GAMMA-RAY SPECTROSCOPY OF HIGH SPIN STATES NEAR $N = Z$ IN THE $f_{7/2}$ SHELL*

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Two pairs of mirror-nuclei, ${}^{49}_{25}$Mn/${}^{49}_{24}$Cr and ${}^{47}_{24}$Cr/${}^{47}_{23}$V, and the odd–odd $N = Z$ nucleus ${}^{46}_{23}$V have been studied up to the $f_{7/2}$-shell band termination states. Differences in energy between isobaric analogue states in these nuclei have been measured and interpreted in terms of Coulomb effects. Through this work, we have shown that Coulomb energies are extremely sensitive to nuclear effects such as particle alignments, band terminations and shape changes. This has allowed us to investigate the extent to which the Coulomb energy can be used as a probe of the nuclear structure.

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1. Introduction

The experimental study of nuclei at high spin around the centre of the $f_{7/2}$ shell has been of considerable interest recently (*e.g.* [1–4]). Full *pf*-shell calculations [5–7] are now available and have shown a remarkable ability to reproduce many experimentally observed features, including those traditionally associated with collective motion. Near the centre of the $f_{7/2}$ shell nuclei are known to have characteristics of deformed rotors (*e.g.* [2,4]), exhibiting effects such as rotational alignments and comparatively large B(E2) values. Such studies in the $f_{7/2}$ shell present a unique opportunity to investigate these phenomena in nuclei with a small valence space and in which the major contribution to the wave-functions of the states originates from one major shell throughout their entire yrast sequences.

Over the last three decades, there has been a considerable amount of effort aimed at understanding the role of Coulomb effects in the structure of nuclei (*e.g.* [8]). In the case of mirror nuclei the work has until recently been limited to attempting to understand the absolute energy difference between the two $T = 1/2$, $Z_>$ and $Z_<$ ground states (higher Z and lower Z respectively). Assuming that the nuclear force is charge-symmetric the absolute difference between the binding energy of the ground states should be due only to Coulomb effects — called the Coulomb Displacement Energy (CDE). Early phenomenological models [9] attempted to estimate the CDE based on calculating the density of the neutron-excess in a one-body nuclear potential. These were found to produce CDEs which were around 6–8% lower than experimental values for a wide range of nuclei. This "Nolen–Schiffer" anomaly remained unresolved following the application of more sophisticated models and a number of possible explanations have been proposed. These include a possible charge-asymmetric component of the nucleon–nucleon interaction, the effect of differences of isospin impurities in the $T = 1/2$ ground states and the Coulomb distortion of the wavefunction of the level occupied by the excess nucleon (the "Thomas–Ehrman" shift). Estimates of the sizes of these effects have been made (*e.g.* [8]) but the size of the discrepancy has not yet been fully explained.

In the last decade, experimental techniques have advanced in the gamma-ray spectroscopy of nuclei near $N = Z$ allowing detailed information on the excited states of mirror nuclei be investigated (*e.g.* [10,11]). In these studies, the differences between energies of excited states of the same spin are measured resulting in a Coulomb energy difference (CED) having first normalized the two ground-state energies. This having been done, the effects contributing to the Nolen–Schiffer anomaly may be expected to cancel out when comparing energies of excited states. A question then arises regarding the extent to which these effects contribute to the differences between

Coulomb energies of excited states and how the CED between these states may yield real information on "conventional" nuclear structure effects. In this presentation we have attempted to address these points by investigating the CED for the high spins states of the mid-$f_{7/2}$ mirror nuclei $^{49}_{25}$Mn/$^{49}_{24}$Cr and $^{47}_{24}$Cr/$^{47}_{23}$V. In addition we report on a comparison of the $T = 1$ analogue states in the odd–odd $N = Z$ nucleus $^{46}_{23}$V$_{23}$ and the neighbouring isobaric analogue nucleus $^{46}_{22}$Ti$_{24}$. The energy differences between these states are interpreted in terms of Coulomb effects.

