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Isovector pairing in odd–odd $N = Z$ ^{50}Mn

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Abstract

High-spin states in the odd–odd $N = Z$ nucleus $^{50}_{25}$Mn have been investigated. A sequence of states up to $J^\pi = 6^+$ has been assigned as the $T = 1$ analogue of the yrast band in $^{50}_{24}$Cr for the first time. The differences in energy between levels in these bands are interpreted in terms of rotational alignments and the effect they have on the Coulomb energy of the nucleus. Comparisons with shell model calculations show that the Coulomb energy difference between the $T = 1$ analogue structures is an important indicator of the competition between isovector pairing modes in $N = Z$ nuclei and their isobars.

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Pairing correlations between nucleons are an important part of the description of nuclear behaviour. Effects associated with proton–proton (pp) and neutron–neutron (nn) pairs are well understood, but neutron–proton (np) pairing is a phenomenon which has only recently been opened up for experimental investigation.

An isovector np (isospin $T = 1$, 3-axis component $T_Z = 0$) pair involves correlations in time-reversed orbits coupled to orbital angular momentum $L = 0$ and spin $S = 0$ in a manner similar to like-nucleon pairs pp ($T = 1$, $T_Z = +1$) and nn ($T = 1$, $T_Z = -1$). Under the assumption of the charge-independence of the nuclear force, $T = 1$ isospin triplet configurations are degenerate in the absence of the Coulomb interaction. Thus in an odd–odd $N = Z$ nucleus, any observed $T = 1$ structure should exhibit states with energies very similar to those in its $N = Z \pm 2$ partners. The slight differences are expected to be due to the Coulomb effects resulting from different numbers of protons within the triplet. This difference can be referred to as the *Coulomb Energy Difference* or CED. The variation of CEDs with spin has already proven to be a sensitive probe of nuclear structure in the $f_{7/2}$ shell (atomic mass 40 to 56). In the case of mirror nuclei (those with reflected proton and neutron numbers), CEDs were shown [1–6] to indicate the different ways in which a nucleus generates angular momentum. For the $T = 1$ configurations in $^{46}_{23}$V and $^{46}_{22}$Ti [7,8], the measured CED suggested that $T = 1$ np pairing competes more strongly (than like-nucleon pairing) in the $N = Z$ nucleus than in its analogue near the ground state.

Nuclei near the center of the $f_{7/2}$ shell are of topical interest for two reasons. Firstly, due to the relatively small dimension of the shell their states are expected to be well described by the shell model yet they have enough valence particles to allow a degree of collective rotational motion at low to intermediate spins. Secondly, the $f_{7/2}$ shell is reasonably well isolated in energy from the other shells, thus allowing the trends in the structure of the nucleus to be examined without the complication of a significant change in the single-particle configuration of the nuclear states.

Experimental studies of isobaric analogue systems in this region are hampered not only by the low cross-section for populating the $T = 1$ band in the $N = Z$ nucleus, but also the difficulty of accessing the $T_Z = +1$ partner. The results presented here on the odd–odd, $N = Z$ nucleus $^{50}_{25}$Mn$_{25}$ are, therefore, timely as states are now known to high spin in both $^{50}_{24}$Cr$_{26}$ [9] (up to $J^\pi = 18^+$) and very recently in $^{50}_{26}$Fe$_{24}$ [10] (up to $J^\pi = 10^+$). The $T = 1$ band in ^{50}Mn was previously investigated in two separate studies [11,12]. However, since two near-degenerate $J^\pi = 4^+$, $T = 1$ candidates were observed this effectively meant that the band was only known with any certainty up to $J^\pi = 2^+$. In this work we confirm the $T = 1$ assignment of Schmidt et al. [12] for the 4^+ state and present experimental data that establishes the $T = 1$ band in ^{50}Mn to $J^\pi = 6^+$ for the first time. The measured CED between this band and its analogue is compared with predictions from shell-model calculations. The results show that the measured CED can reflect the competition between isovector np and nn/pp pairing modes.

