Mirror Symmetry Up to the Band Termination in ^{49}Mn and ^{49}Cr

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High-spin states have been investigated in the mirror pair nuclei ^{49}Cr ($Z = 24$, $N = 25$) and ^{49}Mn ($Z = 25$, $N = 24$). Mirror symmetry up to the band termination at about 10.7 MeV has been established. A comparison of the corresponding energy levels of the pair shows, for the first time, that the Coulomb energy difference approaches zero as the band termination is approached. This is explained intuitively in terms of a pure $f_{\frac{7}{2}}$ shell framework. For ^{49}Cr, excellent agreement is found between the data and recent full pf-shell calculations. [S0031-9007(97)04648-6]

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The study of light nuclei ($A \leq 50$) near the $N = Z$ line is of significant topical interest, from both experimental [1,2] and theoretical [3–6] viewpoints. The advent of high efficiency γ-ray spectrometers and their use in conjunction with particle detectors have enabled some of the most weakly populated nuclei near the $N = Z$ line to be studied in detail for the first time. The concomitant advance in the ability to perform nontruncated, large-space shell model calculations for nuclei in this region has added an extra dimension to these studies, allowing detailed comparisons with experiment.

Nuclei near the center of the isolated $f_{\frac{7}{2}}$ shell are of particular interest as their states are expected to be well described by the shell model, yet have enough valence particles to allow some degree of collective rotational motion at low to intermediate spins, as confirmed by recent experimental studies (e.g., [1,2,7–9]). At higher spins, the structure should become less collective due to the restricted size of the shell and lead to a band termination at, for example, $J^{\pi} = 16^{+}$ for ^{48}Cr at the center of the shell. This value represents the maximum possible value of the angular momentum within an isolated $f_{\frac{7}{2}}$ shell. The $f_{\frac{7}{2}}$ shell is of particular interest as it is reasonably well isolated in energy from the other shells. This affords the opportunity to study the trends in the structure of the nucleus without a significant change in the single-particle configuration of the nuclear states.

Nuclear structure phenomena traditionally associated with collective rotation, such as rotational quasiparticle alignment, have been observed in nuclei near the center of the $f_{\frac{7}{2}}$ shell [1]. Interestingly, recent calculations of ^{48}Cr [4] show that rotorlike energy systematics and back-bending (alignment) phenomena are well reproduced by both shell model and cranking (cranked Hartree-Fock-Bogoliubov) calculations. It is clearly important to determine the extent to which the behavior of light nuclei such as these compares with that of, for example, the rotational nuclei which are well known in the heavy rare-earth region.

In this paper, we present an experimental study of the mirror nuclei ^{49}Mn and ^{49}Cr, in which we show, for the first time, a detailed comparison of the structures of these nuclei up to the band termination. The nuclei ^{49}Mn and ^{49}Cr have one proton and one neutron added, respectively, to the $N = Z = 24$ midshell nucleus ^{48}Cr. Mirror nuclei such as these, due to the charge symmetry of the nuclear force, are expected to have almost identical energy level structures. The differences in energy between levels of the two nuclei at equal spins are expected to arise entirely from the difference between the Coulomb energy of the two nuclei. This Coulomb energy difference (CED) yields, in turn, crucial information on the spatial correlations of the active valence particles. When studied as a function of increasing angular momentum, the CED provides a unique way of investigating the changes in the structure of the states. This was demonstrated in previous work on the mirror nuclei ^{47}Cr-^{47}V [7] and ^{49}Mn-^{49}Cr [8], where changes in the CED were interpreted in terms of rotational alignments.

An experiment was designed to investigate mirror symmetry up to the band-terminating states in ^{49}Mn and ^{49}Cr and was performed using the "pre-EUROBALL experiment" detector system (PEX). The experiment utilized the Niels Bohr Institute tandem accelerator to bombard a 500 μg/cm^2 enriched ^{24}Mg target with a ^{28}Si beam at a laboratory energy of 87 MeV. The mirror nuclei were produced via the ^{24}Mg(^{28}Si, $2pn$)^{49}Cr and ^{24}Mg(^{28}Si, $p2n$)^{49}Mn reactions. Previous experimental work [8] has shown that ^{49}Mn is populated with a cross section of the order of 2–3 mb ($\approx$100 times weaker than ^{49}Cr).