2. Experimental details

An experiment was performed at the Niels Bohr Institute Tandem-Accelerator Laboratory in which a 500 μg/cm^2 enriched ^{24}Mg target was bombard with a ^{28}Si beam at 87 MeV. The nuclei of interest were populated via the ^{24}Mg(^{28}Si, $2pn$)^{49}Cr, ($p2n$)^{49}Mn, (αp)^{47}V, (αn)^{47}Cr and (αpn)^{46}V reactions. Gamma rays de-exciting the nuclei of interest were measured using the PEX detector system consisting of four Euroball cluster detectors [12]. Evaporated protons and neutrons were detected using two additional arrays — an array of 31 silicon detector elements surrounding the target [13] and a 15-element neutron wall [14] located downstream of the target. In this way, nuclei populated with low fusion-reaction cross sections can be cleanly selected by associating the γ rays with the number and type of evaporated particles. Particle-gated γ-γ coincidence matrices were constructed from which the level schemes were deduced. Further experimental details can be found in O'Leary *et al.* [15] and Bentley *et al.* [16].

3. The mirror nuclei $^{49}_{25}$Mn/$^{49}_{24}$Cr and $^{47}_{24}$Cr/$^{47}_{23}$V

The level schemes for the $A = 49$ and $A = 47$ mirror pairs have been determined in the original work of Cameron *et al.* [10, 11] with significant corrections and additions from this work [15, 16]. Level schemes for all four nuclei have now been confirmed up to the band-terminating state of $J^\pi = (31/2)^-$ — the maximum spin allowed in the isolated $f_{7/2}$ shell. Figure 1 shows one example for the $A = 47$ mirror pair (the $A = 49$ schemes can be found in reference [15]). The extent of the mirror symmetry is clearly evident from these schemes, where both energy levels and feeding patterns in these rotational yrast structures are nearly identical.

The CED for these mirror nuclei can be determined by a simple comparison of the level energies of the same spin. This is shown for the $A = 49$ mirror pair [15] in Fig. 2(a). The most striking feature is the large rise in the CED at around $(21/2)^-$. This has been attributed [10, 15] to the rotational alignment of a pair of $f_{7/2}$ particles, causing a decrease in their spatial

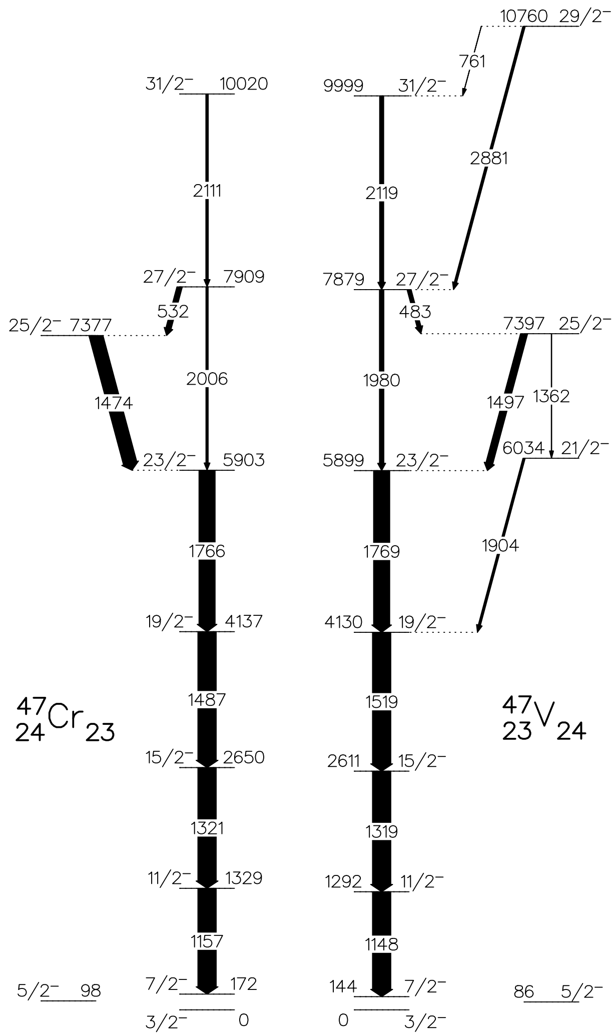

Fig. 1. Energy level scheme deduced from this work for the mirror nuclei ^{47}Cr and ^{47}V. Energies are in keV and the widths of the arrows are proportional to the gamma-ray intensity.

