Isospin Symmetry of Odd-Odd Mirror Nuclei: Identification of Excited States in $N = Z - 2$ ^{48}Mn

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Excited states have been observed in the $N = Z - 2$ odd-odd nucleus ^{48}Mn for the first time. Through comparison with the structure of ^{48}V, a first high-spin study of an odd-odd mirror pair has been achieved. Differences between the $T = 1$ analogue states in this pair have been interpreted in terms of Coulomb effects, with the aid of shell-model calculations in the full pf valence space. Unlike other mirror pairs, the energy differences have been interpreted almost *entirely* as due to a monopole effect associated with smooth changes in radius (or deformation) as a function of angular momentum. In addition, the large energy shift between analogue negative-parity states is interpreted in terms of the *electromagnetic* spin-orbit interaction in nuclei.

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The fact that the attractive nuclear force acting between all neutrons and protons is approximately charge symmetric yields some startling and beautiful symmetries in nuclear behavior (e.g., [1]). The classic example is mirror symmetry, where two nuclei with interchanged numbers of protons and neutrons exhibit near-identical energy-level schemes. Formally, this neutron-proton exchange symmetry is described by the use of the isospin quantum number, T, and its corresponding projection quantum number, $T_z = (N - Z)/2$, where, in general, the low-lying (yrast) structures of a nucleus will have $T = |T_z|$. For example, for an odd-A mirror pair, differing only through the exchange of one proton for one neutron, we have $T_z = \pm\frac{1}{2}$ and the low-lying states will have $T = \frac{1}{2}$ in both nuclei. In the absence of Coulomb effects, or other isospin nonconserving phenomena, these two sets of analogue states will be degenerate in energy.

The Coulomb interaction lifts this degeneracy, of course, and energy shifts result. However, the underlying spatial symmetry of the wave functions of these analogue states is generally preserved, and the resulting energy differences can be interpreted in terms of Coulomb phenomena. The long-range and well-understood Coulomb force thus has the potential to provide an extremely sensitive probe of spatial correlations and distributions of the protons in the nucleus. Over the last decade, experimental advances have allowed for the study of the proton-rich members of mirror pairs in the $A \sim 40$–60 region—the pf shell (e.g., see [2–6] and references therein). Fortuitously, one of the most successful nuclear models—the large scale pf shell model [7]—is now able to perform calculations in the whole pf shell, and has been applied to model Coulomb effects (e.g., [3,8,9]). The differences in excitation energy [mirror energy differences (MED)] between the analogue states have been shown to be remarkably sensitive to nuclear structure effects and, through detailed comparison with the shell-model results, can now be interpreted with *quantitative* reliability.

Mirror-pair spectroscopy in this region has so far been restricted to odd-A $T_z = \pm\frac{1}{2}$ (e.g., [2–5]) or even-even $T_z = \pm 1$ mirror pairs (e.g., [8,10]). In each case, the dominant Coulomb effect observed is a multipole effect associated with the angular-momentum recoupling of pairs of $f_{7/2}$ protons as a function of angular momentum. As the nuclear angular momentum increases, the time-reversed coupling of $f_{7/2}$ proton pairs is broken and the spatial overlap of the proton pair reduces, yielding a reduction in the Coulomb energy. This contributes a major component to the MED in mirror pairs. The systematic study of MED in this region has also begun to reveal the need to account for other more subtle phenomena, such as the bulk Coulomb effect of the changing nuclear radius and/or deformation as a function of angular momentum [8,9]. There is also the need to include an additional isospin nonconserving component for $J = 2$ couplings in the shell model—the so-called $J = 2$ *anomaly* [9,11]. In this Letter, we report on an analysis of the MED for the odd-odd $T = 1$ mirror pair ^{48}Mn/^{48}V at high spin—the first detailed spectroscopy of *any* odd-odd nucleus with $A > 40$ and $N - Z \geq 2$. The MED behavior is unlike any other observed in this region and, uniquely, is interpreted almost entirely in terms of a subtle shrinking of the nuclear radius as a function of angular momentum. In addition, the MED have been analyzed for analogue negative-parity states, and provide evidence for the influence of the *electromagnetic* spin-orbit effect.