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Gamma rays deexciting the nuclei of interest were detected using four EUROBALL cluster detectors [10] providing a total γ-ray detection efficiency of $\epsilon_\gamma \approx 2\%$ for 1.33 MeV γ rays. One pair of clusters was situated at an angle of 105° to the beam direction, with the other pair at 155°. Each cluster detector is a composite of seven hexagonal-faced hyperpure germanium crystals, each separately encapsulated, operable as either individual or composite detectors. Each cluster was surrounded by its own Bismuth-Germanate (BGO) escape suppression shield. The large crystal sizes, coupled with the ability to add signals together from adjacent capsules within a cluster, result in a higher relative efficiency for high energy γ rays [11] than for any previous type of germanium detector. Events in which two or three adjacent cluster capsules were in prompt coincidence were found to correspond mostly to single (scattered) γ rays, and for these events the energy signals from the capsules were added.

To aid the selection of events from weakly populated nuclei, evaporated particles were detected using two further arrays of detectors. The target was encapsulated within a dodecahedral array [12] of pentagonal 170 μm thick silicon wafers. Each wafer surface had a number of detector elements measuring the energy deposited in the wafer by the incident charged particles. There were 31 detector elements in the whole array. The detection efficiency for protons and alpha particles was $\epsilon_p \approx 55\%$ and $\epsilon_\alpha \approx 35\%$, respectively. Discrimination between protons and alpha particles was achieved entirely on the basis of the energy loss of the particles in the silicon wafers. In addition, an array of 15 liquid scintillator neutron detectors [13] was mounted ≈50 cm downstream of the target to capture the forward-focused neutron flux from the reaction. The efficiency of the array was measured to be $\epsilon_n \approx 10\%$. Approximately 3.8×10^8 particle–γ-γ coincidence events were recorded.

For ^{49}Cr, a γ-γ coincidence matrix was built with $pn\gamma\gamma$ and $2pn\gamma\gamma$ coincidence events, while for ^{49}Mn the condition was set at $pn\gamma\gamma$ and $p2n\gamma\gamma$. Although the $pn\gamma\gamma$ events were dominated by ^{49}Cr, it was possible to cleanly identify the ^{49}Mn events through γ-γ coincidence techniques.

Figure 1 shows spectra created by requiring a coincidence with the strongest ($\frac{7}{2}^- \rightarrow \frac{5}{2}^-$) transition in each nucleus. The deduced energy level schemes of the two nuclei are shown in Fig. 2. The multipolarities of the ^{49}Cr γ rays were determined with a technique exploiting directional correlations from oriented states (DCO) in which relative intensities of the γ rays at the two detector angles were compared. This technique allows discrimination between the stretched quadrupole ($J \rightarrow J - 2$) and stretched dipole ($J \rightarrow J - 1$) transitions, but cannot discriminate between stretched quadrupole and $J \rightarrow J$ dipole transitions.

Previous work [8] had already determined the ^{49}Cr level scheme up to the 10 706 keV state—see Fig. 2(b).

