Evidence for shape coexistence in ^{52}Cr through conversion-electron and pair-conversion spectroscopy

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Abstract. Electric monopole ($E0$) transitions are a highly sensitive probe of the charge distribution of an atomic nucleus. A large $E0$ transition strength ($\rho^2(E0)$) is a clear indicator of nuclear shape coexistence. In the region between doubly magic ^{40}Ca and ^{56}Ni, $E0$ transitions have never been observed in the Ti or Cr isotopes, nor in the heavier iron isotopes (^{56,58}Fe). We have performed the first measurements of the $E0$ transitions in ^{52}Cr via conversion-electron and pair-conversion spectroscopy using the Super-e spectrometer at the Australian National University Heavy Ion Accelerator Facility. We present the first spectra obtained for ^{52}Cr, including the first observation of the $E0$ transition from the first-excited 0^+ state in ^{52}Cr, in both electron-positron pairs and conversion-electron spectroscopy. The preliminary values for the $E0$ strength in the 1531-keV $2_2^+ \rightarrow 2_1^+$ transition in ^{52}Cr is $\rho^2(E0) \times 10^3 = 470(190)$, and for the 1728-keV $2_3^+ \rightarrow 2_1^+$ transition, it is $\rho^2(E0) \times 10^3 = 1800(1200)$. The large $E0$ strengths observed are consistent with shape coexistence in this region. However, despite the relatively precise observation of the conversion-electron and electron-positron pair intensities, the $E0$ strengths have large uncertainties. More precise determinations of relevant spectroscopic quantities, such as the state lifetimes and transition mixing ratios for mixed $M1 + E2$ transitions, are needed to determine the $E0$ strength more precisely.

1 Introduction

Nuclear shape coexistence is a phenomenon in which the atomic nucleus can take different shapes at low excitation energy [1]. Nuclear shape coexistence appears to be a phenomenon that is present across the nuclear landscape [1–3] with important implications for our current understanding of nuclear structure. For example, recent work on Cd isotopes casts doubt on the widely-held notion of spherical, quadrupole vibrations in these nuclei [4, 5] and instead explains their behaviour by multiple shape-coexisting rotational bands [5].

The presence and behavior of 0^+ states in even-even nuclei, and their association with nuclear shapes play a pivotal role in understanding shape coexistence [1]. $E0$ transitions, the only possible decay path between two $J^\pi = 0^+$ states, provide a unique probe into these nuclear shapes. The nuclear $E0$ transition strength ($\rho^2(E0)$) is large when there is a sizable change in the nuclear mean-square charge radius, and when there is also strong mixing between states of different deformation [6]. The measurement of $E0$ transition strengths is then a direct experimental tool to investigate nuclear shape coexistence and shape mixing.

Large $E0$ strengths have been recently observed in the Ni isotopes ($Z = 28$) [7, 8], but it is unknown if shape coexistence is present in the $N = 28$ isotones between doubly magic ^{48}Ca and ^{56}Ni. Theoretically, shape coexistence has been predicted in the $N = 28$ isotones [9], resulting from the excitation of a neutron pair across the $N = 28$ closed neutron shell from the $f_{7/2}$ shell into the fp shell. This creates a deformed prolate band above a spherical ground state, possibly mixing with the spherical, seniority states in these nuclei [9–13]. There are candidates for the shape-coexisting band in ^{50}Ti, ^{52}Cr and ^{54}Fe, but no $E0$ transitions have been reported in ^{50}Ti or ^{52}Cr [14, 15].

In this article, we report the preliminary results of our investigation into $E0$ transitions in ^{52}Cr.

2 Experiment

The experiments were performed at the Heavy Ion Accelerator Facility at the Australian National University (ANU) using the Super-e spectrometer [16] to measure the electron-positron pair, conversion-electron, and γ-ray transitions.

