Searching for octupole collectivity in neutron-rich Ce isotopes and isomer depletion pathways in ^{113}Cd

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Context and Aims

Nuclear physics is first and foremost the study of nuclei, of which there are hundreds. Among the various experimental and theoretical projects being undertaken in this field, there are researchers performing experiments to try and understand the patterns of nuclear structure that exist across the chart of nuclides. One such phenomenon exhibited by isotopes with neutrons numbers N around 88 is that of strong octupole collectivity: long-range interactions between nucleons that reside in orbitals separated by three units of both orbital and total angular momentum. Predictions based on models of nuclear structure have been made for the range of nuclides that should exhibit this behaviour, but it has not been experimentally observed for each isotope in this list.

At the same time, a dedicated research campaign is being undertaken to assess the potential of excited states of certain isotopes with relatively long half-lives (known as *nuclear isomers* or metastable states) for storing large amounts of energy in a space-efficient manner over long periods of time.

The original plan was to perform experiments at the start of May to collect data for an exploration centred around ^{113}Cd. Preparations for these experiments were already well underway. However, given the restrictions on access to experimental equipment instated by the ANU in response to the global COVID-19 pandemic, these preparations have had to be halted. Hence, the first stage of this project will now comprise an investigation of yet unanalysed experimental data collected during an experiment with the aim of exploring the structure of isotopes ^{148,150,152}Ce. These nuclides have N = 90, 92 and 94 respectively and are thus expected to exhibit strong octupole collectivity.

This stage will extend until the end of June, at which point the progress of this project will be re-assessed to determine whether experiments to study ^{113}Cd are worthwhile. This second stanza of the project would comprise making new measurements to search for isomer depletion pathways within the structure of ^{113}Cd and explore its energy storage potential. If possible, the experiments for this study will be performed sometime in July or August to allow time for analysis of the resulting data.

Octupole collectivity

The correlations associated with octupole collectivity are one key factor that governs the level schemes of different nuclides. Most isotopes that exhibit this property have mass numbers A in the vicinity of either 146 or 222. Nuclei of Ce with N$\sim$88 fall into the former category, having traits linked to the presence of significant octupole correlations, rendering them as intriguing cases from which we can learn about nuclear structure.

However, currently only some of the excitation energies and lifetimes of the low lying negative-parity states of ^{148,150,152}Ce are known. Measuring values of these quantities enables determination of the quadrupole and dipole moments for these nuclides, which in turn allows their quadrupole and octupole collectivity to be assessed. By analysing gamma ray spectra recorded using an array of gamma ray detectors (known as Gammasphere) this project aims to make measurements of these quantities and thus gauge the afore-mentioned collectivities for these isotopes. Ideally, this will include the first measurement of octupole collectivity in ^{150}Ce. For the ground state of ^{152}La, determination of its lifetime and placing bounds on its spin are some additional goals of this part of the project. Doing so will enhance the existing understanding of octupole correlations displayed by the low spin excited states of these cerium nuclei.

Nuclear isomers

By and large, excited states of atomic nuclei release their excess energy on femtosecond time scales. Yet, there exist long-lived excited nuclear states with half-lives up to 30 orders of magnitude greater than this [1]. The typical energy densities of these isomers are around 10^9 J/g, approximately five orders of magnitude higher than the limit placed on chemical means of energy storage (fuels, batteries, food) by the binding energy between particles ($\lesssim$ 100 eV).

For the goal of harnessing this dense energy source, many nuclear isomers with half-lives on the order of years (or greater) have been identified as potentially useful. The question for each such metastable, however, is are there ways by which this energy can be released? Current work in this field is centred around searching for a reaction pathway that will cause the isomer to dispense its energy by moving into a lower energy state.

The leading suggestion for such a reaction pathway is that of isomer depletion. In this process, a sample containing some nuclear isomer is exposed to a beam of high-energy photons. If the isomer absorbs a photon that has the appropriate energy to excite the isomer to a state with a much shorter half-life, then the isomer will decay (via either a single gamma ray transition, or a cascade of multiple gamma ray emissions) to the ground state of that isotope. This process was first reported when a sample of the isomer ^{180m}Ta was excited to a so-called depletion level (or intermediate state) in 1988, demonstrating that the energy of these isomers can be released on demand [2]. The decay of the metastable state was followed by the decay of the ground state, which resulted in a total of 780 keV being emitted.

However, the energy required to initiate this depletion process was 1000 keV, prompting investigation of other isomers with half-lives in excess of one year, of which ten others have been identified for an ongoing research campaign [1]. With funding provided as part of this campaign, this project aims to experimentally study the isomer ^{113m}Cd (with energy 263.54 keV above the ground state and a half-life of 14.1 yr) of the isotope ^{113}Cd, with the primary goal of identifying such an energy-releasing pathway. As part of this overarching aspiration, there are the sub-goals of gaining expertise in gamma ray spectroscopy, nuclear instrumentation and the operation of the 14UD tandem accelerator located at the ANU. In addition, I am to develop my skills in analysing multi-parameter data sets that will be generated as a result of the experimental part of this project. Finally, I aim to meaningfully interpret the results of this analysis under the framework of a range of theoretical models of nuclear structure.

