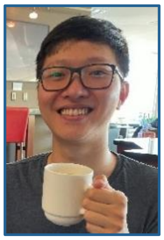
LIFETIME MEASUREMENT OF THE FIRST 2^+ AND 4^+ STATES IN ^{40}CA USING AN ALPHA-TRANSFER REACTION

SUMMARY: The first 2^+ (2_1^+) and 4^+ (4_1^+) states in the doubly magic ^{40}Ca were directly populated in a sub-barrier reaction to measure their lifetimes using the Doppler-Shift Attenuation Method (DSAM).



By FRANK (TONGAN) WU[1] <twa73@sfu.ca>, KRZYSZTOF STAROSTA[1] <starosta@sfu.ca>, GREG HACKMAN[2], PHIL VOSS[1], JONATHAN WILLIAMS[2], AARON CHESTER[1], CORINA ANDREOIU[1], GORDON BALL[2], DAVID S. CROSS[1], ADAM GARNSWORTHY[2], JENNIFER PORE[3], TOM E. DRAKE[4], CARL SVENSSON[5], and CARL D. UNSWORTH[6]

[1]Department of Chemistry, Simon Fraser University, Burnaby, BC, Canada V5A 1S6
[2]TRIUMF, 4004 Westbrook Mall, Vancouver, BC, Canada V6T 2A3
[3]Lawrence Berkeley National Laboratory, Berkeley, California 94720, United States
[4]Department of Physics, University of Toronto, ON, Canada M5S 1A7
[5]Department of Physics, University of Guelph, ON, Canada, N1G 2W1
[6]Department of Physics, University of Liverpool, United Kingdom, L69 7ZE

Frank Wu received 2nd place in the 2022 CAP Best Overall Student Oral Presentation

Precise gamma-ray spectroscopy uses the well-understood electromagnetic interaction to explore the less-understood inter-nucleon strong interaction. In particular, lifetimes of nuclear states are determined by the matrix elements which can be calculated from electromagnetic transition operators and wavefunctions of the initial and final states. While the electromagnetic operators are well-understood, the nuclear wavefunctions, which nuclear structure theories attempt to construct, are less understood. Although some *ab-initio* theories have tried to model these wavefunctions with QCD, they still need to be experimentally validated. As a result, accurate and precise measurements of nuclear lifetimes are required to benchmark these theories. In the chart of nuclides, ^{40}Ca (N=Z=20) is among the few "doubly-magic" nuclides characterized by its full proton and neutron shells. Analogous to the closed electron shells in noble gasses, these closed nucleon shells give the system extra stability and make ^{40}Ca a popular testing ground for nuclear structure theories. The goal of this experiment was to reduce the 20% uncertainties in ^{40}Ca's 2_1^+ and 4_1^+ lifetimes in the literature.

EXPERIMENT

At TRIUMF, Canada's particle accelerator centre, nuclei can be accelerated by the super-conducting linear accelerator (SC-LINAC) in the ISAC-II facility to a few MeVs per nucleon [1]. Using the SC-LINAC, the low-lying 2_1^+ and 4_1^+ states in ^{40}Ca were directly populated by accelerating an ^{36}Ar beam onto a gold-backed carbon target [2] of natural abundance. While the Coulomb barrier for the reaction is 17.9 MeV, the kinetic energy in the centre of mass frame was only 15.8 MeV. As a result, the reaction:

$$^{36}\mathrm{Ar} + {}^{12}\mathrm{C} \rightarrow 2\alpha + {}^{40}\mathrm{Ca}$$

was sub-barrier which allowed precise lifetime measurements in ^{40}Ca by suppressing the population of higher-lying excited states and limiting the decay to predominantly first order, which can be characterized by a simple exponential decay.

The TIGRESS Integrated Plunger (TIP) [3] and its 44-element PIN diode array were used to detect the alpha particles in coincidence with gamma rays for doppler-shift lifetime measurements using gamma-ray spectroscopy with the TIGRESS High-Purity Germanium (HPGe) array, shown in Figure 1.

