First Observation Of Excited States In The $T = -1$, Odd–Odd Nucleus ^{48}Mn

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Abstract. Gamma decays depopulating excited states in the odd–odd N=Z – 2 nucleus ^{48}Mn have been observed for the first time. The yrast band has been built up from the 4^+ ground state to 13^+, just shy of the expected band termination at 15^+. When compared with its mirror, ^{48}V, the Coulomb energy differences are unlike any other previously measured which, until now, have been dominated by a sudden rotational alignment. Such an alignment is expected to be blocked in these odd-odd nuclei and calculations not only confirm this, but also infer that any Coulomb difference is mostly due to monopole effects.

INTRODUCTION

To date there exists a large body of work devoted to understanding the exchange symmetry between protons and neutrons [1, 2]. Assuming a charge independent nuclear force, the energy differences between states of mirror nuclei arise solely due to Coulomb effects, giving rise to the name Coulomb energy differences, or CED. The relative isolation of nuclei in the $f_{7/2}$ shell provides an ideal arena for the study of such effects and, as such, efforts have been concentrated here. This region is also accessible to full pf shell model calculations and it is therefore important to study these nuclei in order to both test and further improve the calculations.

So far, a number of $T_z = \pm\frac{1}{2}$ pairs have been examined up to band termination – the highest accessible spin – allowing an investigation of the evolution of Coulomb effects with increasing angular momentum [2, 3, 4, 5]. Remarkably, the results can be understood in terms of some quite subtle nuclear structure effects. One such effect has been shown to dominate the CED in all cases to date, that of the alignment of pairs of particles, more specifically the re–coupling of a pair of $f_{7/2}$ protons from $J = 0$ to $J = 6$, the maximum allowed spin in the $f_{7/2}$ shell. In the other member of the mirror pair, the odd proton has a blocking effect and it is a pair of neutrons which align and the Coulomb energy remains the same. This multipole effect, which has been observed across the entire shell, causes a sudden and dramatic change in the CED and full pf shell model calculations have performed very well in predicting these changes.

More recently, this work has been extended to isobaric ($T = 1$) triplets, namely A=46 [6] and A=50 [7]. These represent the largest value of total isospin for which isobaric analogue states have been studied to high spin. Again the CED may be understood in terms of particle alignment. Although the blocking effect in odd mass nuclei favours alignment of the even particle type, it is less evident which particle aligns first in even–even nuclei. However, in the case of the ^{50}Fe/^{50}Cr pair, cranked shell model calculations indicate the first alignment to be a pair of protons (neutrons) in ^{50}Cr (^{50}Fe).

In studying the A=50 pair it became clear that although initial calculations predicted the overall trend of the CED, the quantitative agreement was poor. In order for a more accurate description, the calculations required the inclusion of another term associated with the monopole part of the Coulomb field. Responsible for large displacement energies of the ground state (which for the most part cancel in the CED) the monopole term is relatively small and is therefore

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swamped by the multipole effects. Its contribution, however, becomes more pronounced in pairs of larger difference in Z. For an odd–odd nucleus both proton *and* neutron alignments are expected to be blocked and the monopole effects should be amplified.

The main focus of the present work concerns the $T_z = -1$ nucleus ^{48}Mn. Together with its mirror, ^{48}V [8, 9], it represents the first time an odd–odd pair has been studied and as such it is the first experiment designed to highlight the monopole effects discussed earlier. The level scheme of ^{48}V has been well established [9] up to the expected band terminating state at 15^+. A number of other bands were also observed, including three of unnatural parity. Previous studies of ^{48}Mn revealed a 4^+ ground state through β–decay and an excited proton emitting 0^+ state above 2 MeV [10].