Manganese-50 was populated in the reaction ^{24}Mg (^{32}S, αpn) ^{50}Mn using a beam of energy 95 MeV incident upon a 0.5 mg/cm^2 enriched and self-supporting ^{24}Mg target. Prompt gamma rays were studied using the GAMMASPHERE hyper-pure Germanium-detector (HPGe) array at the Argonne National Laboratory. Events in which at least three gamma rays were detected within the 101 HPGe detectors present in this GAMMASPHERE configuration were written to tape. Analysis was performed with gamma-ray triples and quadruples events.

Where statistics permitted, multipolarities of gamma rays were determined via a technique exploiting directional correlations from oriented states (DCO). Relative intensities of gamma rays at detector-angle groupings were measured, with values obtained for transitions of unknown multipolarity compared to those from known transitions. This technique allows us to distinguish between the stretched quadrupole $J \to J - 2$ and stretched dipole $J \to J - 1$ transitions, but not between stretched quadrupole and $J \to J$ dipole transitions.

Fig. 1(a) shows events in coincidence with any two of the 149, 343 and 651 keV transitions, and shows most of the gamma rays present in the right-hand side of the level scheme in Fig. 2. The 5^+_1 state at 229 keV is known to be isomeric from previous work [13] with a half-life of 1.75 minutes. No transitions were observed to connect the yrast

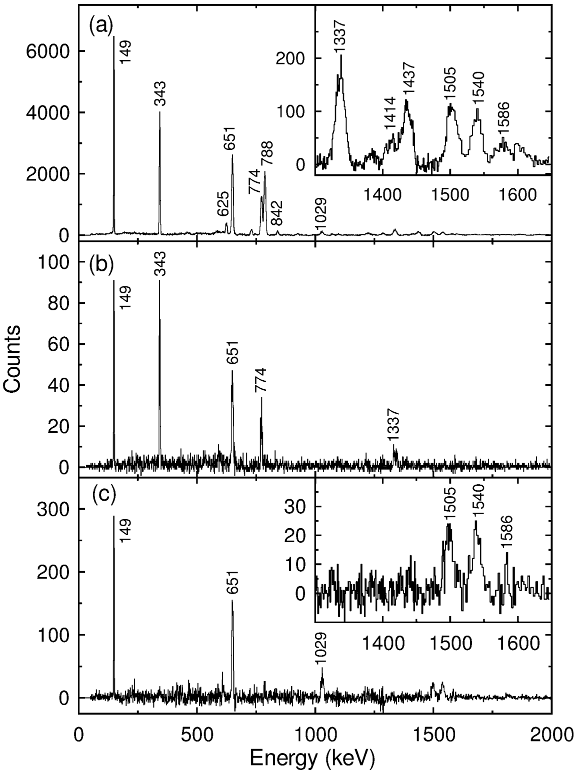

Fig. 1. (a) Events in coincidence with any two of the 149, 343 or 651 keV transitions. The inset shows an expansion of the same spectrum between 1300 and 1650 keV. (b) Events in coincidence with either the 774 or 1337 keV transition and any two of the 149, 343 and 651 keV transitions. (c) Events in coincidence with both the 149 and 1540 keV transitions or with both the 651 and 1029 keV transitions. The inset shows an expansion of the same spectrum between 1300 and 1700 keV. All spectra are at 1 keV per channel.

Table 1
DCO values for transitions in ^{50}Mn as measured in this experiment, where I_{90} represents the intensity of each peak in a spectrum only including events from detectors at 80.7°, 90.0° and 100.8° and in coincidence with any two of the 149, 343 and 651 keV transitions. I_0 is the equivalent value for events in detectors at 17.3°, 31.7°, 148.3° and 162.7°. M1 transitions have values around 1.5 and above, E2 transitions have values around unity. Associated absolute errors are given in brackets