overlap. The blocking effect of the odd particle means that the alignment is due to a pair of protons in ^{49}Cr and neutrons in ^{49}Mn. In the case of ^{49}Cr this causes a corresponding decrease in the Coulomb energy whereas in ^{49}Mn there is no Coulomb effect. These effects cause the rise in the CED. The reduction of the CED at the highest spins is due to the fact that at the non-collective band termination, the angular momentum is generated by a full alignment of *all* of the $f_{7/2}$ valence particles. Thus a full alignment of protons and neutrons occurs for both nuclei, causing an overall reduction in the CED. Thus the CED can be shown to reflect the changes in the structure of the nucleus with increasing spin - from deformed rotational states at low spin, through a rotational alignment of a pair of $f_{7/2}$ particles to a fully aligned band termination at the maximum allowed spin for the $f_{7/2}$ shell of $J^{\pi} = (31/2)^{-}$.

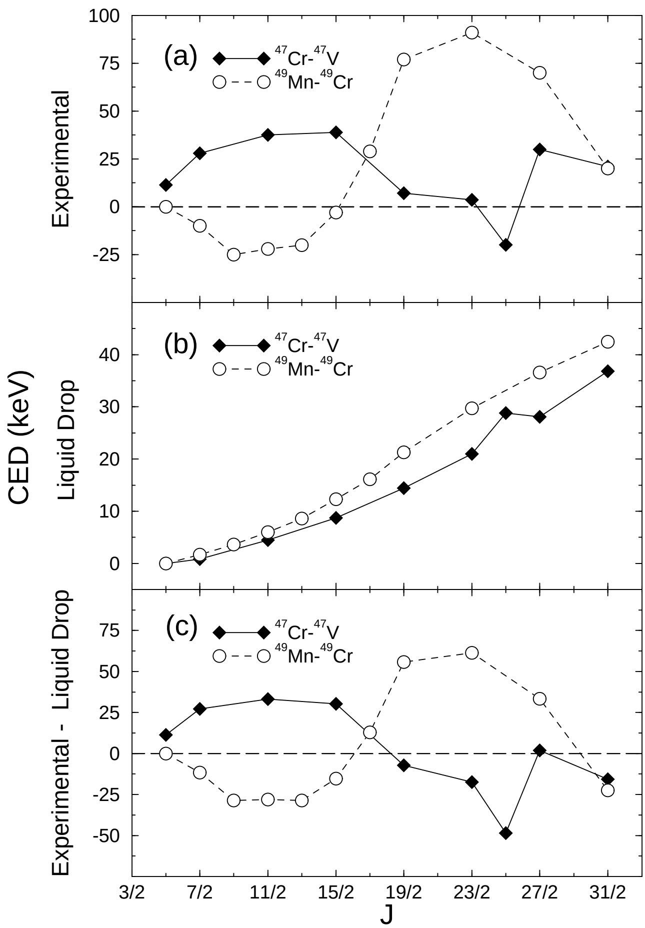

Fig. 2. (a) The experimental Coulomb energy difference as a function of spin for the $A = 49$ and $A = 47$ mirror pairs. The CED is defined as $E_x(Z_>) - E_x(Z_<)$. (b) The calculated effect on the CED from the change in the liquid-drop Coulomb energy due to the reduction in the deformation with increasing spin. (c) The Experimental CEDs as in (a) following subtraction of the liquid-drop effect shown in (b).