EXPERIMENTAL DETAILS AND RESULTS

^{48}Mn was produced in the inverse reaction ^{40}Ca + ^{10}B at a beam energy of 110 MeV and target thickness 400 μg/cm^2. Recoiling nuclei were selected by the Fragment Mass Analyzer according to their A/Q, and Z identification was provided by an ionisation chamber placed at the focal plane. In this way, mass 48 recoils were selected with a charge state of 16^+, i.e. A/Q = 3. Gamma rays were detected in the Gammasphere array which consisted of 98 HPGe detectors, of which 58 located around 90° were segmented allowing for better determination of Doppler effects for high energy decays.

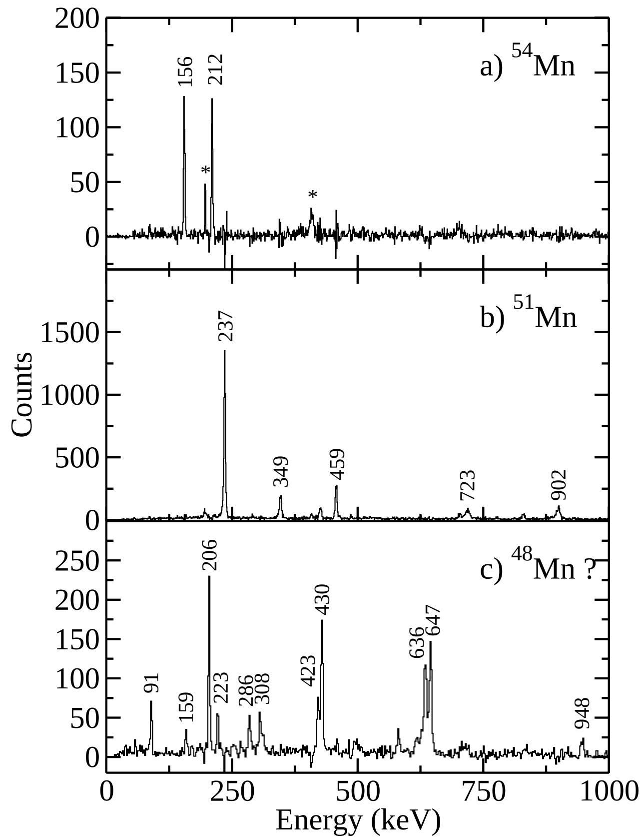

FIGURE 1. Mass gated manganese spectra showing a) ^{54}Mn, the asterisks indicate transitions from ^{54}Fe which have leaked through the Z gate. The dominant contribution, shown in b), is from ^{51}Mn. The spectrum in c) shows transitions in coincidence with a manganese isotope with A/Q = 3 whose mass is less than 51.

An initial examination of the data, in the form of a Z(=25) gated singles spectrum revealed a number of candidates for decays in ^{48}Mn. However, the spectrum also showed a number of γ rays which are known already from ^{51}Mn [4, 8] and ^{54}Mn [11]. These appear in the data due to contaminants in both the beam (^{40}Ar) and target (^{16}O) and pass selection in charge states 17^+ (^{51}Mn) and 18^+ (^{54}Mn), yielding A/Q = 3 in both cases.

In order to unambiguously identify decays from ^{48}Mn, a two–dimensional matrix of γ–ray energy versus ET^2 gated by $Z = 25$ ions was created, whereby E is the total energy of the recoil, as measured in the ionisation chamber, and T is the time–of–flight through the FMA. It may be shown that the value ET^2 is proportional to the mass of the recoiling nucleus and making specific cuts on such a matrix allows for a basic mass selection. This technique has been used to good effect in the analysis of neutron rich nuclei near N=28 [12]. The resulting analysis led to the three distinctly different γ–ray spectra which are shown in Fig. 1. Figure 1a and b contain transitions from the previously known nuclei, ^{54}Mn and ^{51}Mn, respectively. Figure 1c contains previously unidentified transitions corresponding to the ET^2 expected for ^{48}Mn and which are similar in energy to those in ^{48}V. Thus we present the first unambiguous identification of γ rays in ^{48}Mn.