E_γ (keV)	$\frac{I_{90}}{I_0}$ (err.)
149	1.52(0.11)
343	1.59(0.06)
625	1.42(0.19)
651	1.60(0.07)
730	2.01(0.39)
774	1.07(0.09)
788	1.40(0.08)
842	0.98(0.19)
1029	0.99(0.16)
1337	1.51(0.18)
1437	0.94(0.13)
1505	1.18(0.16)
1586	0.89(0.16)

sequence (labeled 'Band 1' in Fig. 2) with the ground state and so the value of 229 ± 7 keV is taken from previous work. In addition to the transitions shown in Fig. 2, gamma rays of energy 1866, 2192, 2549 and 2635 keV are observed to feed into the state at 1932 keV, but could not be placed in the level scheme. The sequence labeled 'Band 2' extending from $J^\pi = 0^+$ to 6^+ with states at 0, 800, 1932 and 3254 keV is proposed to be the $T = 1$ analogue to the yrast band in ^{50}Cr [9] for reasons described below.

In the work of Svensson et al. [11], the $T = 1$ states are assigned to the 800 (2^+) and 1917 keV (4^+) levels on the basis of similarity in excitation energy compared to the ^{50}Cr case (which has states of those spins at 783.6 and 1881.5 keV, respectively, [9]). In more recent work by Schmidt et al. [12] the state at 1932 keV is assigned as the $J^\pi = 4^+$, $T = 1$ analogue though they also assign the 1917 keV state as $J^\pi = 4^+$. However, they do not rule out either 3^+ or 5^+ as possible assignments for the 1917 keV state. The present work confirms that the 774 keV displays quadrupole characteristics (see Table 1), we, therefore, suggest that its correct assignment is $J^\pi = 5^+$, as has been made in a parallel study [14]. This is consistent with shell-model calculations presented by Schmidt et al. [12] which have a second 5^+ state lying close in energy but below the first ($T = 1$) $J^\pi = 4^+$ state, thereby supporting our assignment.

The 1337 keV transition was observed for the first time in the present work. It has a DCO value consistent with a dipole transition (see Table 1) and is in coincidence with the 774 keV transition, as shown in Fig. 1(b). It is known that isoscalar M1 transitions (those that do not change isospin, i.e., $\Delta T = 0$) in self-conjugate nuclei are strongly hindered in comparison