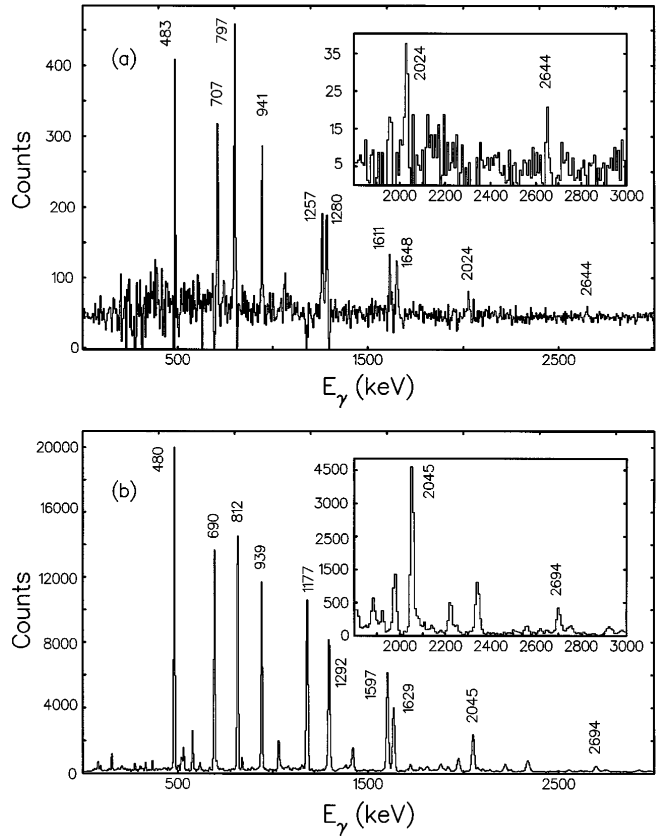

FIG. 1. Transitions in coincidence with the strong ($\frac{7}{2}^- \rightarrow \frac{5}{2}^-$) transition in both nuclei; (a) the 262 keV γ ray in ^{49}Mn from the $(pn + p2n)\gamma\gamma$ matrix, at 2 keV per channel, and (b) the 272 keV γ ray in ^{49}Cr from the $(pn + 2pn)\gamma\gamma$ matrix, at 2 keV per channel. The insets in both spectra show the corresponding expanded region from 1.80 to 3.00 MeV, at 4 keV per channel.

However, the spins and parities of the 5967, 8012, and 10 706 keV states were previously assigned as $J^\pi = \frac{19}{2}^-, \frac{23}{2}^-$, and $\frac{27}{2}^-$, respectively. In this paper, an additional state at 8879 keV has been observed which decays via a 2744 keV transition to the $\frac{21}{2}^-$ state, and a 2912 keV transition decays to the 5967 keV level. These two γ rays were measured as being consistent with stretched quadrupole and stretched dipole transitions respectively. The 8879 keV level is therefore assigned as $J^\pi = \frac{25}{2}^-$ as it is most likely to be an extension of the unfavored positive signature structure. As a result of this assignment, the 5967 keV level is now assigned as $J^\pi = \frac{23}{2}^-$. In the previous experiment [8], an assignment of either $J^\pi = \frac{19}{2}^-$ or $J^\pi = \frac{23}{2}^-$ for this level was consistent with the data, but with the current high statistics data set this ambiguity has now been resolved. The states above now have two more units of angular momentum than previously assigned, and the uppermost 10 706 keV level now has $J^\pi = \frac{31}{2}^-$. This is therefore the band terminating state corresponding to the maximum spin which can be generated with seven

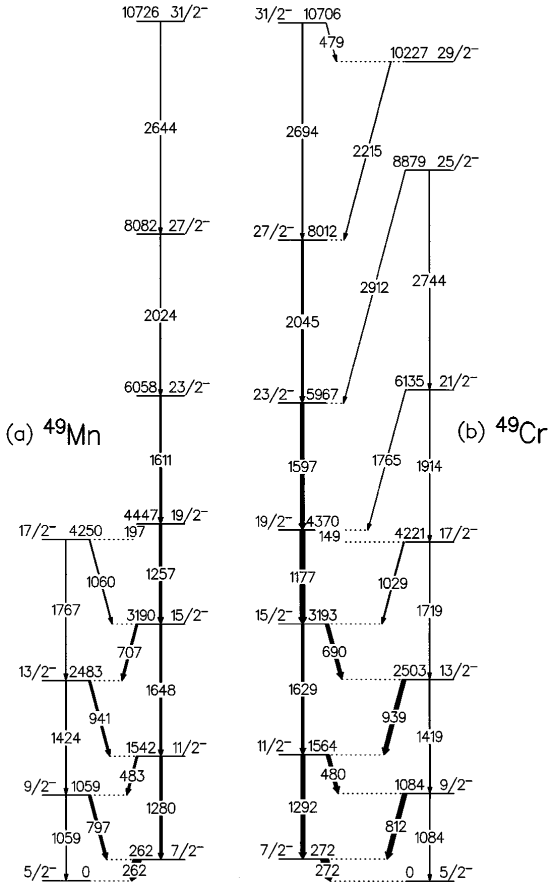

FIG. 2. Level schemes deduced from this experiment for (a) ^{49}Mn and (b) ^{49}Cr. The levels are labeled with the assigned spin and parity as well as the excitation energy in keV, with widths of arrows proportional to γ-ray intensity.