The mass-47 mirror pair, $^{47}_{23}V_{24}$ and $^{47}_{24}Cr_{23}$, can be considered to be the cross-conjugate partners of the $A = 49$ mirror pair. In a single-j shell-model picture, cross-conjugate partners (corresponding to a simultaneous exchange of protons for neutrons and particles for holes) will have identical energy levels. Thus the schemes of all four nuclei (two cross-conjugate pairs and two mirror-pairs) would be identical. In reality, the contribution to the wavefunctions from the major shells above and below the $f_{7/2}$ shell results in significant differences between the levels of the cross-conjugate partners. However, the *underlying* changes in the behaviour as a function of spin and the microscopic effects which result (such as valence particle alignments) are expected to be very similar for the yrast structures of the four nuclei.

As the $A = 47$ nuclei are the cross-conjugate partners of the A=49 nuclei (*i.e.* exchanges of protons/neutrons and particles/holes) then the observed Coulomb effects should be very similar, but of the opposite sign. Indeed, if the changes in the CED really reflect only the alignment properties of the valence nucleons, then in a pure $f_{7/2}$ picture the CED plot for the yrast-bands of the A=47 pair as a function of spin should be the inverse of that observed for the A=49 pair. The A=47 CED is shown in Fig. 2(a) along with the A=49 data. These data bear out the cross-conjugate symmetry arguments to some extent as it can be seen that the trends in the CED with spin are generally of the opposite sign for the two mirror pairs. However, the two curves are not"reflections" of each other, as the symmetry arguments proposed above would suggest.

One possible interpretation of this is that for all four of these nuclei, the deformation is expected to reduce as the spin increases — approaching a spherical shape at the band termination. Configuration dependent cranked Nilsson calculations [17] have shown that for all these nuclei the quadrupole deformation changes from around $\epsilon_2 = 0.2$ (prolate) to a nearly spherical shape at the band termination. In a purely classical liquid drop picture, the Coulomb energy of the nucleus will increase. This increase occurs for both members of a mirror pair, though the effect will be larger for the higher-Z nucleus. We have calculated the size of this effect using the predicted deformation parameters and the deformed liquid drop paramaterisation of Larsson [18]. The resulting effect on the CED is shown for both mirror-pairs in Fig. 2(b). Thus we expect a gradual rise in the CED for both pairs, indicating that the observed CED for these nuclei is likely to have two separate and significant components — a macroscopic effect from the shape change and a microscopic effect from the valence proton alignments. The calculated liquid drop effect can now be subtracted from the experimental CED to attempt to isolate the effects associated with microscopic alignments. The result of this, shown in Fig. 2(c), shows that the variation of the "microscopic" CED for the two mirror pairs is now more symmetrical about the CED= 0 axis. This would seem to verify the cross-conjugate symmetry arguments proposed earlier.

A shell-model calculation for the two mirror pairs has been performed using the full pf-shell calculations based on the model described by Caurier *et al.* [7]. It is important to establish how well the shell-model can reproduce the CED effect, as it now appears to be directly related to the spatial correlations and alignments of the valence particles. Thus it provides a more stringent test of the veracity of the shell model results than would normally be possible.

