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Mirror symmetry at high spin in ^{51}Fe and ^{51}Mn

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Gamma decays from excited states in the $T_z = -\frac{1}{2}$ nucleus ^{51}Fe have been observed for the first time. The differences in excitation energies as compared with those of the mirror partner, ^{51}Mn, have been interpreted in terms of Coulomb effects and the resulting Coulomb energy differences (CED) can be understood intuitively in terms of particle-alignment effects. A new CED effect has been observed, in which different CED trends have been measured for each signature of the rotational structures that characterize these mid-$f_{7/2}$ shell nuclei. Large-scale fp-shell model calculations have been used to compute the trends of the CED as a function of spin. The result of comparing these calculations with the data demonstrates an ability to reproduce the fine details of the Coulomb effects with a precision far greater than has been previously achieved.

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Gamma-ray spectroscopy of high spin states in mirror nuclei has been revitalized in recent years through the development of large gamma-ray spectrometers. Such spectrometers, especially when coupled to ancillary devices for the selection of low cross-section channels from fusion-evaporation reactions, have yielded a wealth of new information on high spin states in $N=Z$ nuclei (e.g., [1–4]) and proton-rich nuclei (e.g., [3,5,6]) in the $f_{7/2}$ shell. This shell is unique as it remains the only region in which these exotic nuclei have been studied experimentally up to the maximum spin available in the configuration valence space (the band termination). Furthermore, the relative isolation of the shell means that the wave functions of the nuclear states are dominated by contributions from one major shell only. This is particularly true at the highest spins, where the wave functions become completely dominated by $f_{7/2}$ components [7]. At intermediate and low spins, however, contributions from the higher lying fp orbitals become more important. The advent of large-scale fp-shell model calculations (e.g., [7–9]) has successfully addressed this and has provided us with a remarkably accurate theoretical representation of excitation energies and electromagnetic properties of such nuclei in the upper half of the shell.

In recent work [5,6] we have investigated high spin states of the $T=\frac{1}{2}$ isospin doublet mirror nuclei $^{49}_{25}$Mn/$^{49}_{24}$Cr and $^{47}_{24}$Cr/$^{47}_{23}$V. States up to the band terminating state ($J^{\pi}=\frac{31}{2}^{-}$) were observed and the level schemes of the $T_z=\pm\frac{1}{2}$ members of each mirror pair were found to be virtually identical—as expected if the charge symmetry of the nucleon-nucleon interaction is assumed. The Coulomb interaction breaks the isospin symmetry and small differences in excitation energy between states of the same spin in the two members of the pair can generally be interpreted in terms of Coulomb effects. The resulting Coulomb energy differences (CED) were analyzed [5,6] as a function of spin and found to be extremely sensitive to both microscopic and macroscopic nuclear structure effects. These nuclei are close to the $N=Z$ midshell nucleus ^{48}Cr, where long-range correlations between the eight $f_{7/2}$ valence nucleons outside the ^{40}Ca closed shell give rise to a significant quadrupole deformation and rotor-like characteristics. Such deformation and rotation effects were found to influence the CED strongly. For example, the trends in the Coulomb energy as a function of spin were understood qualitatively in terms of changes in the spatial behavior of the valence nucleons due to rotational alignments [10,11] and the evolution towards a fully aligned noncollective band termination [5]. The resulting shape change from a deformed prolate to spherical system with increasing spin was also found to influence the CED [6]. Large-scale fp-shell model calculations were used to model the Coulomb effects and it was found that the calculations reproduced the general trends of the CED as a function of spin when empirical Coulomb matrix elements were used for the $f_{7/2}$ protons [6]. These matrix elements, as would be expected, decreased systematically with increasing angular mo-

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mentum coupling ($J=0$ to $J=6$). A good *quantitative* agreement, however, required the use of a different set of Coulomb matrix elements which did not show this property and were therefore somewhat unphysical.

