Level lifetimes in ^{52}Cr from DSAM following inelastic neutron scattering: implications for shape coexistence and $E0$ strengths

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Abstract. Nuclear shape coexistence is a widespread but not yet well understood phenomenon. Electric monopole ($E0$) transitions are a particularly sensitive probe of shape coexistence. The first $E0$ measurements on the Cr isotopes were performed at The Australian National University, but were hampered by missing and imprecise data of the key spectroscopic quantities such as level lifetimes. To address these needs, the low-lying states in ^{52}Cr were investigated at the University of Kentucky Accelerator Laboratory with inelastic neutron scattering. γ-ray angular distribution and excitation function measurements were performed to determine level lifetimes, spins and parities, transition mixing ratios, and γ-ray branching ratios. We present new level lifetimes for three states in ^{52}Cr along with the implications for $E0$ transition strengths and shape coexistence in ^{52}Cr.

1 Introduction

Nuclear shape coexistence occurs where atomic nuclei exhibit multiple distinct configurations at relatively low excitation energy with different deformations [1]. Moreover, shape coexistence appears to be present all over the nuclear landscape.

Large $E0$ transition strengths are clear experimental indicators of nuclear shape coexistence [1, 2]. $E0$ transitions are especially sensitive probes of the charge distributions of nuclei and the $E0$ transition strength is directly related to the change in the mean-square charge radius (change in the nuclear deformation) and the mixing between nuclear states [2].

The $N = 28$ region between the Ca ($Z = 20$) and Ni ($Z = 28$) isotopes is poorly understood from the perspective of $E0$ transitions [2] and is a promising region for observing shape coexistence [3]. Excluding the most recent spectroscopy on the Cr isotopes by Dowie *et al.* (discussed in this work) [4, 5], $E0$ transition strengths have only been measured in some of the Ca and Ni isotopes, and ^{54}Fe. Nothing has been measured in the Ti, Cr, and heavier Fe isotopes (and ^{46}Ca and ^{64}Ni). Shape coexistence in the N=28 isotones has been suggested from theoretical calculations using a variety of different methods, with intruder configurations born from neutron $2p-2h$ excitations out of the $N = 28$ closed shell [6].

In 2019, measurements of the $E0$ transitions in the even-even Cr isotopes were attempted for the first time at The Australian National University (ANU) using the Super-e pair spectrometer to measure γ-ray, conversion electron, and electron-positron pair intensities [4, 5]. Difficulty in determining the final $E0$ transition strengths from the measured conversion-electron and electron-positron pair intensities was experienced due to uncertainty in the level lifetimes, but also in the transition mixing ratios and γ-ray branching ratios.

To resolve these questions and difficulties, γ-ray spectroscopy was undertaken at the University of Kentucky Accelerator Laboratory (UKAL) on ^{nat}Cr using inelastic neutron scattering (INS) and level lifetimes were determined via the Doppler-shift attenuation method (DSAM), as well as additional spectroscopic quantities from γ-ray angular distribution and excitation function measurements.

In the following sections, we provide details of the measurement techniques, present the results, and briefly discuss the implications of these results.

2 Method

γ-ray spectroscopy was performed at UKAL following inelastic neutron scattering from a natural abundance chromium metal target.

UKAL features a 7 MV Van de Graaff accelerator, capable of accelerating beams of protons, deuterons, and ^{3,4}He ions. A gas cell is positioned at the end of the primary beam line allowing for the production of secondary neutrons from the following reactions: $p + t \rightarrow n + {}^3He$, $Q = -0.764$ MeV; $d + d \rightarrow n + {}^3He$, $Q = 3.269$ MeV; and $d + t \rightarrow n + {}^4He$, $Q = 17.59$ MeV [7]. Neutrons with continuously variable energies up to 9.5 MeV are available (along with an upper range from $\approx$ 14 to 21 MeV). The secondary neutrons used in the experiments described in this article were produced via the $p+t$ reaction, have an energy spread of $\lessapprox$ 100 keV, and are quasi-monoenergetic in nature. The neutrons used at UKAL are typically pulsed

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with a period of ≈533 ns (1.875 MHz), and a pulse width of < 1 ns. The neutrons have a conical distribution profile, the effect of which on the angular distribution is corrected for in the analysis [8]. Similarly, the finite size of the target, multiple scattering, and target self-attenuation effects are also taken into account in the analysis [8].