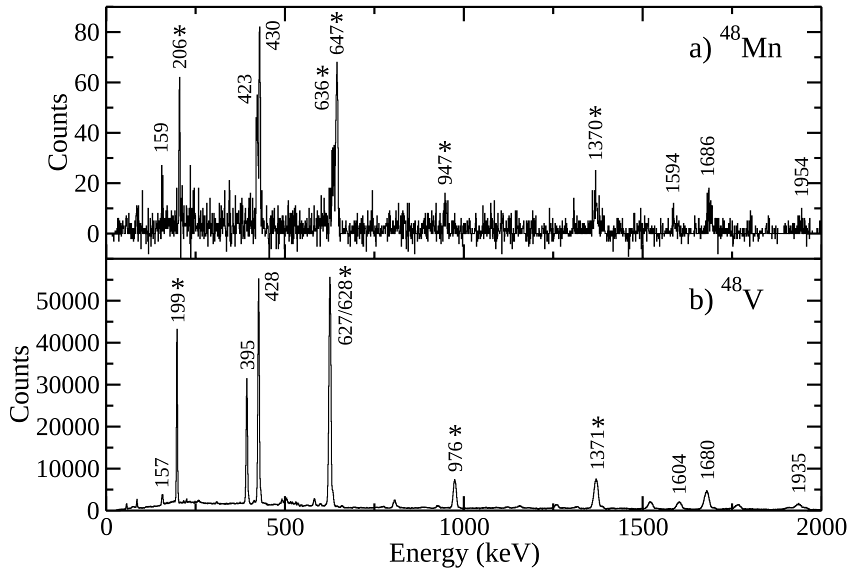

FIGURE 2. (a) A sum of γ–ray spectra for ^{48}Mn, measured in coincidence with the 206, 636, 647, 947 and 1370 keV transitions (marked *). (b) A spectrum similar to (a) but measured in coincidence with the equivalent transitions in ^{48}V.

Data were also sorted into a γ–γ matrix for events in coincidence with a Z=25 recoil. Gates placed on energies obtained from the Z=25, A=48 singles spectrum revealed a sequence of transitions similar in energy and intensity to those in ^{48}V. Figure 2 shows two spectra which are the result of a sum of gates for transitions marked with an asterisk in a) ^{48}Mn and b) ^{48}V. The correspondence of relative energies and intensities lends further weight to the assignment of these transitions to ^{48}Mn. The level scheme deduced in this work, along with a partial scheme for ^{48}V taken from [9], is shown in Fig. 3.

The strongly populated doublet in ^{48}V at ∼627 keV ($6^+ \rightarrow 4^+$ and $7^+ \rightarrow 6^+$) is not 'mirrored' in ^{48}Mn, but is replaced with γ rays at energies 636 keV and 647 keV respectively. Their position within the decay scheme was therefore based on coincidence analysis. The 423 keV ($9^+ \rightarrow 8^+$) and 430 keV ($5^+ \rightarrow 4^+$) transitions in ^{48}Mn formed their own doublet and were also placed due to coincidence relationships alone, their mirrors in ^{48}V being 395 and 428 keV respectively.

In addition to the $f_{7/2}$ band, other more weakly populated γ rays were observed in the singles spectrum (Fig. 1c). Further analysis of the γ–γ matrix showed a sequence of γ rays which were not in coincidence with the main structure. However, the energies and relative intensities bear a striking resemblance to a negative parity band in ^{48}V, labelled 'K^π=1^-' in the work of Brandolini *et al.* [9]. There is also evidence for the mirrors of the two lowest states in the band in ^{48}V labelled 'K^π=1^+', which link the negative parity band to the ground state.