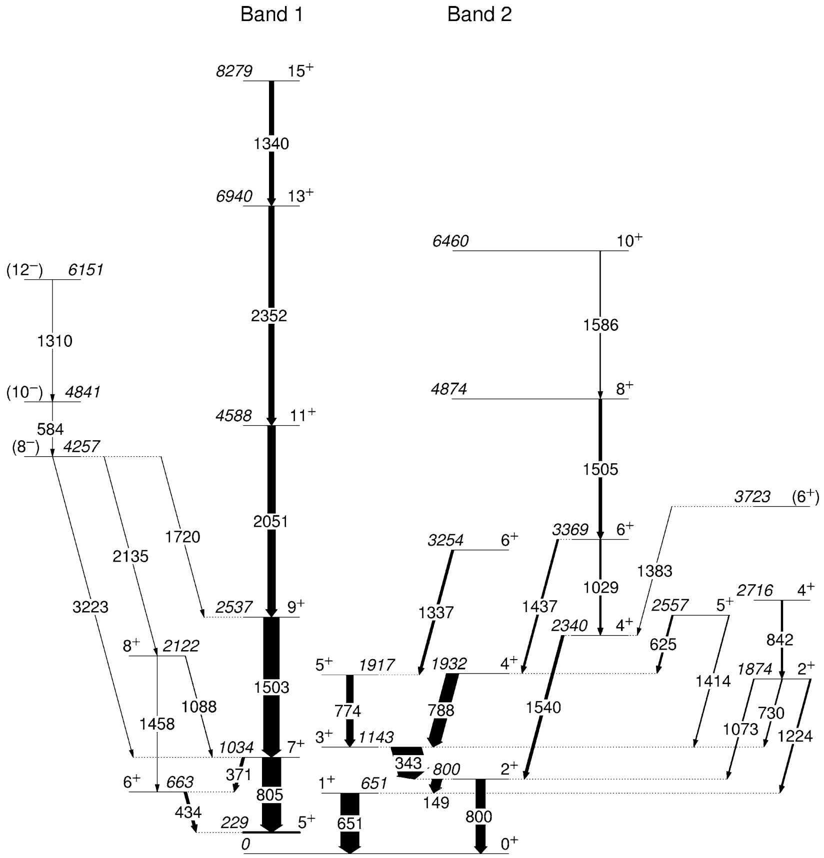

Fig. 2. Energy level scheme deduced from this experiment for ^{50}Mn. The levels are labeled with the assigned spin and parity as well as the excitation energy in keV. Widths of arrows are proportional to relative gamma-ray intensity. Bracketed spin assignments are tentative. The 5^+ level at 229 keV is isomeric and carries an uncertainty of ±7 keV.

with equivalent transitions in $N \neq Z$ nuclei [15]. Conversely, isovector ($\Delta T = 1$) M1 transitions in self-conjugate nuclei are known to be relatively strong [15, 16] and this can be seen in the right-hand side of the level scheme, where the only M1 transitions observed are those feeding into and out of the $T = 1$ band. It is this evidence along with the smoothness of the CED curve (discussed below and shown in Fig. 3) that forms the foundation for our $J^\pi = 6^+$, $T = 1$ assignment to the 3254 keV state rather than the 3369 keV. In fact, this feeding pattern is remarkably similar to that found in $^{46}_{23}$V [7,8], the cross-conjugate nucleus in the $f_{7/2}$ shell.

The 1029–1540 keV branch is in coincidence with the 149, 651, 1505 and 1586 keV transitions, but not the 343, 788 or 1437 keV gamma rays. This is apparent from Fig. 1(c) which shows events in coincidence either with the 149 and 1540 keV transitions or the 651 and 1029 keV transitions. The 1029, 1437 and 1505 keV gamma rays all display quadrupole characteristics, on this basis we re-assign the 2340 keV state as $J^\pi = 4^+$ and the 3369 keV state as $J^\pi = 6^+$. Again, shell model calculations [12] have two $J^\pi = 6^+$ states very close in energy, one with $T = 1$ and one $T = 0$ and this agrees with our proposed level scheme.

We assign the state at 4874 keV as $J^\pi = 8^+$ and the state at 6460 keV as $J^\pi = 10^+$ but a unique assignment of isospin cannot be made. These two states would represent excellent candidates for the $T = 1$ analogues to the 8^+ and 10^+ states in ^{50}Cr [9]

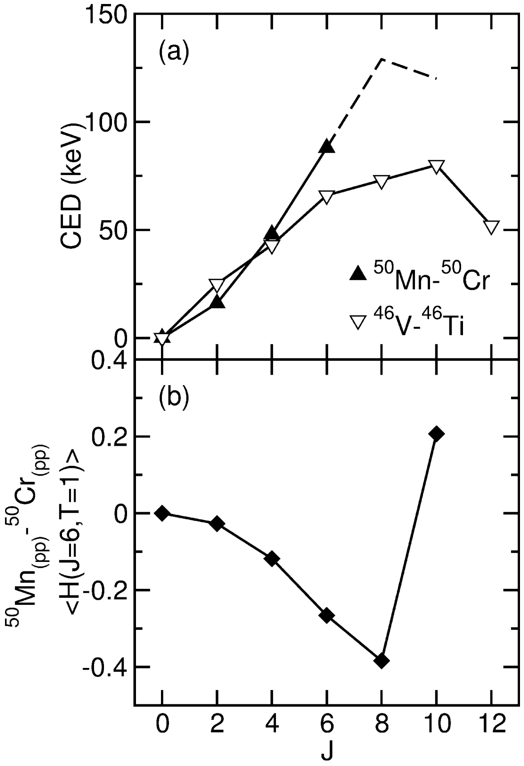

Fig. 3. Coulomb Energy Differences (CEDs) between the $T = 1$ bands in ^{50}Mn and ^{50}Cr (solid up-triangles) and ^{46}V and ^{46}Ti (open down-triangles) as a function of spin (J). The dashed line indicates the shape of the curve for a $T = 1$ assignment to the 4874 and 6460 keV states in ^{50}Mn. The ^{50}Mn data are from this work, the ^{50}Cr data are from Lenzi et al. [9] and the $A = 46$ data from Garrett et al. [17]. (b) Shell model calculation of the difference in quasi-alignment between $J = 6$, $T = 1$ pp pairs in ^{50}Mn and those in ^{50}Cr. The units on the y-axis are arbitrary.