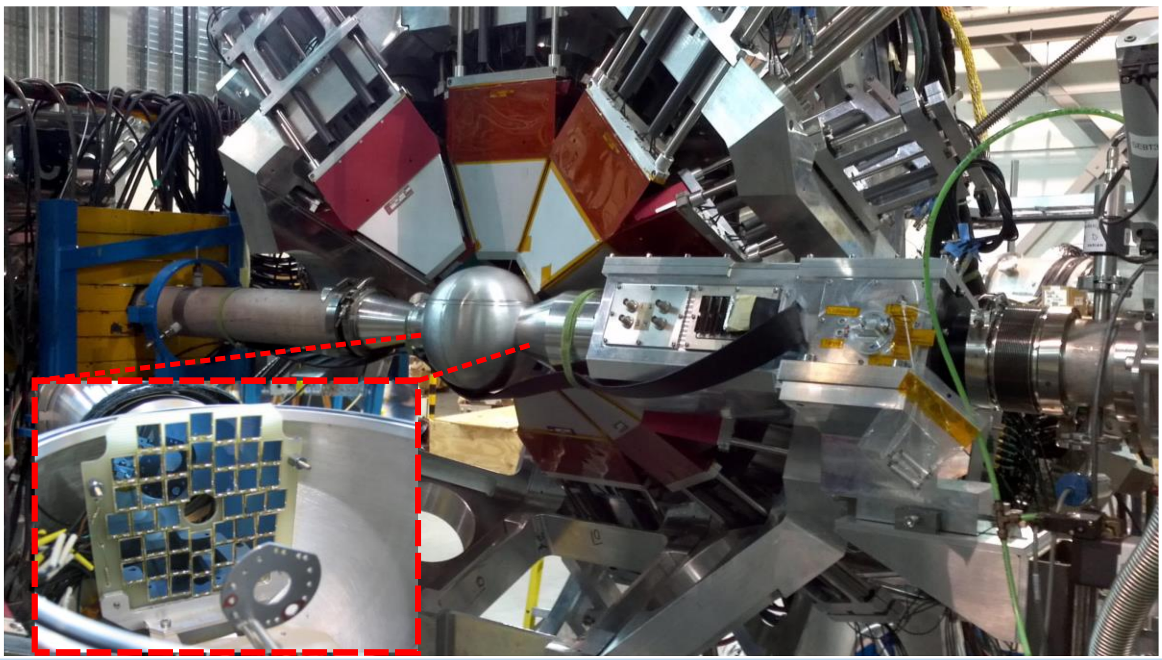


Figure 1. The TIGRESS HPGe array with the TIGRESS Integrated Plunger (TIP) chamber in the centre. The insert shows the inside of TIP, in its 44-element PIN diode array configuration.

ANALYSIS OF EXPERIMENTAL GAMMA-RAY SPECTRA

The ^{40}Ca reaction channel was isolated using the time-coincidence method and verified with the gamma-ray spectrum, shown in Figure 2. Alpha-gamma coincidence removed peaks from the Coulomb excitation of the gold backing, while additional alpha-alpha coincidence, chosen because the reaction which produced ^{40}Ca emitted two alphas, removed the peaks from competing reaction channels. The ratio of counts in the $2_1^+ \rightarrow 0_1^+$ and $4_1^+ \rightarrow 2_1^+$ peaks, shown in the bottom panel of Figure 2, was $6.9(\pm 0.7)\colon 1$. After accounting for the HPGe detectors having lower efficiencies for higher-energy gamma rays, this ratio became $21(\pm 2)\colon 1$. This ratio was further increased to $35(\pm 7)\colon 1$ by selecting events with more energetic alpha particles, as more energy removed by the alpha particles meant less energy was available for the ^{40}Ca excitation. The lack of $4_1^+ \rightarrow 2_1^+$ feeding allowed for precise lifetime measurement of the 2_1^+ state. Similarly, no transitions were observed to feed into the 4_1^+ state.