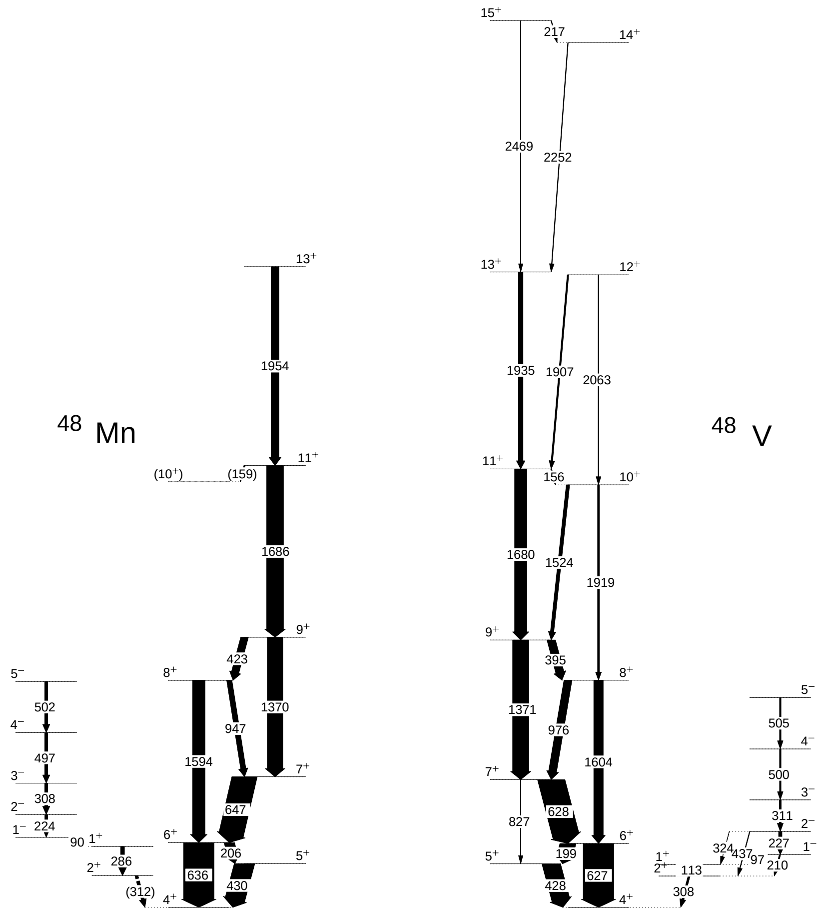

FIGURE 3. The level scheme obtained from the present work for ^{48}Mn alongside a partial scheme for its mirror, ^{48}V, [9].

DISCUSSION

The Coulomb energy difference (CED) for the A=48 pair is shown in Fig. 4a. All previous CEDs for both $T=\frac{1}{2}$ and T=1 nuclei have been interpreted mostly in terms of a rotational alignment which manifests itself in the form of a dramatic change in the CED of around 100 keV. In the case of the odd–odd, A=48 pair, all of the first alignments are expected to be blocked and this is borne out in the CED whose magnitude never exceeds 55 keV. Despite the fact that this CED bears no resemblance to any other previously measured CED, the calculations performed in the full pf shell show remarkable agreement (Fig. 4a).

The two multipole contributions, V_B, representing an isospin non–conserving part of the nucleon–nucleon interaction [13] and V_{CM}, related to Coulomb effects associated with the re–coupling of proton angular momenta as discussed earlier, are plotted individually in Fig. 4b. In this case they are not enough to reproduce even the direction of the CED. The particle/hole occupation of the $f_{7/2}$ orbital is $\pi(f_{7/2})^{-3} \otimes \nu(f_{7/2})^{3}$ for ^{48}Mn and $\pi(f_{7/2})^{3} \otimes \nu(f_{7/2})^{-3}$ for ^{48}V. Assuming a pure j–shell, the active valence protons are three particles in ^{48}V and three *holes* in ^{48}Mn. Thus one may expect that any multipole effects will cancel out, contributing little to the CED and this is indeed borne out by the calculations.