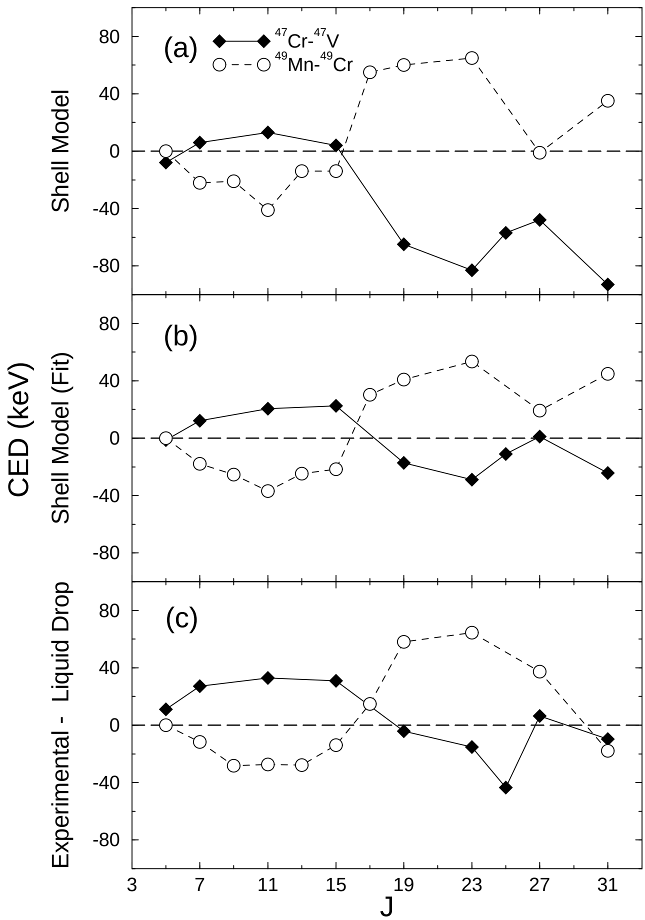

Fig. 3. (a) Results of the shell model where the $f_{7/2}$ Coulomb matrix elements were determined empirically from the nuclei ^{42}Ca and ^{42}Ti. (b) As in (a) except that the four $f_{7/2}$ Coulomb matrix elements are fitted to the CED's for both $A = 47$ and 49 mirror pairs (see text for details). (c) Experimental CEDs for $A = 47$ and 49 corrected for the liquid drop energy associated with the deformation of the core.

To calculate the CED, the Coulomb interaction is added to the effective nuclear force, with specific Coulomb matrix elements defined for the $f_{7/2}$ levels. These matrix elements were determined two ways. Firstly, empirical $f_{7/2}$ matrix elements were derived from the energy level differences between the mirror pair nuclei ${}^{42}_{20}\mathrm{Ca}_{22}$ and ${}^{42}_{22}\mathrm{Ti}_{20}$, and the results using these are shown in Fig. 3(a). For the second technique, the four matrix elements were determined by allowing their values to vary freely to obtain the best correspondence with the experimental data. These results are shown in Fig. 3(b) and the experimental data is shown again for comparison in Fig. 3(c). The results using both sets of matrix elements are extremely gratifying, with only one or two experimental points deviating significantly from the predicted behaviour. Thus the shell-model seems capable of reproducing the Coulomb effects in detail, indicating that the microscopic alignment properties of the high-spin states are well reproduced in the calculations.

4. The odd–odd $N = Z$ nucleus ${}^{46}_{23}\mathrm{V}_{23}$

The degree to which the charge-symmetry of the nuclear force can be observed and utilised at high spin has been demonstrated in the preceding section. An investigation of the more strict condition of charge independence, however, requires study of isobaric analogue states between nuclei *other* than mirror nuclei. One important way in which this can be achieved is through comparison of the $T = 1$ triplet isobaric analogue states in the three nuclei with $T_Z = +1, 0,$ and -1. An example of such a triplet is ${}^{46}_{24}\mathrm{Cr}_{22}$, ${}^{46}_{23}\mathrm{V}_{23}$ and ${}^{46}_{22}\mathrm{Ti}_{24}$. With a charge-independent nuclear force, the $T = 1$ states in the odd–odd $N = Z$ ($T_Z = 0$) system should have identical energy levels to that of the $T = 1$ ground-state bands of the two neighbouring even–even systems. As with mirror nuclei, the small energy differences observed should be due to the Coulomb interaction, which breaks the isospin symmetry. In the two even–even systems, the $T = 1$ ground states are expected to correspond to fully paired systems containing principally (though not exclusively) *nn* and *pp* pairs. This $T = 1$ pairing mode corresponds to like particles in time reversed orbits with their orbital and spin angular momenta anti-parallel. The corresponding $T = 1$ state in the odd–odd system will also contain such $T = 1$ pairs, though in this case the pair condensate will also contain a significant fraction of *np* pairs. This *np*-pairing mode is enhanced in odd–odd $N = Z$ nuclei due to the close proximity of the neutron and proton Fermi levels. The study of *np*-pairing in odd–odd $N = Z$ nuclei is currently of considerable interest (*e.g.* [19, 20]). Here we present extensive new results on ${}^{46}_{23}\mathrm{V}_{23}$ and details of the comparison of the $T = 1$ isobaric analogue states between this nucleus and ${}^{46}_{22}\mathrm{Ti}_{24}$.