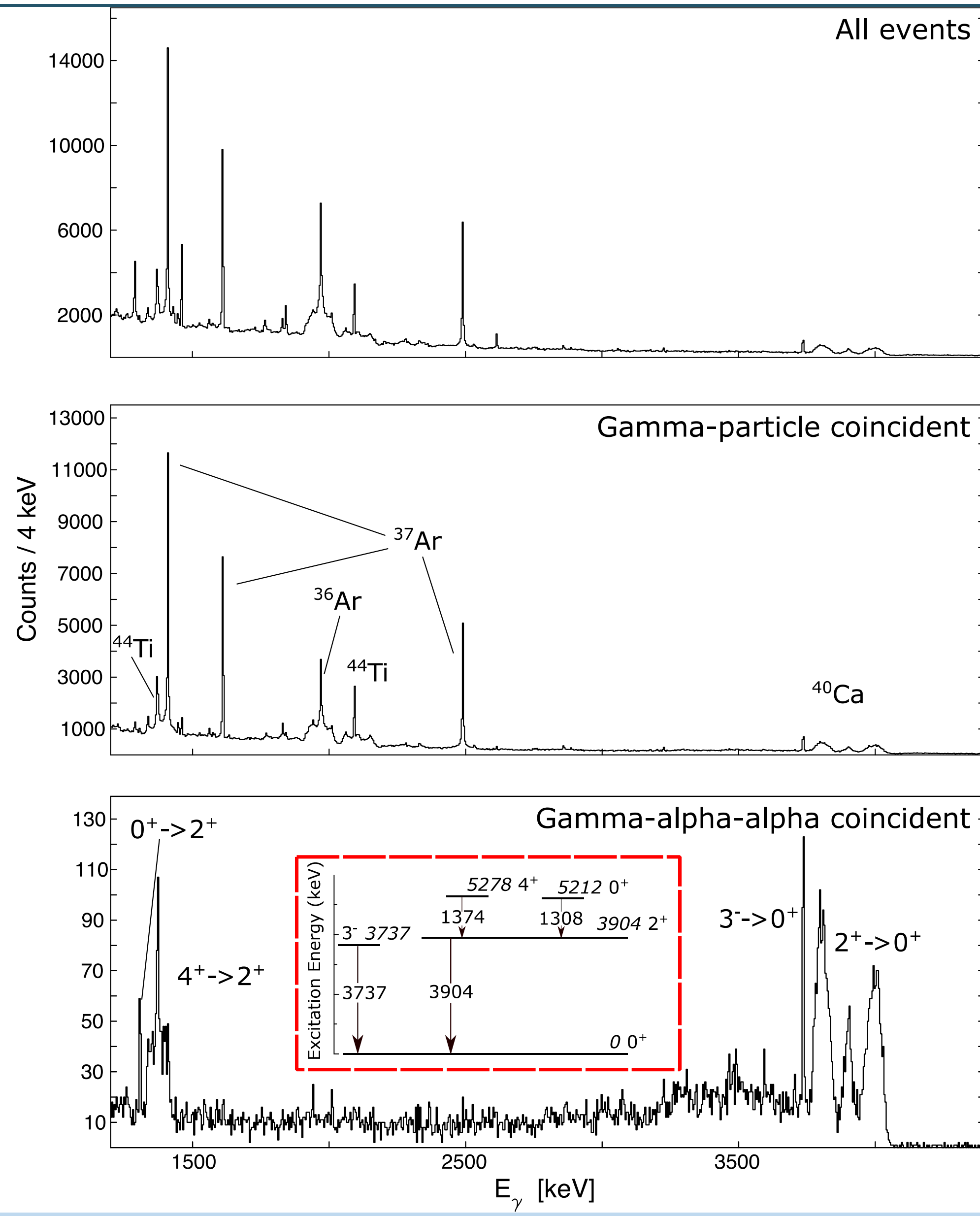


Figure 2. The Compton-suppressed gamma-ray spectra sorted before time coincidence (top), with gamma-particle (TIGRESS-PIN) coincidence (middle), and gamma-alpha-alpha (TIGRESS and 2 hits in separate PIN diodes) coincidence (bottom). Each bin is 4 keV wide. The insert in the bottom panel shows the relationship between the excited states in ^{40}Ca.