The overall CED is only reproduced theoretically via the inclusion of V_{Cm}, the monopole contribution, shown together with the two multipole contributions in Fig. 4b. Described in detail by Lenzi *et al.* [7], the monopole effect originates due to the difference in radii of the f and p orbits, the latter being larger, and their relative occupations which change with increasing spin. As first highlighted in Ref. [2] with regard to the A=47 [2] and A=49 [3] mirror pairs, band termination is generated by a full alignment of all particles in the $f_{7/2}$ orbital and thus one would expect

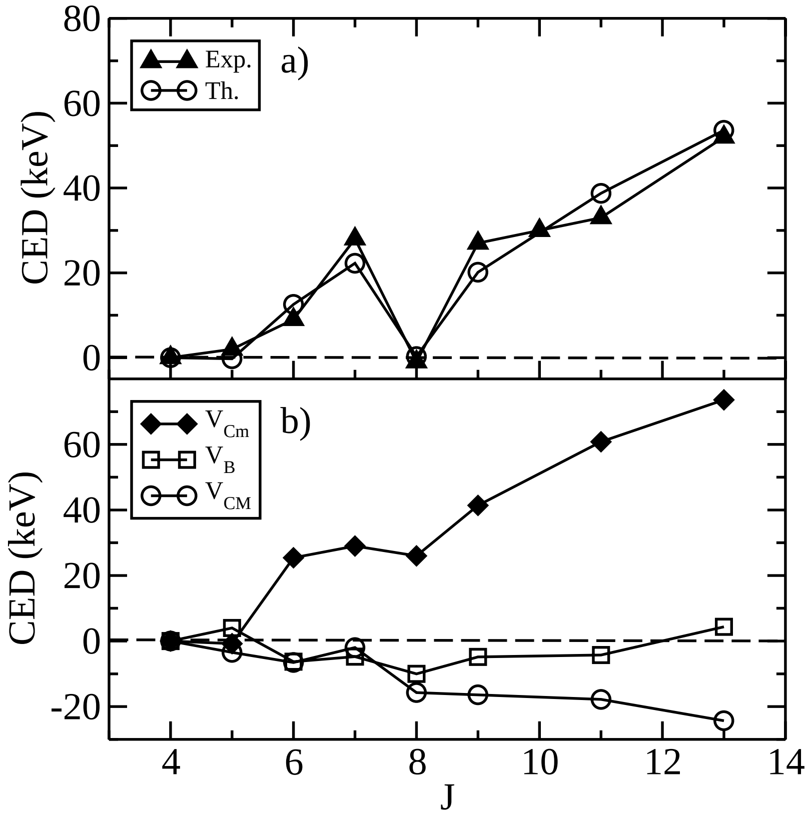

FIGURE 4. The experimental CED obtained from this work shown together with the full pf shell model results in a). Below, in b), are the separate components: V_B and V_{CM}, the two multipole contributions and V_{Cm}, which represents the monopole part of the Coulomb field.

the mean radius and shape of the nucleus to change with spin. In general this equates to an overall rise in the CED, since for the high Z member the increase in Coulomb energy is greater and the CED is always calculated as $E_J(high\,Z) - E_J(low\,Z)$. In Fig. 4b, V_{Cm} does indeed show a gradual rise of around 80 keV and this is the first time evidence of monopole effects has been so clearly extracted from the data.

As yet we have no physical explanation for the sudden, but relatively small, dip which occurs at around 8^+. The calculations give no clear indication as to the cause and it will be interesting to see whether this occurs for other odd–odd, T_Z=–1 nuclei in this region.

CONCLUSION

The level scheme for the T_Z=–1, odd–odd nucleus ^{48}Mn has been built up to a J^π of 13^+ in the yrast band. A second band of unnatural parity was also populated, although with less intensity. The resulting CED, when compared to its mirror ^{48}V, is unlike any other previously measured for either $T=\frac{1}{2}$ or T=1 pairs. The particle alignment which has so dominated all CED studies to date is conspicuous by its absence in this case. Calculations indicate that the most significant contribution to the CED arises due to the monopole part of the Coulomb field indicating a change in the size and/or deformation of the nucleus between the ground and band terminating states. It is now clear that the role of Coulomb energy differences as a probe of nuclear structure is expanding, from investigating rotational alignments to the evolution of nuclear radii as a function of spin.

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