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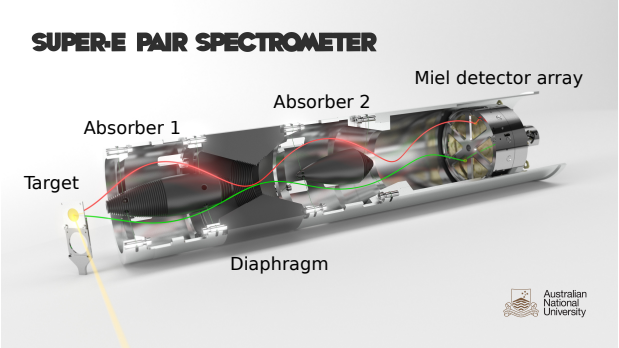

Figure 1. A cut-away, rendered image of the Super-e spectrometer. The target is on the left and the *Miel* detector array is at the right end of the bore of the solenoid. Around the outside of the bore are the superconducting coils – *not pictured*. Down the centre of the bore are the *HeavyMet* baffles, in dark grey. Example trajectories of an electron and a positron emitted from the target are shown in red and green.

The Super-e is a superconducting magnetic-lens spectrometer for the measurement of conversion electrons and electron-positron pairs, with excellent background suppression [16–18]. It consists of the *Miel* detector array, two HPGe detectors, a superconducting solenoid, and central *HeavyMet* baffles. An image of the Super-e rendered from the engineering drawings is shown in Fig. 1.

The *Miel* detector array consists of six Si(Li) detectors, each with an active area of 260 mm^2 and a thickness of 9 mm, allowing measurement of electron and positron energies up to 3.5 MeV and nuclear pair transitions up to 8 MeV in energy. The *Miel* detector array along with accompanying electronics has a time resolution of 10 ns and an energy resolution of 2.5 keV at an electron energy of $\approx$ 1.1 MeV. Each Si(Li) detector is separated from its neighbours by *HeavyMet* barriers to prevent cross-talk.

There are two HPGe detectors mounted as part of the experimental apparatus. The first is Compton suppressed and positioned at $\approx$ 135° relative to the beam axis and $\approx$ 25 cm from the target; the second is not Compton suppressed, positioned at $\approx$ 135° to the beam axis and 1.5 m from the target and is collimated, positioned within a polyethylene and lead radiation shield to provide beam-current normalization in high beam-current experiments [18].

The central *HeavyMet* baffles, along with the axial magnetic field of the solenoid, define an acceptance window for the emitted conversion electrons and electron-positron pairs as a function of take-off angle and energy. Only those particles with energies and take-off angles that lie within the acceptance window will reach the detector. The Super-e can only observe electron-positron pairs where the electron and positron have similar energy and separation angles up to 84°. The trajectories of the electrons and positrons that reach the detector are helical, making 2.5 orbits between the target and the detector; such orbits can be seen schematically in Fig 1. More details of the operation of the Super-e can be found in a number of recent papers [7, 8, 19].

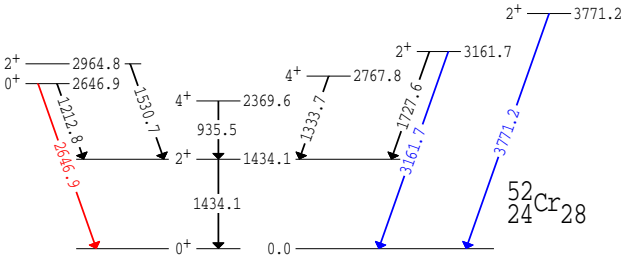

Figure 2. Level scheme of ^{52}Cr showing levels and transitions that were observed in conversion electrons or electron positron pairs. Transitions that were observed in conversion electrons are in black, transitions observed in electron-positron pairs are shown in blue, and transitions that were observed in both are shown in red.

The 14UD pelletron accelerator at the ANU Heavy Ion Accelerator Facility delivered a 5.4-MeV proton beam to the Super-e pair spectrometer. The nuclear states of interest in ^{52}Cr were excited with the (p, p') reaction. The ^{52}Cr target had a thickness of 1.3 mg/cm^2 and was isotopically enriched to 99.9(1)%, and mounted at 45° to both the beam axis and the solenoid axis as shown in Fig. 1.

Data was collected in two modes: singles mode collecting electron singles with the *Miel* detector array and both HPGe detectors; and doubles mode, with only the far HPGe detector, and collecting only *Miel* coincidence events. The Super-e was operated in swept-field mode, scanning the magnetic field between an upper and lower value continuously. The solenoid current for each of the modes was different. For the singles mode, the solenoid current range was 1.700 – 11.569 A, while for the doubles mode was 2.712 – 7.720 A; these correspond to transitions of energy 200 – 2500 keV in singles mode and 2200 – 4352 keV in doubles mode.