THE DOPPLER-SHIFT ATTENUATION METHOD (DSAM)

DSAM is a gamma-ray spectroscopy technique [3] to indirectly measure lifetimes on the order of femtoseconds to picoseconds by relating it to the stopping of the nucleus, illustrated in Figure 3. The DSAM target used for this experiment was made by depositing a gold layer onto a carbon film [2]. As the excited ^{40}Ca was formed in its 2_1^+ or 4_1^+ state within the carbon layer, it continued travelling in the beam direction and entered the gold backing. The longer the ^{40}Ca travelled in the gold, the slower it travelled, and eventually stopped. This means that the gamma rays emitted at different times experienced different amounts of Doppler shift, and the lifetimes of these excited states were encoded in the Doppler-shifted gamma ray spectrum. The lifetimes were extracted with Monte-Carlo simulations [4], described in the next section.

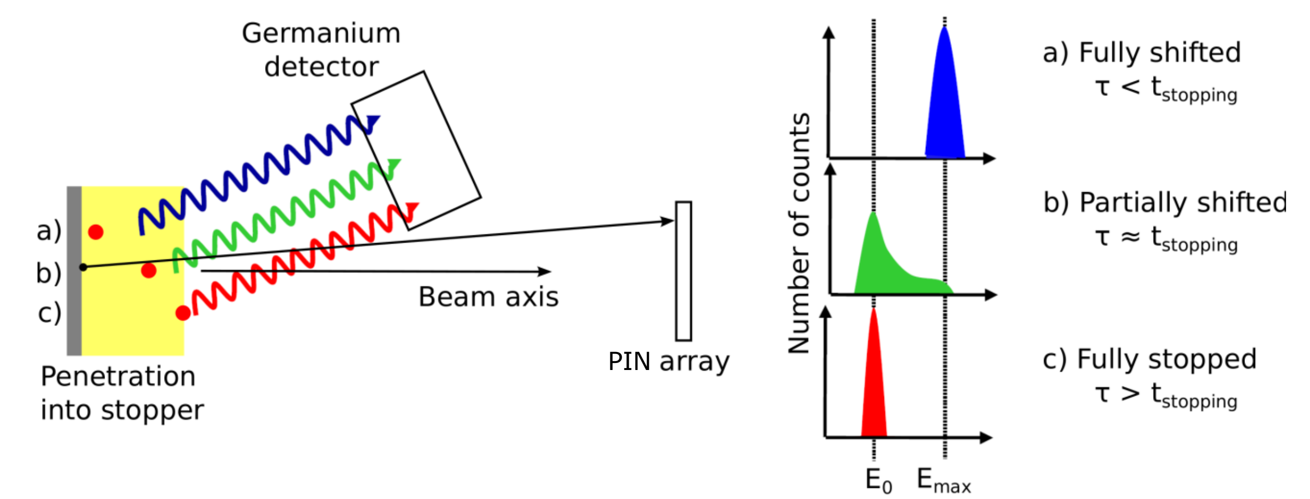


Figure 3. An illustration of the Doppler-Shift Attenuation Method (DSAM). As the ^{40}Ca (red circle) is produced in its excited state in the $^{nat.}C$ target (grey), it continues to travel in the beam's direction and enters the gold backing (yellow) where it slows down and eventually stops. The longer the nucleus travels, the slower it gets. As a result, gamma rays that are emitted at different times experience different amounts of Doppler shift. This means that the lifetime information of the excited stated is encoded in the gamma-ray spectrum registered by the TIGRESS detectors, which can be extracted using Monte-Carlo simulations.

LIFETIME EXTRACTION USING GEANT4

Geant4 [5] is a Monte-Carlo framework which tracks the interaction of radiation with matter. It was used for lifetime determination by simulating gamma-ray spectra with various lifetimes, illustrated in Figure 4.