The experiment was performed at the ATLAS facility of the Argonne National Laboratory, where a beam of 110 MeV ^{40}Ca bombarded a 0.4 mg/cm^2 ^{10}B target. The nuclei ^{48}Mn or ^{48}V were produced via the evaporation of two neutrons or protons, respectively. The γ rays were detected with the Gammasphere array, which comprised 98 large-volume Compton-suppressed Ge detectors. The cross section leading to ^{48}Mn is expected to be a few tens of microbarns (e.g., [8,10]), a factor of $\sim 10^4$ weaker than the expected intensity of the mirror, ^{48}V, and thus unique identification of the recoils is essential. The recoiling nuclei were analyzed using the Fragment Mass Analyzer—a zero-degree recoil-mass spectrometer that provides dispersion in A/Q (Q = atomic charge state) and separates recoils from beam particles. Z identification is achieved using a split-anode isobutane-filled ionization chamber beyond the focal plane. For a given set of isobars the different Z's can be separated and identified in a two-dimensional $\Delta E - E$ plot (energy loss in the first section versus total energy). In the experiment, $A/Q \sim 3.0$ was selected through both offline analysis and use of physical slits before the focal plane: this corresponds to selection of $A/Q = 48/16$.

Figure 1 shows γ-ray spectra following application of 2D windows (gates) on the $\Delta E - E$ plot. Figure 1(c) gives the result of the gate corresponding to V ($Z = 23$) recoils, which, as expected, is completely dominated by γ rays from ^{48}V [12]. The corresponding $Z = 25$ (Mn) spectrum, in Fig. 1(a), should therefore contain ^{48}Mn. However, the strongest peaks correspond to ^{51}Mn—created by a reaction with ^{16}O contamination in the target and appearing in the data due to an $A/Q = 51/17 = 3.0$ charge-state ambiguity. Weak ^{40}Ar contamination in the beam also led to contamination in the same spectrum from ^{54}Mn. In order to remove these, an analysis of total energy E and time of flight T was undertaken. For a given flight path, $A \propto ET^2$, and so an ET^2 analysis can be used to discriminate between the $\Delta A = 3$ charge-state ambiguities (e.g., [13]). Figure 1(b) shows a Mn-gated spectrum with an additional (background-subtracted) cut on ET^2 at the value expected for $A = 48$. A small contamination from ^{48}Cr has also been subtracted from this spectrum. All the charge-state ambiguities have clearly been removed, and Fig. 1(b) now contains a pure spectrum of ^{48}Mn. A comparison with the spectrum of ^{48}V in Fig. 1(c) reveals the expected mirror symmetry.

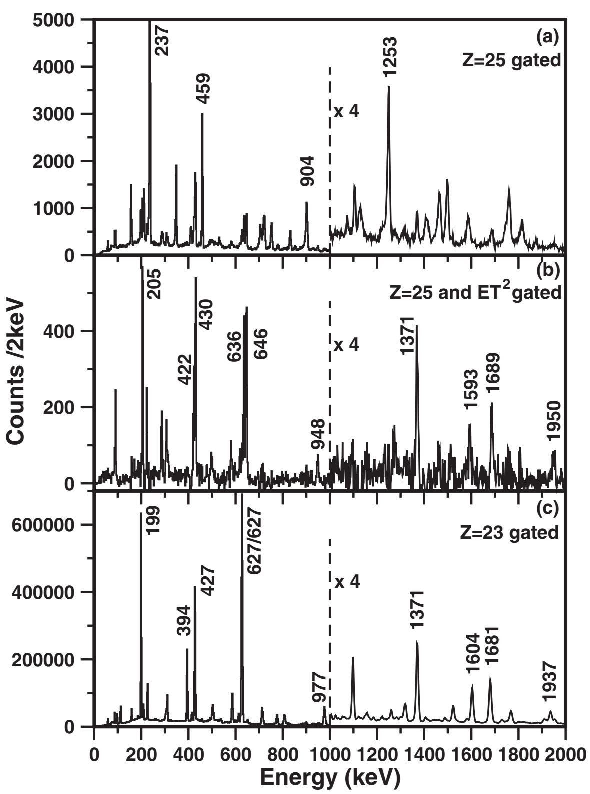

FIG. 1. Gamma-ray spectra gated by different regions (Z's) of the ion chamber spectrum and requiring $A/Q \sim 3.0$. (a) A spectrum requiring $Z = 25$. (b) Same as (a) but with a cut on ET^2 (see text). (c) A spectrum requiring $Z = 23$. The marked γ rays belong to ^{51}Mn in (a), ^{48}Mn in (b), and ^{48}V in (c).