The natural chromium metal target was a right circular cylinder, approximately 52 g in mass, with a 0.9525 cm radius and 2.54 cm height, positioned downstream of the tritium gas cell, with the cylindrical axis of rotation oriented vertical, perpendicular to the beam axis, producing rotational symmetry of the target for the γ-ray angular distribution measurements. A single HPGe detector was placed in a shielded carriage, approximately 1 meter from the scattering sample, mounted on a goniometer, which rotates around the scattering sample, varying the angle with respect to the beam axis. The HPGe γ-ray detector is Compton suppressed by a BGO shield, and is shielded with an assembly of lead, copper, and boron-loaded polyethylene. Further details of the experimental arrangement including the signal processing electronics can be found in [9, 10].

The inelastic neutron scattering reaction with quasi-monoenergetic neutrons is a powerful technique for probing nuclear states. There is no Coulomb barrier for this reaction so levels can be excited close their threshold energies, and the excitation is non-selective, although favouring low-spin states, allowing for easy population of all states below threshold energy, including non-yrast states [11].

Two types of experiments were conducted: a γ-ray excitation function and γ-ray angular distributions. In both measurements the same experimental set-up was used. The γ-ray excitation functions are recorded to determine the nuclear level spin and parity using the CINDY program [11, 12] to compare with theoretical excitation cross sections for 21 neutron energies from 2.43 to 4.5 MeV. The γ-ray angular distributions were measured to determine level lifetimes via the Doppler-shift attenuation method [8, 11] at neutron energies of 2.9 and 3.4 MeV along with transition mixing ratios, and γ-ray branching ratios. Eleven angles from 40 to 150 degrees were used in the measurement.

3 Results

The γ-ray spectrum observed with 3.4 MeV neutrons is shown in Fig. 1. The transitions in ^{52}Cr are labelled. The key transitions of interest are the 1531- and 2965-keV γ rays from the 2965-keV 2^+_2 state, the 1728- and 3162-keV γ rays from the 3162-keV 2^+_3 state, and the 1213-keV γ ray from the 2647-keV 0^+_2 state. These are the transitions needed to determine the $E0$ transition strengths in ^{52}Cr from the conversion-electron and electron-positron pair measurements performed at the ANU [4, 5].

A plot of the transition-energy Doppler-shift against the γ-ray detector-beam axis angle for the 3162-keV $2^+_3 \rightarrow 0^+_1$ transition in ^{52}Cr is shown in Fig. 2 as an example. Linear fits to the energy shifts as a function of angle ($\cos(\theta)$) determine the $F(\tau)$ values.

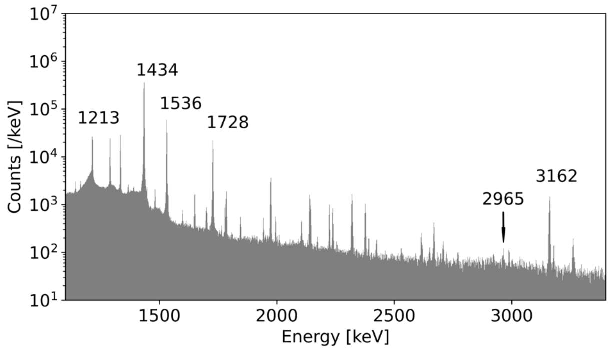

Figure 1. Gamma-ray spectrum of ^{nat}Cr for 3.4 MeV incident neutrons at detector angle of 125°. The transitions in ^{52}Cr that were observed in this work are labelled with the energy according to the Nuclear Data Sheets [13].

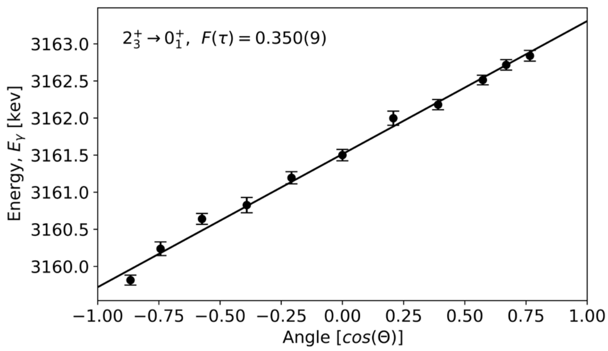

Figure 2. The observed energy of the 3162 keV transition as a function of the detection angle respect to the beam axis. The fitted straight line determines the $F(\tau)$ value of $F(\tau)$ = 0.350(9).