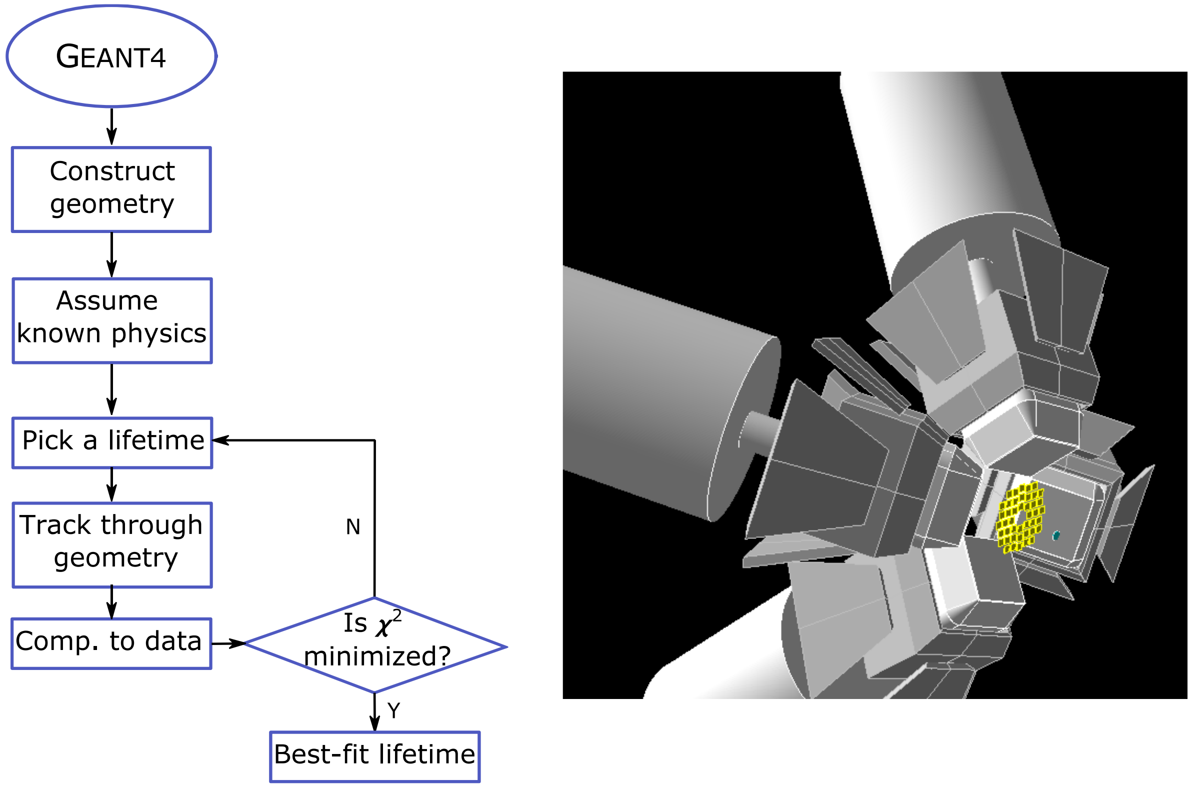


Figure 4. (Left) An illustration of the lifetime determination using Geant4. Geant4 takes user-defined reaction kinematics and lifetimes to track the simulated reaction products through the geometry and generates a set of simulated gamma-ray spectra for each lifetime. These simulated gamma-ray spectra can then be compared to the experimental spectra to find the best-fit lifetime.
(Right) Visualization of the experimental set-up in Geant4. Some TIGRESS detectors were removed to show the PIN Array.

The preliminary best-fit 2_1^+ lifetime was 42±5fs, and the 4_1^+ lifetime was 270±10 fs, as shown in Figure 5. Both uncertainties are statistical only. Systematic uncertainties are still under investigation.