The scheme of ^{46}V has been investigated previously by Poletti *et al.* [21]. In that work, states up to $J^{\pi}=9^{+}$ had been established built on a previously established $T=1, J^{\pi}=0^{+}$ ground state. Our new scheme for ^{46}V is shown in Fig. 4, which has now been extended to the $f_{7/2}$ shell band-terminating state at $J^{\pi}=15^{+}$.

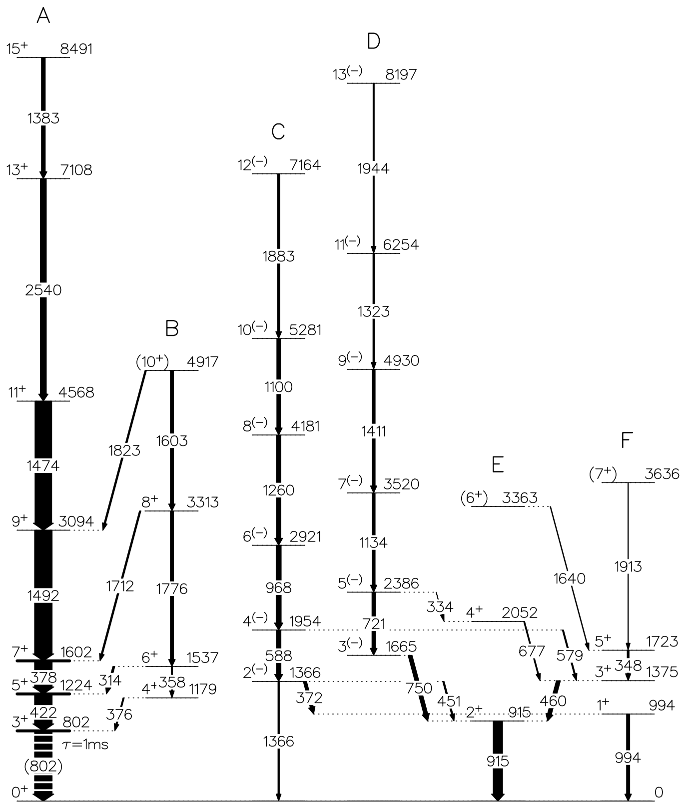

Fig. 4. Energy level scheme deduced from this work for the odd–odd $N=Z$ nucleus $^{46}_{23}V_{23}$. Energies are in keV and the widths of the arrows are proportional to the gamma-ray intensity. Tentative spin/parity assignments are in parentheses.

A striking aspect of the revised level scheme is the existence of two separate strongly populated structures built upon the ground state. The yrast structure **A** demonstrates apparently non-collective behaviour, with irregular level spacings despite the stretched E2 sequence. In contrast, structures **C** and **D** display collective characteristics, with rotational-like level spacings. The parities of bands **C** and **D** (which appear to be signature partner sequences) have not been determined experimentally, though negative parity has been tentatively assigned. It seems likely that these bands correspond to a well-deformed rotational structure built upon a configuration involving an excitation from the $d_{3/2}$ shell. This type of opposite-parity structure is well known in a number of odd-A nuclei in the region (*e.g.* [1, 22]).

These structures are discussed more fully in a forthcoming publication [23], and in this work we concentrate on the sequence of states labelled **E** in Fig. 4. These states have near identical energies (915, 2052 and 3363 keV) to the yrast band in the isobaric analogue nucleus ^{46}Ti (at 889, 2010 and 3299 keV). This structure is therefore assigned as a $T = 1$ configuration and it must therefore be assumed that all the other states in Fig. 4 have T=0, as they possess no equivalents in ^{46}Ti.

As stated above, assuming a charge-independent nuclear force, the $T = 1$ energies in the two nuclei should be identical with the exception of small differences due to Coulomb effects. A plot of the difference in energy — the Coulomb energy difference or CED — between levels of equivalent spin and isospin in the two nuclei is shown in Fig. 5.