Over the last three decades a considerable amount of effort has been devoted to trying to understand Coulomb effects, and in particular understanding the Coulomb displacement energy (CDE)—the absolute binding energy difference between the ground states of isobaric multiplets (such as $T_z=\pm\frac{1}{2}$ mirror nuclei). Early phenomenological models [12] could only account for 90–95% of the experimental CDE for these $T=\frac{1}{2}$ mirror nuclei—a discrepancy amounting to several hundred keV (the ''Nolen-Schiffer'' anomaly [12]). Other effects have been considered (see, e.g., [13]) such as isospin impurities, core polarization due to the odd particle, and the Coulomb distortion of the wave function of the odd particle. Nevertheless, even taking into account these effects, the Nolen-Schiffer anomaly could not be resolved if a charge symmetric interaction is assumed. Given these difficulties, it seems rather surprising that the measured CED (which is usually less than 100 keV and normally a few tens of keV) can be interpreted and understood in terms of simple and intuitive nuclear structure arguments involving subtle effects such as rotational alignments and shape changes. It is therefore of considerable interest to investigate these effects further and to examine the extent to which these Coulomb effects can be used as a sensitive probe of detailed nuclear structure. In this Rapid Communication we report on the recent observation of high spin states up to the band termination in the nucleus ${}^{51}_{26}$Fe, the mirror nucleus of ${}^{51}_{25}$Mn. These excited states have also been reported at the same time in an independent study [14]. This is the heaviest mirror-pair system in which such high spin states have been observed. The CED will be discussed and compared with the large-scale fp shell model calculations.

The experiment was performed at the ATLAS facility at the Argonne National Laboratory using a 95 MeV ^{32}S beam impinging on a 500 μg cm^{-2} self-supporting ^{24}Mg target. Gamma rays were detected using the GAMMASPHERE spectrometer array in a configuration consisting of 101 Compton-suppressed HpGe gamma-ray spectrometers. The mirror nuclei ^{51}Mn and ^{51}Fe were populated through the αp and αn reaction channels with estimated cross sections of 7 mb and 0.3 mb, respectively. High-fold ($\geqslant 3$) gamma-ray coincidences were recorded and the data were sorted into a RADWARE gamma-ray cube with the subsequent analysis performed using the LEVIT8R gamma-ray analysis package [15].

A spectrum of ^{51}Mn was identified using double gates on the known transitions [16] in the yrast band of this nucleus. A typical spectrum is shown in Fig. 1(a) which is the result of a sequence of double gates including the 237 keV $\frac{7}{2}^- \rightarrow \frac{5}{2}^-$ transition which feeds the ground state of ^{51}Mn [see Fig. 2(a)]. No gamma decays in ^{51}Fe have been previously observed, although a state with excitation energy 262 ± 6 keV had been observed in a study of the ^{54}Fe(^{3}He,^{6}He) reaction [17]. It was assumed that this was the ''mirror'' state of the 237 keV $\frac{7}{2}^-$ first excited state in ^{51}Mn. In order to search for the gamma-ray transitions in ^{51}Fe, a two dimen-

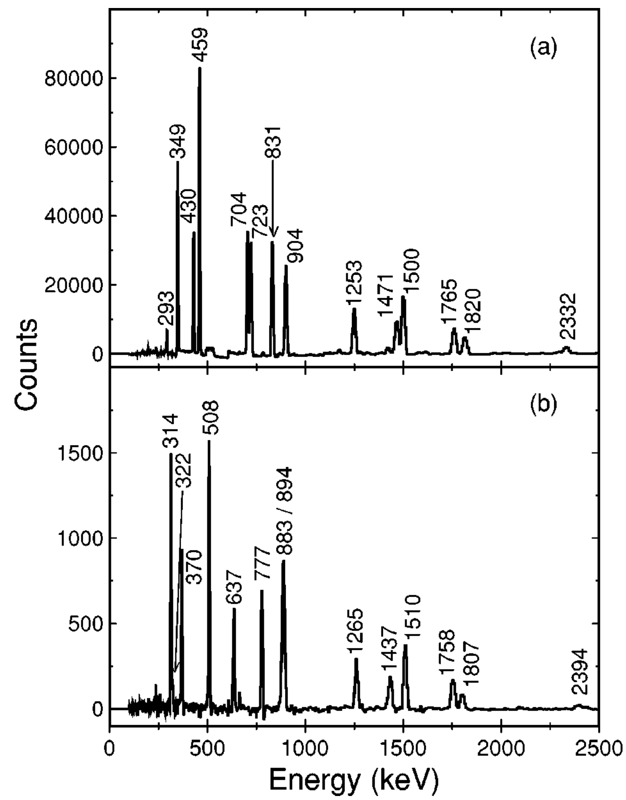

FIG. 1. (a) ^{51}Mn$-$a double-gated spectrum obtained by requiring a coincidence with the 237 keV $\frac{7}{2}^- \rightarrow \frac{5}{2}^-$ transition and any one of the 459, 430, 349, and 723 keV transitions in the yrast sequence of ^{51}Mn. (b) ^{51}Fe$-$a spectrum generated in the same way as (a) but gating on the equivalent ''mirror'' transitions in ^{51}Fe (i.e., the 253 keV transition and any one of the 508, 314, 370, and 637 keV transitions).