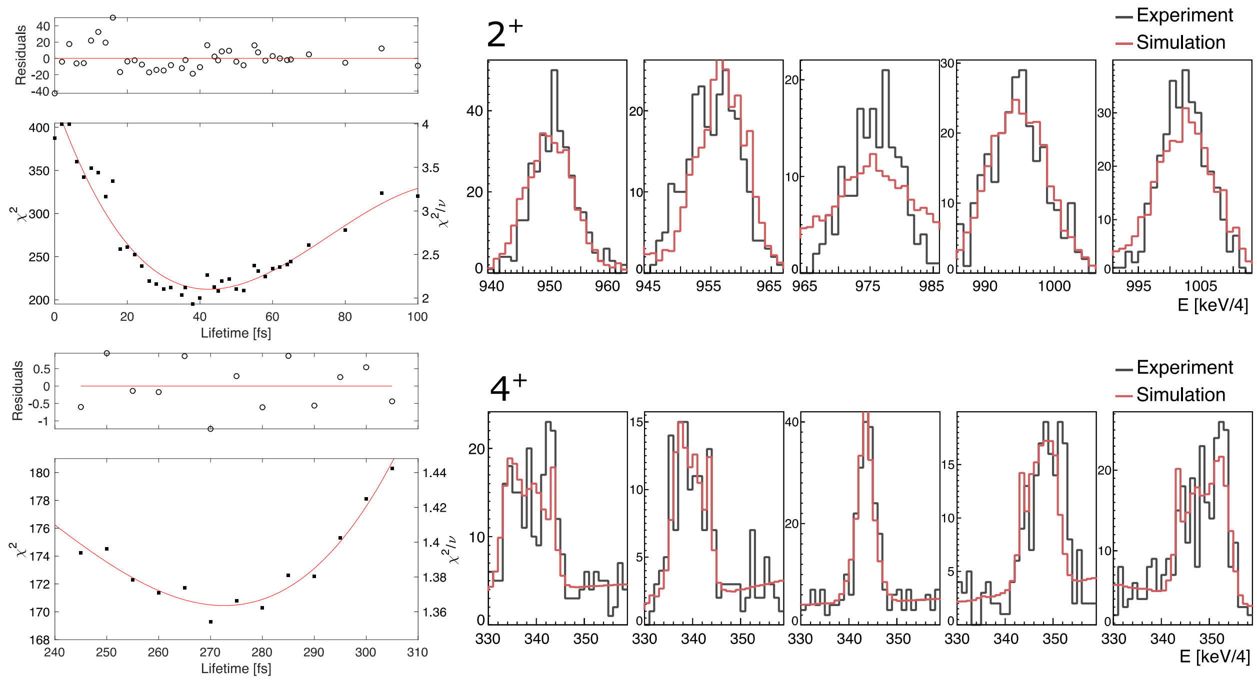


Figure 5. The determination of lifetimes for the 2^+ (top) and 4^+ (bottom) excited states in ^{40}Ca. The best-fit lifetime was defined to be the lifetime which generates the simulated gamma-ray spectra with the lowest chi-square when compared to the experimental spectra. The simulated spectra (red) with the best-fit lifetimes are shown with the experimental spectra (black). The spectra in horizontal panels correspond to Doppler groups at forward and backward angles with respect to the ^{40}Ca's direction, which was calculated from kinematic reconstruction.

Although the simulated gamma-ray spectra for the 4^+ peak agreed with the experiment, the simulated 2^+ peak was too wide in the centre panel where the gamma rays were emitted near $90°$ with respect to the momentum of ^{40}Ca. This indicates that the simulated initial angular distribution of ^{40}Ca, from the simplified reaction used to date, was inconsistent with that in the experiment. Current work is being done to constrain the reaction mechanism further using the charged-particle information.

SUMMARY AND OUTLOOK

The 2_1^+ state in ^{40}Ca was directly populated with a direct-population-to-feeding ratio of $35(\pm 7)\colon 1$, while the 4_1^+ was directly populated with no observed feeding. The lifetimes with statistical uncertainties for the 2_1^+ and 4_1^+ states were measured to be 42±5fs and 270±10fs, respectively, providing factors of 2 and 5 reduction from current literature values. The systematic uncertainties, which depend on the initial angular distribution of ^{40}Ca and the stopping powers used in the simulation, are currently under investigation.

REFERENCES

1. M. Marchetto, "ISAC-II Operation and Future Plans", Proceedings of LINAC08 (Victoria, BC, Canada) **MO101**, 2008.
2. J. P. Greene, *et al.*, "Thick backed carbon targets via mechanical rolling," J Radioanal Nucl Chem **299**, pp. 1121–1124, Feb. 2014.
3. P. Voss, *et al*., "The TIGRESS Integrated Plunger ancillary systems for electromagnetic transition rate studies at TRIUMF", NIM A **746**, pp. 87–97, May 2014.
4. J. Williams, *et al.,* "Implementation of the Doppler shift attenuation method using TIP/TIGRESS at TRIUMF: Fusion-evaporation lifetime measurements in ^{22}Ne". NIM A **859**, pp. 8–17, Jul. 2017.
5. S. Agostinelli, *et al.*, "Geant4 – A Simulation Toolkit", NIM A **506**, pp. 250-303, 2003.