at 4745 keV and 6339 keV, respectively. However, the observed feeding pattern is not that normally associated with $T = 1$ bands. If the 4874 keV state were $T = 1$, one would expect the dominant decay mode to be an isovector M1 transition. Failing that, the isoscalar E2 transition to the $T = 1$ 6^+ state at 3254 keV should be preferred over the isovector one. The decay pattern therefore favours a $T = 0$ assignment.

The variation with spin of the CED between analogue bands in ^{50}Mn and ^{50}Cr is plotted in Fig. 3(a) as solid up-triangles. We follow the convention of plotting the energy of the state in the higher-Z nucleus minus that of its lower-Z counterpart. The speculative 8^+ and 10^+ states are indicated by dashed lines. A comparison with the nuclei ^{46}V and ^{46}Ti (open down-triangles) from Garrett et al. [17] is also shown, which illustrates the approximate validity of the cross-conjugate symmetry.

Nuclei near the middle of the $f_{7/2}$ shell have enough valence quasi-particles to exhibit collective behaviour such as rotational alignments. It has been shown for the $A = 49$ [1,2] mirror nuclei that the rise in their CED is due to an alignment of a pair of $f_{7/2}$ protons in ^{49}Cr at around $J = 17/2$, with an alignment of a pair of neutrons at the same point in ^{49}Mn. This argument can be made as each nucleus has an odd particle (proton for Manganese-49, neutron for Chromium-49) which has a blocking effect preventing the alignment of protons in ^{49}Mn and neutrons in ^{49}Cr. At a simple level, the resulting reduction in the spatial overlap of the aligned particles causes a decrease in the Coulomb energy if the aligning pair are protons. As protons align in one case and neutrons in the other, this causes a change in the CED between the nuclei as a function of spin. The identification of the $J^{\pi} = 4^+$ and 6^+ $T = 1$ states now provides the opportunity to apply these same arguments to these $A = 50$ nuclei. The experimental data in Fig. 3(a), therefore, suggests that there are more protons aligning in ^{50}Cr than in ^{50}Mn as a function of spin.

In order to gain a deeper understanding of the detailed nuclear structure phenomena taking place, we present here new results from a large-scale shell model calculation for ^{50}Mn. The model, described in Caurier et al. [18] has been extremely successful in this mass region, reproducing accurately many experimentally observed features—including the details of CED variations with spin (e.g., [3,4,8]). The current results come from a calculation using a KB3G interaction in a full fp-space (non-truncated). In order to demonstrate the connection between particle alignments and Coulomb effects, we have calculated the "quasi-alignment" for $f_{7/2}$ proton pairs (see, Bentley et al. [4] for details). Essentially, this quantity reflects the contribution from $f_{7/2}$ proton pairs coupled to $J = 6$, $T = 1$. Fig. 3(b) is a plot of the difference in proton "quasi-alignment" between the two nuclei as a function of spin. If proton alignments decrease the nuclear Coulomb energy, then the experimental CED should have an inverse shape to the alignment-difference plot, and this can be seen to be approximately the case. This supports the suggestion that $f_{7/2}$ protons take part in an alignment process in ^{50}Cr, but not in ^{50}Mn. This leaves open the question of which nucleons dominate the alignment process in the $N = Z$ case.