The relative efficiencies of the HPGe detectors were determined from the measurement of well-known calibration sources: ^{152}Eu, ^{56}Co, and ^{170}Lu. ^{152}Eu and ^{170}Lu sources were also used to calibrate the relative efficiency of the Super-e spectrometer in singles by sweeping the solenoid current over the same current range used in the singles measurement. The efficiency of the Super-e to pair conversion was determined via Monte-Carlo simulation of the trajectories of the electrons and positrons inside the bore of the Super-e using PENELOPE and Poisson Superfish [20, 21]. The *Miel* detector efficiency was then also determined via Monte Carlo simulation, using PENELOPE. More details are given in Refs. [14, 18, 19].

3 Results

The transitions observed in conversion electrons and electron-positron pairs are shown in Fig. 2 along with the populated levels of ^{52}Cr. The observed γ-ray, conversion-electron, and electron-positron pair spectra are shown in Figs. 3a, b, and c, respectively. We have observed the transitions from the second- and third-excited 2^+ states to the first-excited 2^+ state at energies of 1531 and 1728 keV in both internal conversion and γ-ray spectroscopy, see

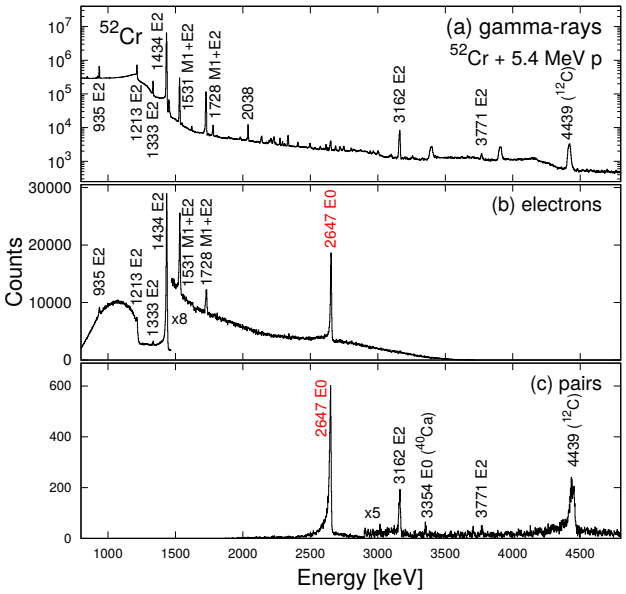

Figure 3. Gamma-ray (a), conversion-electron (b), and electron-positron pair (c) energy spectra collected using the Super-e pair spectrometer for ^{52}Cr.

Table 1. $E0$ Transition strengths and related quantities

Quantity	Value
$\rho^2(1531\ M1+E2+E0)\times 10^3$	470(190)
$\rho^2(1728\ M1+E2+E0)\times 10^3$	1800(1200)
$X(2647\ E0/1212\ E2)$	0.41(9)

Figs. 3a and b. The 2647-keV $E0$ transition can also be clearly observed from the first-excited 0^+ state in ^{52}Cr to the ground state in both conversion electrons and electron-positron pairs which can be seen in Figs. 3b and c. Note that there is no strong γ-ray line at 2647 keV in the γ-ray spectrum, clearly indicating that the 2647-keV transition corresponds to a $0^+ \rightarrow 0^+$ transition.

Table 1 shows the $E0$ strengths determined in this work. These use the determined detector efficiencies, adopted values for the transition mixing ratios, branching ratios, and state lifetimes from Nuclear Data Sheets [22], conversion coefficients from the *BrIcc* database [23], electronic factors from the recent tabulation [24], and the measured conversion-electron and electron-positron pair intensities from the present work. Unfortunately, without a lifetime for the 2647-keV first-excited 0^+ state in ^{52}Cr, the $E0$ transition strength cannot be determined [15]. Instead, we report the $X(B(E0)/B(E2))$ value – a measure of the relative strength between the $E0$ and $E2$ transitions depopulating the 0^+ state [25].

4 Discussion

We have observed large $E0$ strengths in the mixed $M1$ + $E2$ + $E0$ transitions from the second and third-excited 2^+ states in ^{52}Cr to the first-excited 2^+ state. An expected $E0$ strength for a nucleus of $A = 52$ from a simple shell-model picture is 36 milliunits [6], while the largest reported $E0$ strength across the nuclear chart is 500(81) milliunits from the Hoyle State in ^{12}C [15].