sional γ-γ matrix was created and a sequence of very narrow coincidence gates were placed in the matrix in the region of 262 keV. By this method, a group of very weak transitions with energies similar to those in ^{51}Mn were observed to be in coincidence with a 253 keV gamma ray. Double gates were then placed on these transitions in the cube, and the resulting spectrum is shown in Fig. 1(b). On the assumption that the gamma rays belong to ^{51}Fe, a level scheme was constructed for ^{51}Fe with the ordering of gamma rays determined solely from coincidence relationships and relative intensity measurements. The resulting scheme is shown in Fig. 2(b). The combination of the close similarity with the ^{51}Mn level scheme, the comparison of the spectra, the one-to-one correspondence of the gamma rays observed, and the fact that the absolute intensities are consistent with the predicted cross sections suggests that our identification of this structure as ^{51}Fe is correct. Independent confirmation of the assignment of these levels to ^{51}Fe is reported in Ref. [14]. Statistics for ^{51}Fe were not sufficient to allow an angular correlation analysis, and the assignment of spins and parities is made on the basis of mirror-symmetry arguments alone. The ^{51}Mn level scheme established in this Rapid Communication is also shown in Fig. 2(a) and agrees with that observed by Cameron *et al.* [16]. The ^{51}Fe scheme has now been estab-

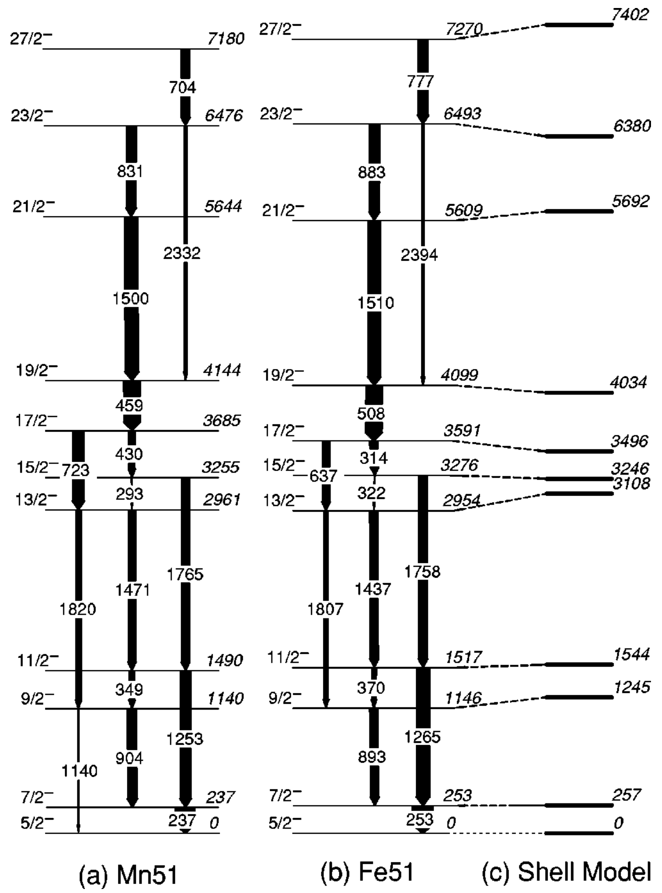

FIG. 2. (a) and (b) The level schemes of ^{51}Mn and ^{51}Fe, respectively, as measured in this work. The ^{51}Mn scheme is consistent with that measured by Cameron *et al.* [16]. The gamma-ray energies below the $J^{\pi}=\frac{17}{2}^{-}$ states have been corrected for both nuclei assuming a lifetime of 2.2 ns (see text for details). The plotted widths of the gamma rays are proportional to the relative intensities. For ^{51}Fe, the levels are ordered on the basis of coincidence relationships and relative intensities. The spins and parities are assigned through mirror-symmetry arguments. (c) A comparison of the level scheme of ^{51}Fe with the large-scale fp shell model calculations including the Coulomb effect (see text for details).