Simple blocking arguments cannot be applied in order to explain the behaviour of valence nucleons for the $T = 1$ states in these $A = 50$ nuclei, unlike the $A = 49$ mirror pair situation. It, therefore, becomes necessary to refer to theoretical predictions of pairing correlation strengths in order to understand the contribution of the various $T = 1$ nucleon pairs. Recently, shell-model calculations have provided expectation values for correlation strengths of nn, pp and np pairs for lighter $f_{7/2}$ shell nuclei [8]. In Fig. 4(a) we present results from the current work for similar calculations (as described above) for ^{50}Mn and ^{50}Cr. It is apparent from this plot that although the np correlations in ^{50}Mn are strong near the ground state, they steadily weaken with increasing spin while in ^{50}Cr the same is true of the pp and nn correlations. A gradual reduction in correlation strength naturally implies a process in which the pairs change their coupling from $J = 0$ to $0 < J \leqslant 6$—a gradual alignment process. The inference is thus that in ^{50}Mn it is one or more np pairs that recouple in this way, with resulting angular momentum alignment along the axis of rotation, whereas in ^{50}Cr the corresponding effect takes place predominately between pairs of protons. Similar calculations of pairing correlation strengths in ^{46}V and ^{46}Ti have been published by Lenzi et al. [8] and these are shown for comparison purposes in Fig. 4(b). Once again, the cross-conjugate symmetry is evident.

The shell model calculations, therefore, point clearly to a dominance of np-pair correlations in the odd–odd $N = Z$ system at low spins while like-nucleon pairing dominates at low spins in the $N = Z + 2$ system. With increasing excitation energy, the angular momentum is then generated by a gradual alignment of pairs of the dominant type. The experimental data on the CED up to $J^\pi = 6^+$ are entirely consistent with these ideas. Thus it seems that due to our improved understanding of the nature and underlying causes of CED variations between isobaric analogue states, crucial information can be gained on the competition between np-pairs and like-nucleon pairing modes in nuclei near the $N = Z$ line.

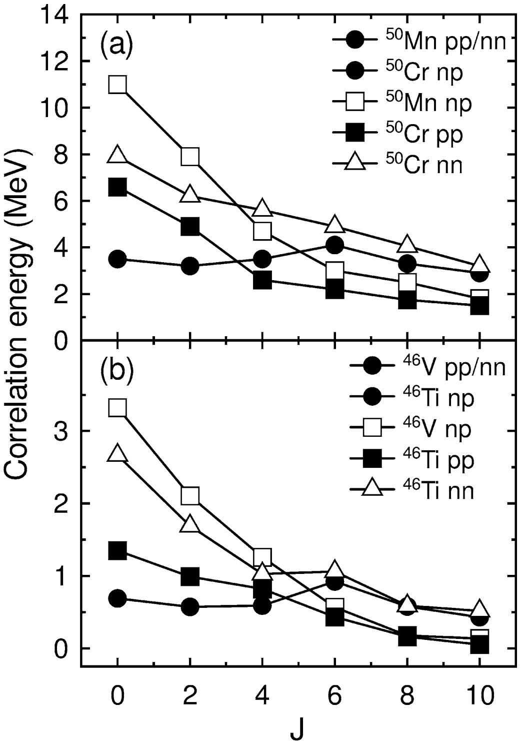

Fig. 4. Pairing correlation energies versus spin for $T = 1$ isobaric analogue states in (a) ^{50}Mn and ^{50}Cr. (b) ^{46}V and ^{46}Ti from Lenzi et al. [8]. Values for ^{50}Mn pp/nn and ^{50}Cr np pairs are identical, as are those for ^{46}V pp/nn and ^{46}Cr np pairs.

In summary, the near-yrast states have been investigated to high spin in the odd–odd $N = Z$ nucleus ^{50}Mn. Recent results [10] extending the $T = 1$ band in ^{50}Fe mean that analogue states in the $A = 50$ triplet have been established to $J^\pi = 6^+$. The variation with spin of the difference in energies between analogue states in ^{50}Mn and ^{50}Cr has been interpreted as due to the start of a rotational alignment of a neutron–proton pair in the $N = Z$ nucleus compared with a proton–proton pair in its $N = Z + 2$ counterpart.

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