Mirror Energy Differences at Large Isospin Studied through Direct Two-Nucleon Knockout

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The first spectroscopy of excited states in ^{52}Ni ($T_z = -2$) and ^{51}Co ($T_z = -3/2$) has been obtained using the highly selective two-neutron knockout reaction. Mirror energy differences between isobaric analogue states in these nuclei and their mirror partners are interpreted in terms of isospin nonconserving effects. A comparison between large-scale shell-model calculations and data provides the most compelling evidence to date that both electromagnetic and an additional isospin nonconserving interactions for $J = 2$ couplings, of unknown origin, are required to obtain good agreement.

Symmetries play a central role in physics, and can greatly simplify a model space and introduce experimentally verifiable predictions, such as conservation laws. In the case of the atomic nucleus the introduction of isospin (T), and the associated projection [$T_z = (N - Z)/2$] [1], the formalism by which the proton [$t_z = -(1/2)$] and neutron [$t_z = +(1/2)$] are treated as two states of the same particle, led Wigner to the concept of isospin symmetry [2]. The symmetry is based on the assumption that nucleon-nucleon interactions are charge symmetric and charge independent. In the absence of isospin-breaking interactions, the model requires *exact* symmetry (degeneracy) between analogue states in nuclei with the same mass but interchanged numbers of protons and neutrons [isobaric analogue states (IAS)]. Electromagnetic effects break the degeneracy and provide an interaction that mixes states of different isospin. Historically, accounting for energy differences purely in terms of Coulomb effects has proved problematic (e.g., Ref. [3]), where predicted Coulomb displacement energies (CDE) between IAS differed systematically from experimental values (the Nolen-Schiffer anomaly), suggesting that other isospin-breaking effects need to be accounted for. Indeed, evidence of such symmetry breaking is found in the nucleon-nucleon interaction (e.g., Ref. [4] and references therein). It has been suggested, e.g., Refs. [5,6], that this charge-symmetry breaking (CSB) may contribute to the Nolen-Schiffer anomaly, although the situation has not been fully resolved.

Despite these difficulties, differences between excitation energies of IAS (i.e., having normalized the ground state energies) show a remarkable degree of symmetry and can be well reproduced by shell-model calculations. These calculations include the electromagnetic multipole (i.e.,

two-body Coulomb) effects [7] and monopole effects [8] which affect single-particle energies and are related to radial and deformation changes. Detailed investigation of these phenomena has focused mainly on nuclei in the $f_{7/2}$ shell, those nuclei between doubly magic ^{40}Ca and ^{56}Ni [9,10], although there are new results and shell-model calculations available in the fpg shell also (e.g., Ref. [11]). The $f_{7/2}$ region is particularly attractive for such an investigation, as $N < Z$ nuclei are experimentally accessible and large-scale shell-model calculations are known to provide an excellent description [12]. A systematic study of these nuclei shows that a single shell-model prescription can be used to reproduce the differences in the excitation energy of mirror pairs [mirror energy differences (MEDs)] with excellent accuracy [9]. In this prescription, isospin-breaking effects can be accounted for by the electromagnetic interaction. However, in order to achieve the best fit to the experimental MED, it is found [8,9,13] that an additional repulsive two-body matrix element needs to be added for $f_{7/2}$ protons coupled to $J = 2$. Moreover, the additional $J = 2$ term required is comparable to the Coulomb contribution. This is the so-called $J = 2$ anomaly, which has caused much interest, so far without a satisfactory explanation.

The motivation for the current work, focused on the $T_z = -2$ nucleus ^{52}Ni, was twofold. Firstly, extending these studies to excited states of mirror nuclei with large differences in proton number and where we approach the limits of nuclear binding (i.e., near the proton drip-line) provides a stringent test of the models developed. Secondly, calculations indicated that the $J = 2$ anomaly would play a significant role in *both* the $J^\pi = 2^+$ and 4^+ states in the $A = 52$ pair but be absent for the 6^+ state,

giving a direct prediction that can be tested. In this Letter we report on the first excited states identified in the exotic nuclei ^{52}Ni ($T_z = -2$) and ^{51}Co [$T_z = -(3/2)$]—the latter of which is expected to have excited states which are all above the calculated 88 keV proton separation energy [14]. We used, we believe for the first time, the approach of mirrored two-nucleon knockout to identify the IAS in the $T_z = \pm 2$ nuclei ^{52}Ni/^{52}Cr and to determine the mirror energy differences. The states identified are the highest spin states yet observed in any nuclei with $T_z = -2$ or $-(3/2)$, demonstrating the power of the direct two-neutron knockout approach for populating intermediate-spin states in these proton-rich systems. The MED results are compared with state-of-the-art shell-model calculations, and crucial information on the $J = 2$ effect is extracted.