A partial energy-level scheme of ^{48}V, based on Ref. [12], is shown in Fig. 2, along with the new scheme for ^{48}Mn. This was deduced by identifying the γ rays from Fig. 1(b) and confirming their ordering through a coincidence analysis using an $E_\gamma - E_\gamma$ matrix created with the condition of $Z = 25$. Typical resulting spectra for both the positive- and negative-parity sequences are shown in Figs. 3(a)–3(d). Spin assignments for the new states were made, in part, following a γ-ray angular anisotropy analysis. For the intense transitions in the yrast sequence of ^{48}Mn, anisotropy ratios were measured to be consistent with those of the equivalent transitions in ^{48}V, and the multipolarities were thus taken to be the same. For the weaker negative-parity structures the spins (as well as the ordering of some of the levels) are proposed on the basis of mirror-symmetry arguments.

The main positive-parity sequence in ^{48}Mn is observed up to $J^\pi = 13^+$—two units of spin short of the $f_{7/2}$ terminating state: the mirror symmetry with ^{48}V is evident through comparison of the schemes in Fig. 2. The MED for the positive-parity structure, defined as $E_x(J)_{\text{Mn}} - E_x(J)_{\text{V}}$, is found in Fig. 4(a) (solid squares). Also shown is the result of a full pf shell-model calculation based on the ANTOINE code [7] with Coulomb effects determined by the method described by Zuker *et al.* [9]. In this model, the *multipole* Coulomb effects associated with recoupling of proton pairs are accounted for by the inclusion of Coulomb matrix elements calculated in a harmonic oscillator basis, along with an isovector isospin nonconserving (INC) contribution for $J = 2$ couplings. This latter contribution has been shown to be essential for a complete description of MED in this region [9,11]. Another important effect is a monopole bulk Coulomb effect associated with changes in rms radius as a function of angular momentum [8,9]. In general it is found that the radius reduces slightly with

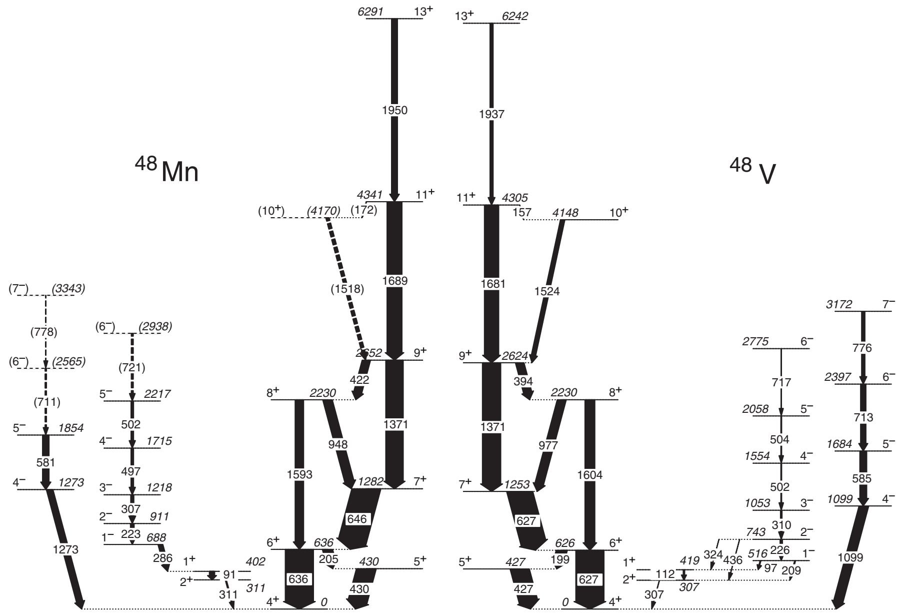

FIG. 2. The level scheme of ^{48}Mn deduced in this work and a partial level scheme of ^{48}V (established in Ref. [12]). The γ ray and excitation energies are in keV, and the widths of the arrows are proportional to relative intensity of the transitions.