Background

Octupole collectivity

Nuclear isomers

The nucleons contained within nuclei preferentially arrange themselves into the most stable (lowest energy) configuration, which is known as the ground state. Nuclei are split into three categories (even-even, odd-even or odd-odd) based on the numbers of protons (Z) and neutrons (N) they possess and the parities of each. The configuration of the nucleons within the nucleus is referred to in terms of the spin-parity (denoted J^π where J is the magnitude of the total angular momentum of the nucleus and π represents its parity in three dimensional space). Where possible, nucleons try and pair up (typically with other like nucleons, i.e. protons (neutrons) with protons (neutrons)) to form coupled states with $J^\pi = 0^+$. Excited states generally arise in one of three ways: either the coupling between a pair of nucleons is broken, an unpaired nucleon in a given nuclear orbital is excited into a higher lying orbital, or some combination of these two effects occurs. These excited states may or may not have a different spin-parity to the ground state, but they are always more energetic.

Due to these energy differences, transitions between different nuclear states are accompanied by either the absorption or emission of a photon. However, based on the principles of quantum mechanics, there are *selection rules* that govern (in terms of the quantum numbers of the initial and final nuclear states) which transitions are allowed. Some states are metastable because there are no lower energy states that they are allowed to decay into in light of these fundamental physical rules. In general, nuclear isomers exist because the decay of the isomeric state is inhibited. One possible reason for this inhibition is that the difference in the total angular momentum of the nuclear state before and after the transition (referred to as the multipolarity, ΔJ) is relatively large. This is because transitions with large ΔJ values are known to be slow in comparison to those with lower multipolarities.

The long-lived isomer ^{113m}Cd exhibits one such high multipolarity transition, shown in Figure 1 as the only photon line between the isomer at 263.54 keV and the ground state. The E5 notation is a shorthand way of expressing that the gamma radiation field for this transition has odd parity ($\pi = (-1)^5 = -1$) and carries (orbital) angular momentum of magnitude $5\hbar$. This is because the isomer has $J^\pi = 11/2^-$ and the ground state has $J = 1/2^+$, giving $\Delta J = 5\hbar$ and $\Delta\pi = -1$. There are no other (known) transitions by which this isomer can decay to the ground state [3].

Project Description

Project Plan and Feasibility

References

[1] E. Shaffer and T. Zheleva, *Innovations in Army Energy and Power Materials Technologies.* Millersville, PA: Materials Research Forum LLC, 2018. OCLC: 1051140034.

[2] C. B. Collins, C. D. Eberhard, J. W. Glesener, and J. A. Anderson, "Depopulation of the isomeric state Ta m 180 by the reaction Ta m 180 (γ , γ ′) Ta 180," *Physical Review C*, vol. 37, pp. 2267–2269, May 1988.

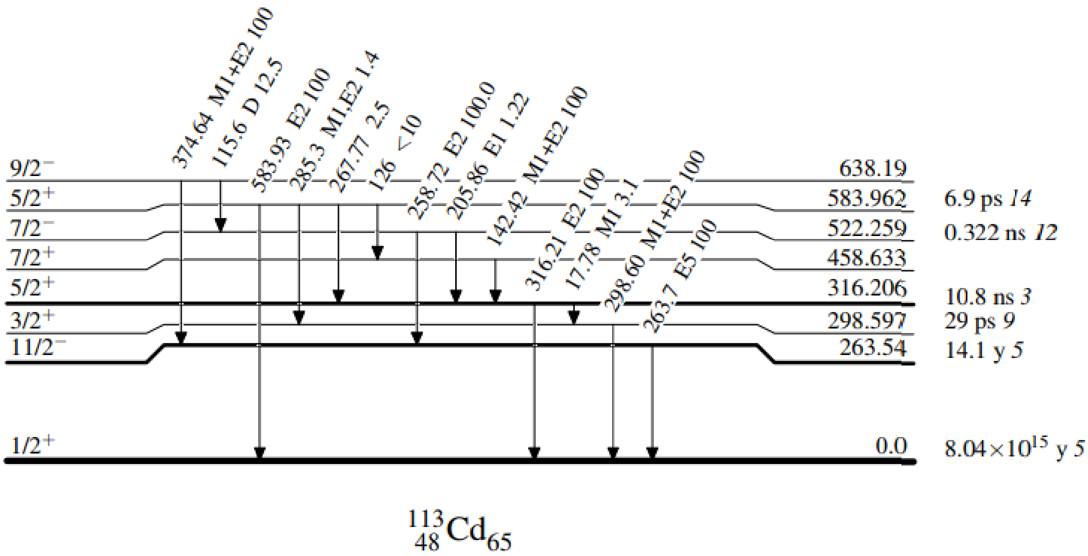

Figure 1: Partial level scheme for ^{113}Cd. The isomeric state has an energy of 263.54 keV [3].

[3] J. Blachot, Nucl. Data Sheets, 111, 1471 (2010), data extracted from the ENSDF database, revision of June 2010.