The experiment was performed at the National Superconducting Cyclotron Laboratory at Michigan State University. The secondary beams of interest were produced by the fragmentation of a 160 A MeV beam of ^{58}Ni incident on a ^{9}Be primary target, with the resulting fragments separated by the A1900 fragment separator [15,16] and identified downstream using their time of flight.

The secondary target was located at the reaction target position of the S800 spectrograph [17,18], and unique identification of the reaction products was achieved using the energy loss in an ion chamber and the time of flight through the S800. Surrounding the S800 reaction target position was SeGA, used to record γ rays emitted in flight [19].

Excited states in ^{52}Ni were populated by two-neutron knockout from ^{54}Ni at 87 A MeV on the secondary ^{9}Be target of areal density 188 mg/cm^2. Since in this case the two nucleons are initially well bound, their sudden removal is expected to be direct as the indirect process (a single neutron removal followed by neutron evaporation) is not favored energetically [20]. Two-neutron knockout was chosen here for two reasons. Firstly, the cross section is expected to be large as both the ^{54}Ni and the yrast states of ^{52}Ni should be dominated by $\nu(f_{7/2})$ configurations. Secondly, the total angular momentum of the removed nucleons can be between $J = 0$ and $J = 6$ and, hence, states up to intermediate spin should be populated. The presence of ^{53}Co in the secondary-beam cocktail also allowed the study of excited states in ^{51}Co, for the first time. The mirror partner to ^{52}Ni (^{52}Cr) was populated through the mirrored reaction—two-proton knockout from the ^{54}Fe beam and the new states in ^{52}Ni identified through the spectral comparison from the mirrored reactions (see, e.g., Ref. [21]). Finally, the mirror of ^{51}Co (^{51}Cr) was produced through $2p1n$ removal from ^{54}Fe.

Figure 1(a) shows the Doppler-reconstructed spectrum for γ rays found in coincidence with ^{52}Ni fragments in the S800. The spectrum is clearly dominated by three γ rays, which are assigned as transitions from the 2^+, 4^+, and 6^+ states. The resulting level scheme of ^{52}Ni is shown in
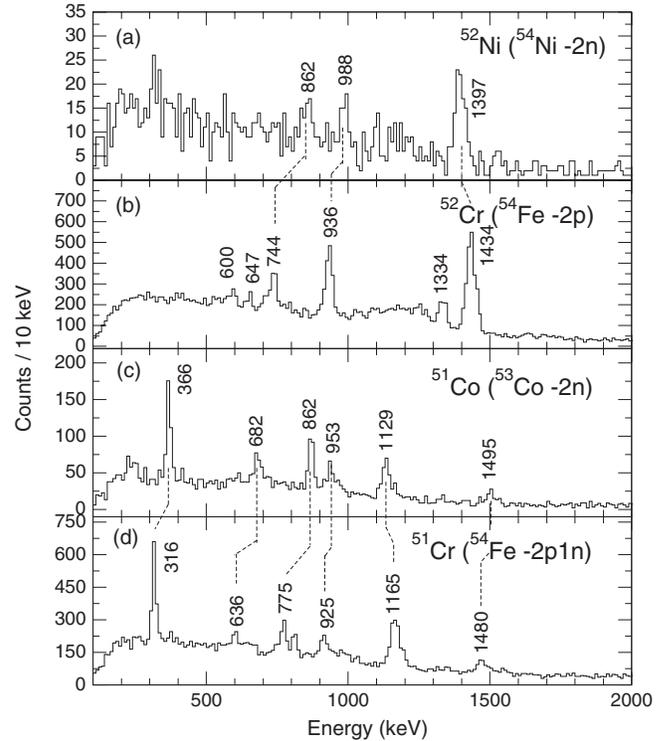

FIG. 1. γ-ray transitions found in coincidence with (a) ^{52}Ni fragments, (b) ^{52}Cr, (c) ^{51}Co, and (d) ^{51}Cr. The dashed lines indicate proposed correspondence between the mirror nuclei.