lished up to $J^{\pi}=\frac{27}{2}^{-}$—the maximum spin available in this $f_{7/2}$ valence space. The $J^{\pi}=\frac{17}{2}^{-}$ level in ^{51}Mn is known to be isomeric with a measured mean lifetime of 2.2 ± 0.3 ns [18] and, as a result of this, the gamma decays below this isomer are emitted downstream of the target position. This causes some loss of intensity for gamma rays deexciting states below $J^{\pi}=\frac{17}{2}^{-}$ and also results in a slight shift of the measured gamma-ray energy away from the true value due to the change in the effective angle of the detectors used for the Doppler correction. This can be corrected, but only if the isomer lifetime is known. For ^{51}Mn this correction yielded gamma-ray energies slightly higher (between 1 and 3 keV) than those published by Cameron *et al.* [16]. This may indicate that the mean isomer lifetime is possibly shorter than the 2.2(3) ns quoted by Noé and Gural [18]. For ^{51}Fe, we have assumed that the $J^{\pi}=\frac{17}{2}^{-}$ state is also isomeric and, for the purpose of the correction, we have assumed that the mean lifetime is the same, but with a larger error of ±1.0 ns. This uncertainty in the lifetime results in larger than normal errors in the energies of the gamma rays (approximately ±2 keV at 1.5 MeV) and the excitation energies of the ^{51}Fe states (approximately ±6 keV for the states above $J^{\pi}=\frac{17}{2}^{-}$).

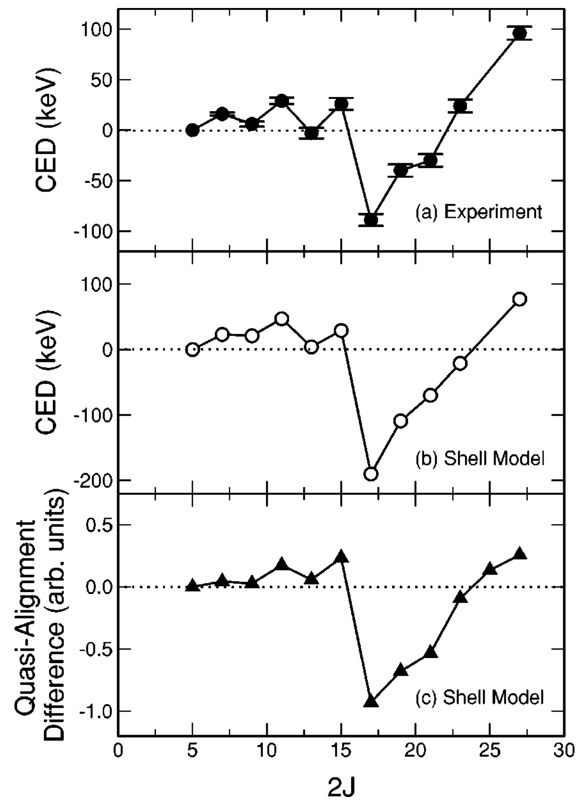

FIG. 3. (a) The experimental CED defined as $E_x(^{51}\mathrm{Fe})-E_x(^{51}\mathrm{Mn})$. The error bars are due to the uncertainties in the level energies caused by the presence of the isomer at $J^{\pi}=\frac{17}{2}^{-}$. For the purpose of this calculation, the ^{51}Mn excitation energies have been taken from Cameron *et al.* [14] as they are susceptible to smaller errors. (b) The CED computed from the fp-shell model calculations (see text for details). (c) A shell model calculation for ^{51}Mn of the differences in ''quasialignment'' of $J=6,T=1$ proton and neutron pairs as defined in the text. This is plotted as the proton alignment *minus* the neutron alignment.