increasing spin, resulting in an increase in the MED. In Refs. [8,9] this is taken to be proportional to the changing occupancy of the $p_{3/2}$ orbital (compared with $f_{7/2}$) as the $l = 1$ orbit is expected to have a larger radius. This *radial* effect can also be seen as an indication of changing deformation along the yrast line [3,6]. Nuclei in the middle of the $f_{7/2}$ shell are known to exhibit strong deformation near the ground state, reducing to a near-spherical shape as the highest spins are approached [3]. This yields a similar increase in the MED. The multipole and radial contributions are compared in Fig. 4(b) and combine to form the dominant component of the complete shell-model result of Fig. 4(a). Using the formalism of Ref. [9], the radial and $J = 2$ INC components were calculated with strength parameters $a_m = 400$ keV and $\beta_1 = 100$ keV, respectively. For completeness, the calculation also includes contributions from single-particle shifts (both Coulomb and electromagnetic spin-orbit effects—see, for example, Refs. [9,14]). These latter contributions are small, typically <5 keV. The overall agreement between the data and the model is extremely good.

In order to understand the behavior of the MED in this case, we consider a single-j shell scenario, where only $f_{7/2}$ configurations are allowed. In this case the five $f_{7/2}$ protons of ^{48}Mn can be viewed as three proton holes, and so the configuration is $\pi(f_{7/2})^{-3} \otimes \nu(f_{7/2})^3$. For the mirror nucleus, the configuration is the same but with protons swapped for neutrons. Thus, in this case, both nuclei have the same number of *active* protons, which will recouple identically with increasing spin. Hence, the multipole component of the MED should be zero, and the only component remaining would be from any bulk Coulomb effects. The calculation in Fig. 4(b) bears this out beautifully: even in the full pf valence space, the calculation reveals only a small multipole component (tens of keV in magnitude), which, unlike any other case studied, has the opposite trend to the data. The radial term, indicating the reduction in deformation or radius with increasing angular momentum, is the only positive component: the model prediction would fail completely without it. In no other

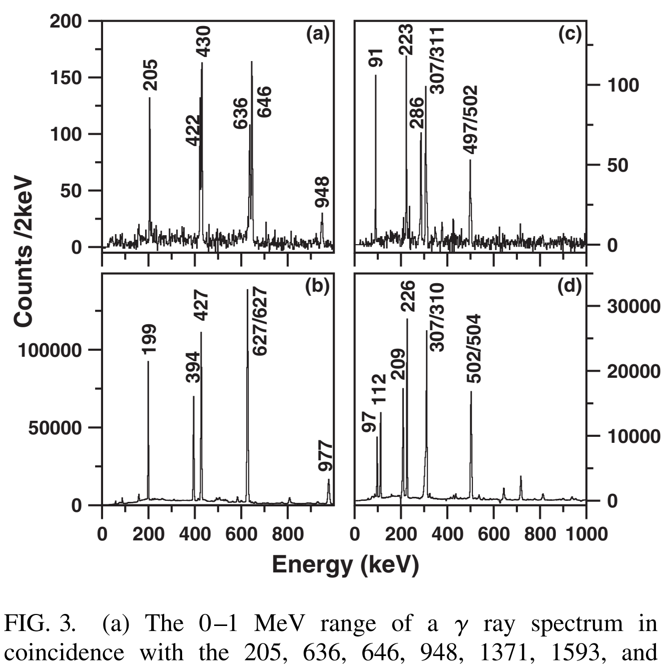

FIG. 3. (a) The 0–1 MeV range of a γ ray spectrum in coincidence with the 205, 636, 646, 948, 1371, 1593, and 1689 keV transitions in the ground-state sequence of ^{48}Mn. (c) γ rays in coincidence with the 223, 307, 497, and 502 keV transitions in the $J^{\pi} = 1^-$ sequence of ^{48}Mn. (b) and (d) are equivalent spectra to (a) and (c) for ^{48}V using analogue conditions.