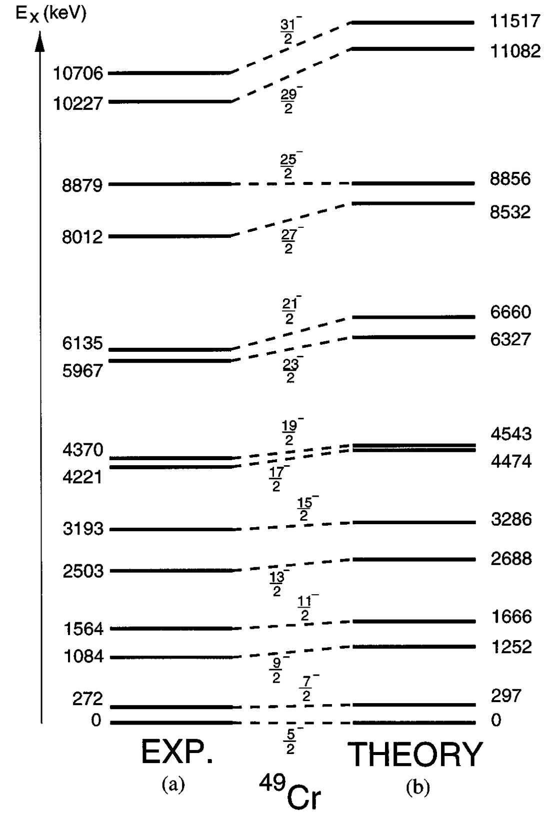

FIG. 3. Excitation energies along the yrast band in ^{49}Cr from (a) this paper and (b) the full pf-shell calculations of Martinez-Pinedo *et al.* [3], and also from Poves [14].

valence particles in the shell, i.e., for ^{49}Cr, $J_{\max} = (\frac{7}{2} + \frac{5}{2} + \frac{3}{2} + \frac{1}{2})_{\text{protons}} + (\frac{7}{2} + \frac{5}{2} + \frac{3}{2})_{\text{neutron holes}}$.

The original level scheme of ^{49}Cr [8] was recently questioned by Martinez-Pinedo *et al.* [3] who found an unusually poor agreement between this scheme and their full pf-shell calculations. Our reinterpretation of the ^{49}Cr scheme is shown in Fig. 3 along with the predictions of Martinez-Pinedo *et al.* [3,14]. The agreement between experiment and the shell model prediction is now striking.

We now turn our attention to the more weakly populated ^{49}Mn nucleus (see Figs. 1 and 2). In this case, due to poor statistics, it was impossible to obtain DCO measurements, and the spins and parities of the states have been assigned on the basis of mirror symmetry arguments only. The work of Cameron *et al.* [8] determined the states in ^{49}Mn up to the 6058 keV level—previously assigned as $J^\pi = \frac{19}{2}^-$. With our reinterpretation of ^{49}Cr, this state is now assigned as $J^\pi = \frac{23}{2}^-$, as it is the mirror state of the 5967 keV level in ^{49}Cr. Additionally, two new very weak transitions at 2024 and 2644 keV have been observed in ^{49}Mn [see Fig. 1(a) inset]. Comparison with the ^{49}Cr scheme leads us to the conclusion that these are the mirror transitions of the 2045 and 2694 keV transitions in ^{49}Cr, and as a result they are assigned as the $J^\pi = \frac{27}{2}^- \rightarrow \frac{23}{2}^-$ and $J^\pi = \frac{31}{2}^- \rightarrow \frac{27}{2}^-$ transitions, respectively.

The new level schemes of the states in the two nuclei are shown in Fig. 2. For the first time, states in both nuclei have been observed up to the band termination, and the continuation of the mirror symmetry is remarkable. Indeed, the difference between the energies of the corresponding band-termination states is 20 keV or $\approx 0.2\%$ of the total excitation energy.

The variation of the CED between the two nuclei can now be determined through a simple comparison of the excitation energies of levels of the same spin. The results are shown in Fig. 4. The plot is unaltered with respect to the previous work [8] up to $J^\pi = \frac{19}{2}^-$. including a sharp rise at about $J^\pi = \frac{17}{2}^-$. The CED now reaches a peak at about $J^\pi = \frac{23}{2}^-$, which is followed by a dramatic reduction towards zero as the band termination is reached.