The 1531-keV $M1$ + $E2$ + $E0$ transition is from the second-excited 2^+ state in ^{52}Cr. This state is suggested to be the first-excited 2^+ state in the shape-coexisting band in ^{52}Cr [9–11]. If there is strong mixing and a large change in nuclear shape, a large $E0$ strength is expected [1, 6]. The large observed $E0$ strength in this transition, see Table 1, supports the shape-coexistence picture of ^{52}Cr.

Using the two-state mixing model and assuming maximal mixing ($a = b = 1/\sqrt{2}$) [6], and a spherical ground state for ^{52}Cr ($\beta_2 = 0$) [9, 12, 13, 22, 26], the expected quadrupole deformation of the excited 2^+ state is $\beta_2 = 0.49(5)$. If the 2^+_2 state is part of a shape-coexisting band built on the first-excited 0^+ state, then the lifetime of the 0^+ state can be estimated by taking the $E0$ strength of the $2^+_2 \rightarrow 2^+_1$ transition. This results in an estimated lifetime of ≈ 0.6 ps, similar to the lifetimes of the first-excited 0^+ states of its neighbours in ^{50}Ti, ^{54}Cr, and ^{54}Fe with lifetimes of 0.50(23) ps, $0.15^{+0.06}_{-0.04}$ ps, and ≥ 1.4 ps, respectively [22].

The very large $E0$ strength in the 1728-keV $2^+_3 \rightarrow 2^+_1$ $M1$ + $E2$ + $E0$ transition of 1800(1200) milliunits is unprecedented [15], however the uncertainty in the value is equally large. The $E0$ strength in this transition is consistent with zero within two standard deviations. Along with the experimental conversion-electron and electron-positron pair intensities, the determination of the $E0$ strength of a mixed $M1+E2+E0$ transition relies on three factors: the parent level lifetime, the transition mixing ratio ($\delta(E2/M1)$), and the transition branching ratio. All of these factors must be known to high precision in order to extract a precise $\rho^2(E0)$ value.

The $E2/M1$ mixing ratio for the 1728-keV $2^+_3 \rightarrow 2^+_1$ $M1$ + $E2$ + $E0$ transition is -0.18(7) [27] and the branching ratio is 0.909(66) [22]. The $E0$ intensity is determined from the difference between the experimental conversion electron and electron-positron pair intensity and that which is theoretically predicted for a mixed $M1+E2$ transition. Uncertainty in the mixing ratio exacerbates the uncertainty in the $E0$ intensity. The $E0$ strength is inversely proportional to level lifetime, $\rho^2(E0) \propto 1/\tau(E0)$. The level lifetime ($T_{1/2} = 0.035(7)$ ps [22]) is short and has large uncertainty; as smaller lifetimes increase the $E0$ strength non-linearly, this uncertainty amplifies the possible $E0$ strength.

In order to determine precise values for the $E0$ strength in the 1531-keV and 1728-keV transitions, precise determinations of the state lifetimes as well as the transition branching ratios and mixing ratios are needed. Without this information, our $\rho^2(E0)$ values for these transitions remain tentative. In order to resolve these limitations, an experimental campaign investigating these properties of ^{52}Cr is planned to take place at the University of Kentucky Accelerator Laboratory (UKAL). The inelastic neutron scattering reaction, (n, n'), has been successfully used to measure nuclear lifetimes via the Doppler-shift attenuation method (DSAM) and mixing ratios via angular distributions in the Ni isotopes, which were needed for accurate $E0$ strength determination [7, 8, 28].

5 Conclusion

We report the observation of the $E0$ transition from the first-excited 0^+ state to the ground state of ^{52}Cr for the first time. We also report the first values for the $E0$ strength in the mixed $M1 + E2 + E0$ transitions from the second- and third-excited 2^+ states to the first-excited 2^+ state in ^{52}Cr. The large $E0$ strengths in these transitions support the current theoretical picture of shape coexistence in the $N = 28$ isotones, particularly in ^{52}Cr [9]. The observed $E0$ strengths are the first experimental evidence for shape coexistence in ^{52}Cr, suggesting a quadrupole deformation for the excited band of $\beta_2 = 0.49(5)$. Using this preliminary $E0$ strength, the predicted lifetime of the first-excited 0^+ state is ≈ 0.6 ps, within the lifetime range for DSAM measurement. Unfortunately, there is a large uncertainty on the reported $E0$ strengths in this work due to the uncertainty in the state lifetimes, and the transition branching and mixing ratios. The unprecedented strength in this region (Ca – Ni) [7, 8, 14, 15] is still not understood, and further measurements of both the $E0$ transition strengths, along with other spectroscopic quantities like mixing ratios, are needed to reduce the uncertainty on the $E0$ transition strengths and to understand the structure of these nuclei.