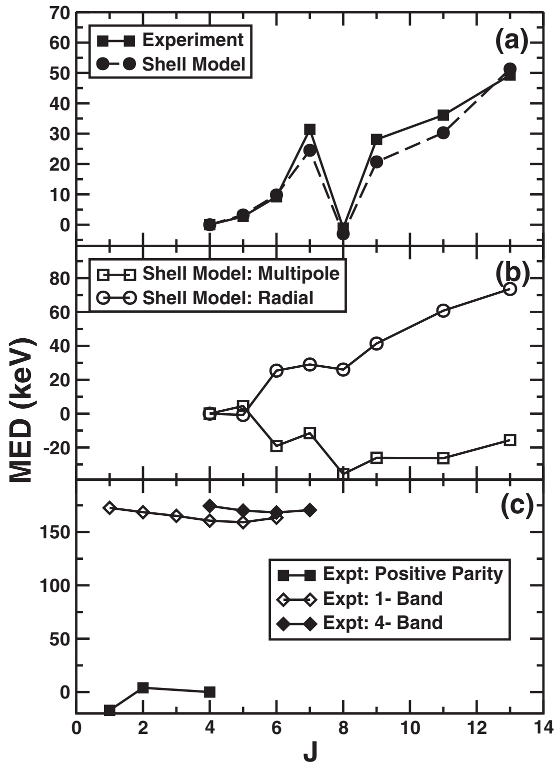

FIG. 4. Mirror energy differences (MED) for the $T = 1$ states of ^{48}Mn/^{48}V. (a) The experimental MED, along with the predictions of the shell model, for the positive-parity states. (b) The calculated multipole and radial contributions to the MED—see text for details. (c) The MED for the negative-parity structures based on the $J^{\pi} = 1^{-}$, 4^{-} states and the MED for the nonyrast positive-parity states into which they feed.

case has the trend of the MED been shown to be almost *entirely* attributable to this subtle radial effect.

It is also of interest to consider the analogue sequences based on the $J^{\pi} = 1^{-}$ and 4^{-} states (see Fig. 2). Following Brandolini *et al.* [12], these states in ^{48}V are formed by a proton excitation from $d_{3/2}$ to $f_{7/2}$. Considering the two Nilsson orbitals involved, the odd $f_{7/2}$ particle and $d_{3/2}$ hole can couple together to give states with $J^{\pi}(= K^{\pi}) = 1^{-}$ and 4^{-}. The analogue excitation in ^{48}Mn would involve a neutron. The MED for these structures is given in Fig. 4(c), along with that of the $J^{\pi} = 1^{+}$, 2^{+} states into which they feed. It is gratifying to observe that the MED for the $J^{\pi} = 1^{-}$ and 4^{-} states are identical to within 1–2 keV: this is expected if the same basic excitation is involved for each state. Of course, for such a single-particle excitation, large energy shifts would be expected associated with differences in single-particle splitting for proton and neutron orbitals. One aspect of this is the electromagnetic spin-orbit interaction (EMSO), introduced in Ref. [15] and first identified in MED data by Ekman *et al.* [14] for the $A = 35$ mirror pair. The EMSO effect contributes significantly to MED when there is a pure single-particle excitation and when the two orbitals involved have opposite spin-orbit couplings. The excitation here from $d_{3/2}$ $(l - s)$ to $f_{7/2}$ $(l + s)$ meets these criteria, and a simple calculation based on a uniformly charged sphere [15] yields a contribution to the MED of $+220$ keV, compared with the experimental shift $\sim +173$ keV. As with the recent other examples in the region (e.g., [14,16]), the EMSO effect accounts for a sizable fraction of the experimental MED, even though it is not expected to be the only significant contribution to the single-particle shift.

In summary, high-spin MED have been analyzed for the odd-odd mirror pair ^{48}Mn/^{48}V and interpreted in terms of Coulomb and magnetic phenomena. Despite the obvious restrictions placed on the shell model by limits on the valence space, and hence the need to assume a significant inert core, the full-pf shell model gives a remarkably accurate state-by-state account of the spin dependence of energy differences throughout the entire yrast sequence. The comparison of these predictions with the data has also enabled the MED trend of the positive-parity states to be interpreted in terms of a subtle shrinking of the nuclear radius as a function of increasing spin. In addition, the differences in excitation energy of the negative-parity states provide further evidence for the influence of the electromagnetic spin-orbit interaction.

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