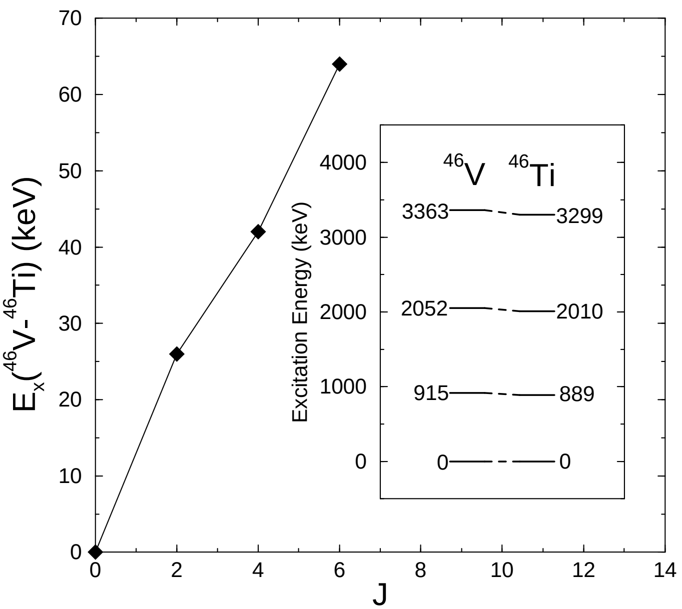

Fig. 5. The difference in energy between the $T = 1$ isobaric analogue states in ^{46}V and ^{46}Ti as a function of angular momentum. The inset shows a comparison of these $T = 1$ energy levels for the two isobars.

We have shown in the previous section how rotational effects coupled to particle alignments can account for the variation of the CED between analogue states as a function of spin. In particular, we have shown previously that an alignment of an $f_{7/2}$ pp pair yields a reduction in the Coulomb energy of the nucleus of around 80 keV. Assuming a rotational structure for ^{46}Ti (which is predicted to be moderately deformed) the first $f_{7/2}$ alignment in ^{46}Ti is predicted [24] to be associated with a *pp* pair, thus causing a reduction in the Coulomb energy. If the rise in the CED shown in Fig. 5 indicates the start of this alignment then the data would seem to imply that in ^{46}V the corresponding $T = 1$ alignment is *not* between a pair of protons. As it is expected that *np*-pairing should play a more significant role in ^{46}V, then one interpretation is that the corresponding alignment in the ^{46}V case is associated with a *np*-pair. The size of the CED effect is consistent with this argument, based on comparisons with the mirror nuclei described above. Thus, it seems that Coulomb effects between analogue states such as this might yield valuable information on the underlying pair structure involved — information which is difficult to access any other way.

Another intriguing feature of band **E** is that E2 transitions between $6^+ \to 4^+$ and $4^+ \to 2^+$ are not observed. Transitions to and from these states occur through the nearby $T = 0$ structures (**C**, **D** and **F**) via strong M1 transitions. This feature is actually not unexpected in odd–odd $N = Z$ nuclei where competing $T = 1$ and $T = 0$ structures are present. This is due to the fact that isovector M1 transitions in self-conjugate nuclei are known to relatively strong [25]. When this effect is coupled to the relatively low B(E2) strength between the $T = 1$ states, this feeding pattern becomes more understandable.

5. Future perspectives

This work, and similar studies elsewhere, has shown that comparisons of isobaric analogue states near $N = Z$ allows the Coulomb energy to be measured which in turn is a sensitive probe of many aspects of nuclear structure. At present these isobaric analogue studies are limited to mirror nuclei ($T = 1/2$ isospin "doublets") and more recently comparison of some members of $T = 1$ isospin triplets. With more sensitive apparatus and the advent of radioactive beam facilities, it may become possible to observe the proton-rich members of the $T = 1$ triplets in these medium mass nuclei. In addition, one should be able to access analogue states in heavier nuclei and possibly of larger isospin.

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