Table 1. Table of newly determined level lifetimes from this work for states in ^{52}Cr. Level energies, spins, and parities are from the Nuclear Data Sheets [13].

E_i [keV]	J^π_i	τ [fs]
2646.9	0^+_2	> 5710
2964.786	2^+_2	984^{+117}_{-88}
3161.74	2^+_3	89(2)

The newly determined lifetimes for the 0^+_2, 2^+_2, and 2^+_3 states in ^{52}Cr are shown in Table 1. For the 2^+_2 and 2^+_3 states, an average lifetime was determined from the Doppler shifts observed in both the $2^+_{2,3} \rightarrow 2^+_1$ and $2^+_{2,3} \rightarrow 0^+_1$ transitions. A limit for the level lifetime of the first-excited 0^+ state in ^{52}Cr has been determined for the first time.

4 Discussion

As mentioned earlier, large $E0$ transition strengths serve as a distinct hallmark of nuclear shape coexistence [1]. These new lifetimes measured at UKAL carry substantial implications for the previously observed $E0$ transition strengths in ^{52}Cr [4, 5]. The application of these new, high-precision lifetimes to the previously observed $E0$ transition strength

Table 2. Estimates of the $E0$ transition strengths in ^{52}Cr applying the new lifetimes from this work using the intensities given in Refs. [4, 5]. Level and transition energies are from the Nuclear Data Sheets [13].

E_i [keV]	$J_i^\pi \rightarrow J_f^\pi$	E_γ [keV]	$\rho^2(E0) \times 10^3$
2646.9	$0_2^+ \rightarrow 0_1^+$	2646.9	< 70
2964.786	$2_2^+ \rightarrow 2_1^+$	1530.67	210(40)
3161.74	$2_3^+ \rightarrow 2_1^+$	1727.53	480^{+220}_{-190}

estimates from the ANU [4, 5] yields the revised values shown in Table 2. The new $E0$ transition strengths were derived from the intensities given in Refs. [4, 5], the new lifetimes reported in this work in Table 1, and the adopted transition mixing ratios and γ-ray branching ratios from the Nuclear Data Sheets [13].

These $E0$ transition strengths are large and provide evidence for shape coexistence in ^{52}Cr. These findings, coupled with the large $E0$ transition strengths observed in the Ni isotopes [14, 15], support the presence of significant shape coexistence across the entire region, as calculated in the $N = 28$ isotones [6].

The 0_2^+ and 2_3^+ states are hypothesised to be the start of a shape-coexisting intruder band arising from ν 2p-2h excitations across the $N = 28$ shell gap predicted by calculations [6] and supported by transfer reaction data [16, 17]. The sizeable $E0$ strength in the 1728-keV $M1 + E2 + E0$ transition from the 2_3^+ state to the 2_1^+ state lends support to the hypothesis along with the identified limit for the $E0$ transition strength in 2647-keV $E0$ transition from the 0_2^+ to the 0_1^+ state. However, the origin of the strength observed in the 1531-keV 2_2^+ to 2_1^+ transition remains enigmatic, demanding consideration of state mixing between the 2_2^+ and 2_1^+ states.

5 Conclusion

^{52}Cr was investigated the University of Kentucky Accelerator laboratory via γ-ray spectroscopy following inelastic neutron scattering to measure spectroscopic information needed for the accurate and precise determination of $E0$ transition strengths: level lifetimes, transition mixing ratios, and γ-ray branching ratios. New high-precision lifetimes for the second- and third-excited 2^+ states in ^{52}Cr from this work are reported here along with the first limit on the lifetime of the first-excited 0^+ state in ^{52}Cr. The revised $E0$ transition strengths in ^{52}Cr resulting from the new lifetimes are large and suggest shape coexistence in ^{52}Cr and potentially the whole region. A full report of the conversion electron and pair conversion as well as lifetime and angular distribution measurements is being prepared. This material is based upon work supported by the U. S. National Science Foundation under Grant No. PHY-2209178.

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