A simple comparison of the level energies for each spin can now be made which yields the Coulomb energy differences (CED)—this is shown in Fig. 3(a). It can be seen that the uncertainties in the CED due to the isomer do not significantly affect the ability to interpret the results. In the $A=49$ and $A=47$ mirror nuclei, a large change in the measured CED was observed at around $J^{\pi}=\frac{17}{2}^{-}$. This was interpreted [5,10,11] as being due to a rotational alignment of a pair of protons in one member of the mirror pair, resulting in a reduction of their spatial overlap and a corresponding reduction in the Coulomb energy. The $A=51$ mirror pair lies further away from the midshell deformed region, and may be expected to show less collectivity due to the smaller number of valence holes in the ^{56}Ni core. Evidence for some collectivity was reported by Noé *et al.* [19] who measured $B(E2)$ rates of ≈20 W.u. for transitions between low-spin states. It may be expected that this collectivity reduces quickly with increasing spin due to the restricted size of the valence space. Nevertheless, the CED for the $A=51$ mirror pair shown in Fig. 3(a) shows evidence of a sudden alignment effect at a similar spin ($J^{\pi}=\frac{17}{2}^{-}$) to the neighboring mirror nuclei. We interpret this as an alignment of a pair of $f_{7/2}$ protons in ^{51}Fe which reduces the overlap of their spatial distributions and causes a corresponding reduction in the Coulomb energy. In ^{51}Mn, the odd proton blocks this alignment and a pair of $f_{7/2}$ neutrons aligns instead—with no resulting Coulomb effect. Thus there is an overall negative effect on the CED at $J^{\pi}=\frac{17}{2}^{-}$. As the band termination at $J^{\pi}=\frac{27}{2}^{-}$ is approached, alignment of the other particle-type is required to generate more angular momentum (i.e., neutrons in ^{51}Fe and protons in ^{51}Mn) and the Coulomb effect is reversed. Thus the CED rises towards zero towards the band termination, at which point a full alignment of protons *and* neutrons is required in *both* nuclei to generate the maximum available spin. The results of recent cranked shell model calculations from Sheikh *et al.* [20] are consistent with this picture, in which proton and neutron alignments are predicted to occur at different frequencies along the yrast bands of these nuclei.

Large-scale fp-shell model calculations have been performed following the model described by Caurier *et al.* [8] using a modified KB3 interaction in the full fp valence space with a truncation which allows for up to five excitations from $f_{7/2}$ to the higher-lying fp orbitals. These calculations have been shown to reproduce very successfully the high-spin behavior of nuclei in the upper part of the $f_{7/2}$ shell (e.g., [7]). For ^{51}Fe, the comparison of the predicted excitation energies with the experimental data is shown in Fig. 2(c). The agreement is extremely good, and somewhat better than that for nuclei nearer the center of the shell where core excitations from below the ^{40}Ca shell closure may play a role. The Coulomb effect has been included in the shell-model by adding the Coulomb interaction to the effective nuclear force using empirical Coulomb matrix elements (taken from the $A=42$ isobaric triplet) for the $f_{7/2}$ protons. The level schemes are calculated in the presence of the Coulomb interaction, and the CED is then calculated in the same way as for the experimental data. The results of this calculation are shown in Fig. 3(b). It can easily be seen that although the absolute values of the CED are slightly larger in the calculations, the overall trends of the CED as a function of spin are exactly reproduced over the whole spin range. In contrast to the case of the $A=49$ and 47 pairs, no adjustment of the Coulomb matrix elements is necessary to obtain a better agreement with the trends of the experimental CED.

In order to gain further insight into the microscopic mechanisms behind these effects, we have calculated the expectation values of the operator

$$[(a^{+}a^{+})^{J=6,T=1}(aa)^{J=6,T=1}]$$

separately for protons and neutrons for each state along the yrast band of ^{51}Mn. These values reflect the contribution from pairs of $f_{7/2}$ protons (or neutrons) coupled to the maximum angular momentum value of $J=6$ and can be thought of as "quasialignments" for protons and neutrons in each state. We then plot the *difference* of these two quantities in Fig. 3(c). The plot clearly shows that a rapid neutron alignment takes place in ^{51}Mn at $J^{\pi}=\frac{17}{2}^{-}$ followed by a gradual alignment of protons. The magnitude of these alignment effects should be the same in ^{51}Fe, but the sign will be opposite. This is entirely consistent with the arguments presented above for the experimental CED. Indeed a comparison with Fig. 3(b) [or even Fig. 3(a)] demonstrates that in this case, the various proton alignment effects seem to account almost entirely for the variations of the CED.