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References

[1] K. Heyde and J. L. Wood, Rev. Mod. Phys. **83**, 1467 (2011).
[2] K. Heyde, P. Van Isacker, M. Waroquier, *et al.*, Phys. Rep. **102**, 291 (1983).
[3] J. L. Wood, K. Heyde, W. Nazarewiczc, *et al.*, Phys. Rep. **215**, 101 (1992).
[4] B. J. Coombes, A. E. Stuchbery, A. Blazhev, *et al.*, Phys. Rev. C **100**, 024322 (2019).
[5] P. E. Garrett, T. R. Rodriguez, A. Diaz Varela, *et al.*, Phys. Rev. Lett. **123**, 142502 (2019).
[6] J. L. Wood, E. F. Zganjar, C. De Coster, *et al.*, Nucl. Phys. A **651**, 323 (1999).
[7] L. J. Evitts, A. B. Garnsworthy, T. Kibédi, *et al.*, Phys. Lett. B **779** 396 (2018).
[8] L. J. Evitts, A. B. Garnsworthy, T. Kibédi, *et al.*, Phys. Rev. C **99**, 024306 (2019).
[9] T. Mizusaki, T. Otsuka, M. Honma, *et al.*, Phys. Rev. C. **63**, 044306 (2001).
[10] R. F. Casten, E. R. Flynn, Ole Hansen, *et al.*, Phys. Rev. C **4**, 130 (1973).
[11] R. Chapman, S. Hinds, and A. E. MacGregor, Nucl. Phys. A **119**, 305 (1968).
[12] T. Komoda, Nucl. Phys. **51**, 234 (1964).
[13] J. Talmi, Phys. Rev. **126**, 1096 (1962).
[14] T. K. Eriksen, Ph.D. thesis, The Australian National University, Canberra, Australia. (2018).
[15] T. Kibédi and R. H. Spear, Atom. Data and Nucl. Data **89**, 77 (2005).
[16] T. Kibédi, G. D. Dracoulis, and A. P. Byrne, Nucl. Instrum. Meth. A **294**, 523 (1990).
[17] T. Kibédi, M. Kerr, E. B. Norman, *et al.*, Astrophys. J., **489**, 951 (1997).
[18] T. Kibédi, T. K. Eriksen, J. T. H. Dowie, *et al.*, Nucl. Instrum. Meth. A, (in preparation).
[19] T. K. Eriksen, T. Kibédi, M. W. Reed, *et al.*, Phys. Rev. C, (in preparation).
[20] K. Halbach and R. F. Holsinger, Part. Accel. **7**, 213 (1976).
[21] F. Salvat, J. M. Fernández-Varea, and J. Sempau, eds., Workshop Proceedings, Barcelona, Spain, 30 June-3 July 2008.
[22] Y. Dong and H. Junde, Nucl. Data Sheets **128**, 185 (2015).
[23] T. Kibédi, T. W. Burrows, M. B. Trzhaskovskaya, *et al.*, Nucl. Instrum. Meth. A **589**, 202 (2008).
[24] J. T. H. Dowie, T. Kibédi, T. K. Eriksen, *et al.*, Atom. Data and Nucl. Data **131**, 101283 (2020).
[25] J. O. Rasmussen, Nucl. Phys. **19**, 85 (1960).
[26] D. J. Rowe and J. L. Wood, *Fundamentals of Nuclear Models: Foundational Models*, (World Scientific Publishing Co. Pte. Ltd., Singapore 596224, 2010) ISBN: 9789812569554
[27] G. Kaye and J. C. Willmott, Nucl. Phys. **71**, 561 (1965).
[28] A. Chakraborty, J. N. Orce, S. F. Ashley, *et al.*, Phys. Rev. C **83**, 034316 (2011).