_{5/2}$ pushes up in energy

$\rightarrow$ possible shell gaps at $N=32$ and $N=34$

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Predicted energy levels

Shell model calculations using one of the newest interactions, GXPF1\(^1\) predict shell gaps at:

- \(N=32\) for \(Z \leq 24\) (Cr)
- \(N=32\) and \(N=34\) for \(Z \leq 22\) (Ti).

Observables:
- Energy levels
- Transition matrix elements

Experimental methods

- Gamma-ray spectroscopy following deep-inelastic reactions
- Coulomb excitation of fast fragments or reaccelerated beams
- $\beta$-decay
- Transfer reactions
- ...


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

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

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

Target-like products of $^{238}\text{U}$ fission

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

relative 6+ state feeding yields, normalized to $^{50}\text{Ti}$
Observations

- Use the recently identified via $\beta$-decay $2^+ \rightarrow 0^+$ transition in $^{56}$Ti as a starting point ($E_\gamma = 1127$ keV)$^1$;
- $\gamma$-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.

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 $E(4^+ \rightarrow 2^+) > E(6^+ \rightarrow 4^+)$
- $\rightarrow$ 1161 keV assigned to $4^+ \rightarrow 2^+$
- $\rightarrow$ 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 ($N_{\gamma}$)
- Number of beam particles detected ($N_{\text{beam}}$)
- Energy of de-excitation gamma ray ($E_{\gamma}$)

Experimental results
- Coulomb excitation cross section ($\sigma$)
- Reduced transition probability $B(E2,\uparrow)$
- Energy of excited state

NSCL experimental setup

- MSU Segmented Germanium Detector Array (SeGA) in conjunction with the S800 spectrograph
- $^{76}\text{Ge}$ at 130MeV/nucl as primary beam
- $^{9}\text{Be}$ production (fragmentation) target
- Particle-$\gamma$ 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$^2$
$\Theta_{\text{max}} = 3.06^\circ$ (CM)
Number of $^{76}$Ge particles detected: 26.1E6

Measured for $^{76}$Ge
• $E_{\gamma} = 562.6(6)$ keV
• $\sigma(\theta<\Theta_{\text{max}}) = 394(47)$ mb
• $B(E2, \uparrow) = 2923(346) \text{ e}^2\text{fm}^4$
• Adopted values:
  • $E_{\gamma} = 562.93(3)$ keV
  • $B(E2, \uparrow) = 2780(30) \text{ e}^2\text{fm}^4$

Measured for $^{197}$Au
• $E_{\gamma} = 547.03(24)$ keV
• $\sigma(\theta<\Theta_{\text{max}}) = 94(20)$ mb
• $B(E2, \uparrow) = 4223(898) \text{ e}^2\text{fm}^4$
• Adopted values:
  • $E_{\gamma} = 547.5(3)$ keV
  • $B(E2, \uparrow) = 4494(409) \text{ e}^2\text{fm}^4$
Observations for $^{52}\text{Ti}$

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

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

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

Preliminary
Observations for $^{54}$Ti

Primary beam: $^{76}$Ge @ 130 MeV/nucl.  
Secondary beam: $^{54}$Ti @ 88 MeV/nucl.  
$\beta = 0.406$

$^{197}$Au target thickness: 257.67 mg/cm$^2$  
$\Theta_{\text{max}} = 3.20^\circ$ (CM)  
Number of $^{54}$Ti particles detected: 91.665E6

Measured for $^{54}$Ti
- $E_\gamma = 1497(4)$ keV  
- $\sigma(\theta < \Theta_{\text{max}}) = 83(15)$ mb  
- $B(E2, \uparrow) = 357(63) e^2fm^4$

Measured for $^{197}$Au
- $E_\gamma = 547.41(17)$ keV  
- $\sigma(\theta < \Theta_{\text{max}}) = 70(11)$ mb  
- $B(E2, \uparrow) = 4041(635) e^2fm^4$
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$^2$  
$\Theta_{\text{max}} = 3.58^\circ$ (CM)  
Number of $^{56}$Ti particles detected: 5.92E6

Measured for $^{56}$Ti
- $E_\gamma = 1123(7)$ keV
- $\sigma(\theta<\Theta_{\text{max}}) = 155(51)$ mb
- $B(E2, \uparrow) = 599(197) \ e^2\text{fm}^4$

Measured for $^{197}$Au
- $E_\gamma = 547.3(4)$ keV
- $\sigma(\theta<\Theta_{\text{max}}) = 117(41)$ mb
- $B(E2, \uparrow) = 6002(2103) \ e^2\text{fm}^4$
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 $^{56}\text{Ti}$ for spins up to $6^+$ (possible $8^+$).
- B(E2) values for $^{52,54,56}\text{Ti}$.
- 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


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