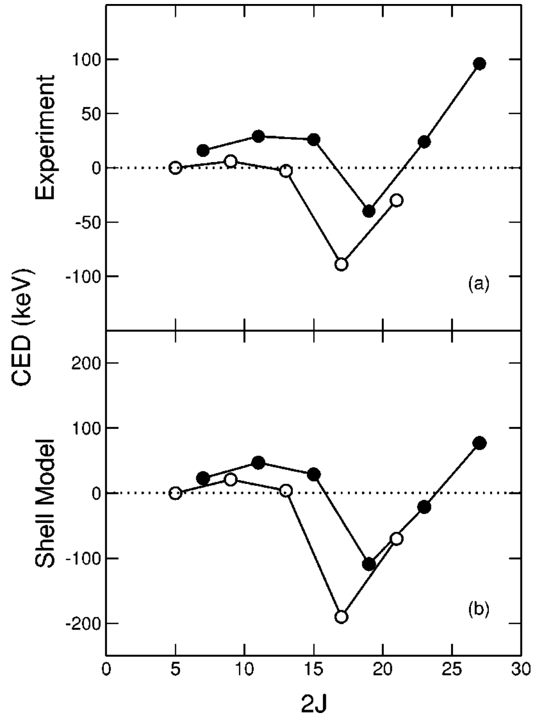

FIG. 4. (a) The experimental CED as in Fig. 3 but plotted separately for the unfavored structure (open circles; $J^{\pi}=\frac{5}{2}^{-},\frac{9}{2}^{-},\frac{13}{2}^{-},\ldots$) and the favored structure (closed circles; $J^{\pi}=\frac{7}{2}^{-},\frac{11}{2}^{-},\frac{15}{2}^{-},\ldots$). (b) The CED from the shell model plotted in the same way as (a).

Further inspection of the experimental CED in Fig. 3(a) reveals phenomena not seen in the other mirror pairs studied. First, the fact that the CED change at the alignment is very sharp compared with the smooth variation observed for the same alignments in the $A=49$ and 47 pairs [5,6]. Second, the staggering in the CED—particularly visible at low spins—has not been seen in other cases. However, we can consider the yrast sequence in each nucleus as consisting of a favored band ($J^{\pi}=\frac{7}{2}^{-},\frac{11}{2}^{-},\frac{15}{2}^{-},\ldots$) and an unfavored band ($J^{\pi}=\frac{5}{2}^{-},\frac{9}{2}^{-},\frac{13}{2}^{-},\ldots$)—referred to from now on as different signatures. If the CED is plotted separately for each signature, then these effects become more clear. This is shown in Fig. 4(a) and it is seen that the CEDs for each signature are smoothly varying and very similar, but offset from each other over the whole spin range. Each signature shows the same alignment effect, but now with a smooth variation in the CED similar to the effect seen in the $A=49$ and 47 mirror nuclei. The offset observed in the CED represents the fact that the difference in excitation energy between the favored and unfavored signatures over the full spin range is consistently larger in one nucleus than the other (i.e., the unfavored signature in ^{51}Mn lies slightly higher in energy relative to the favored signature than it does for ^{51}Fe).

A simple particle-plus-rotor interpretation may present a possible explanation for this effect. In a rotational picture, these coupled sequences are built upon a $K=\frac{5}{2}$ ground state (for a prolate deformation the odd particle occupies the $[312]\frac{5}{2}$ Nilsson level). However, the close proximity of the $\Omega=\frac{1}{2}$, $\frac{3}{2}$, and $\frac{7}{2}$ levels, due to the low deformation, results in large Coriolis mixing as angular momentum increases. This K mixing destroys the strong-coupling of the odd particle to the core resulting in the separation into favored and unfavored bands. The degree of Coriolis mixing present depends critically on the proximity of the other Nilsson levels. If the spectrum of single-proton levels for ^{51}Mn is slightly different from that of neutrons for ^{51}Fe (e.g., due to a different deformation), then the degree of signature splitting will not be the same in each member of the pair. The fact that the effect seems to occur consistently over a large spin range supports the above interpretation. For the $A=49$ mirror nuclei, nearer the center of the shell, this effect was not observed in the data. However, for $A=49$, the deformation is expected to be larger and hence the Coriolis mixing should be smaller and the effect will not be as pronounced. The predicted CED from the shell model for each signature of the $A=51$ pair is plotted in Fig. 4(b) and shows that the effect is reproduced with astonishing precision.

In summary, gamma decays from excited states in ^{51}Fe, the mirror partner to ^{51}Mn, have been observed for the first time. States up to the band termination have been observed, and this represents the heaviest mirror pair studied up to such high spins. The resulting Coulomb energy differences (CED) show trends which can be interpreted in terms of particle alignments occurring at different spins in the two nuclei. For the first time, the two signatures have been found to exhibit distinctly separate CED trends, which has been interpreted in terms of Coriolis mixing effects. These data have provided an important test of the latest fp-shell model calculations in a region of the $f_{7/2}$ shell where they might be expected to work well. The shell model calculations have been shown to reproduce all aspects of the measured Coulomb effects with remarkable accuracy.

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