A full theoretical description of this behavior is beyond the scope of this paper. However, these new results can be understood in an intuitive way. In the work of Cameron *et al.* [8] the sharp rise in the CED was discussed in terms of a rotational picture including rotational alignment effects. It was suggested that an alignment of a pair of $f_{\frac{7}{2}}$ protons takes place in ^{49}Cr at about $J^\pi = \frac{17}{2}^-$ with an alignment of a pair of neutrons at the same point

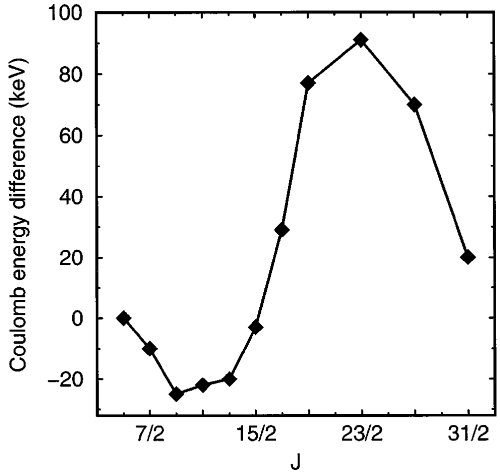

FIG. 4. The Coulomb energy difference in keV, where CED $= E_x(\mathrm{Mn}) - E_x(\mathrm{Cr})$, as a function of angular momentum along the yrast bands of the mirror pair nuclei.

in ^{49}Mn. The odd particle has a blocking effect which prevents the alignment of the other type of particle in each case. It was argued that the change in the spatial overlap of the aligned particles causes a change in the Coulomb energy difference between the nuclei due to the fact that protons were aligning in one case and neutrons in the other. The present paper shows that this alignment effect causes an overall change in the CED of about 100 keV. This is consistent with calculations provided by Cameron *et al.* [7], where the change in the CED due to an alignment of two $f_{\frac{7}{2}}$ protons was predicted to be between 80 and 200 keV. The CED results for the higher-spin states from this paper can now be understood as follows.

To generate a spin of $J^\pi = \frac{31}{2}^-$ within an isolated $f_{\frac{7}{2}}$ shell requires the *maximum* possible alignment of the angular momentum vectors of *all* seven valence particles (or holes) along the symmetry axis of the nucleus. For ^{49}Cr this corresponds to a full alignment of four protons and three neutron (holes), and for ^{49}Mn an alignment of four neutrons and three proton (holes). Thus, if the sharp rise in the CED is caused by an alignment of protons in ^{49}Cr and neutrons in ^{49}Mn, the CED should fall back towards zero as the band termination is approached, as this represents an alignment of both protons *and* neutrons in *both* nuclei. Therefore, the CED between the two nuclei should return to approximately its value for the ground state.

It should be pointed out that this simplistic argument is based on the assumption that the nuclear states are dominated by $f_{\frac{7}{2}}$ components, i.e., if the $J^\pi = \frac{31}{2}^-$ level is an almost pure $(f_{\frac{7}{2}})^7$ band-terminating state, requiring a full alignment of all valence particles. Interestingly, Caurier *et al.* [4] have shown that, in both cranked Hartree-Fock-Bogoliubov calculations and shell-model calculations, the $f_{\frac{7}{2}}$ contribution to the wave functions in the center of the shell becomes increasingly dominant towards high spins, becoming the only significant contribution (>99% for the cranking approach) at the band termination. This picture is entirely consistent with the arguments presented above for the CED results.

In conclusion, the level schemes of the mirror pair ^{49}Mn and ^{49}Cr have been determined up to the band-terminating states for the first time. A close examination of the Coulomb energy difference between the two nuclei has proven to be an extremely sensitive probe of the nuclear structure. This paper has shown, for the first time, that the study of Coulomb effects in a mirror pair reflects the change in the way the nucleus generates its angular momentum, i.e., from collective rotational motion to a *full* (noncollective) alignment of the angular momentum vectors of the valence nucleons. This unique result shows that this simplistic description of nuclear behavior, previously only applied to much heavier nuclei, is also valid for light nuclei such as these. With the advent of more sensitive detector systems and the future use of radioactive beam species, we will be afforded the opportunity to investigate mirror symmetry effects in the next shell. The indications here are that these studies could play a valuable role in understanding changes in structure along the $N = Z$ line.

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