Fig. 2, which also shows a partial level scheme of ^{52}Cr using information from [22], but only showing transitions observed in the current work. The assignment of these transitions to the yrast sequence of ^{52}Ni is based on (a) the intensity profile of the γ rays (decreasing intensity with increasing spin) and (b) mirror-symmetry arguments—i.e., through comparison with the spectrum of ^{52}Cr, presented in Fig. 1(b), populated by the mirrored reaction. Additionally, confidence is given to these assignments through comparison with two-neutron cross-section calculations; see the discussion below.

The Doppler corrected γ-ray spectrum for ^{51}Co, populated by two-neutron knockout from the ^{53}Co beam, is presented in Fig. 1(c). Six γ-ray transitions are observed, and the comparison with the spectrum in Fig. 1(d) for ^{51}Cr indicates, at least initially, the one-to-one correspondence between the mirrored transitions as shown by the dashed lines. The known partial level scheme of ^{51}Cr is shown in Fig. 2 [23], and the proposed scheme for ^{51}Co, based on the spectral comparison, is also presented in Fig. 2. However, care must be taken in making these initial assignments, as the population mechanisms for the spectra in Figs. 1(c) and 1(d) are rather different, and the states of interest in ^{51}Co are well above the proton-separation energy. To give more confidence to the proposed scheme, two-neutron knockout cross-section calculations were utilized.
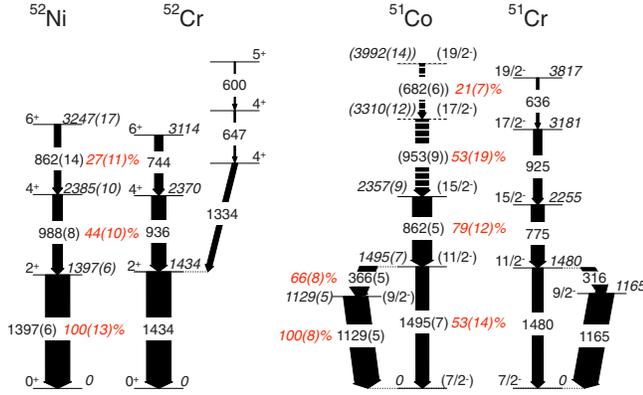
FIG. 2 (color online). The energy level schemes for ^{52}Ni and ^{51}Co deduced from the current work. Tentative assignments are indicated by dashed lines, and the efficiency corrected relative intensities of γ rays in ^{52}Ni and ^{51}Co are given in italic red text as a percentage. These are compared with the partial level schemes of ^{52}Cr and ^{51}Cr.

FIG. 3 (color online). Calculated relative cross sections for states in ^{51}Co populated in a direct two-neutron knockout reaction, using shell-model input from NUSHELLX@MSU with the KB3G interaction (see Refs. [20,24] for details). The fraction of the intensity directly feeding the yrast (black) and nonyrast (red) states is shown. The horizontal axis is the calculated energy of the states from the shell model, and the dashed lines indicate the observed energies of the states in this work.

Two-neutron cross sections were calculated using the formalism presented in Refs. [20,24], combining eikonal reaction dynamics and shell-model structure input. The two nucleons are assumed to be suddenly removed from the projectile, the core (i.e., reaction residue) of which acts as a spectator during the reaction. Full fp shell-model calculations using the KB3G interaction [12] were used to compute the two-nucleon amplitudes, the amplitudes for each two-nucleon configuration with angular momentum J^{π}, coupled to residue state J_f^{π} in the projectile ground state J_i^{π}. Valence nucleon radial wave functions are calculated in a Woods-Saxon plus spin-orbit potential, the geometry of which is constrained by Hartree-Fock calculations. For convenience of the interface with the reaction model, these structure amplitudes were computed using NUSHELLX@MSU [25,26].

For ^{52}Ni the calculations predict that 75% of the cross section for excited states goes directly to the yrast 2^+, 4^+, and 6^+ states, and predicts that the γ ray from the 6^+ state will be at least twice as intense as any from the nonyrast states. This is entirely consistent with the intensities in the observed spectrum and lends weight to the assignments presented in Fig. 2. For ^{51}Co the situation is more complicated as the intensity is expected to be more fragmented; see Fig. 3 for the calculated relative cross sections. It is clear from the spectra and γ-ray energies that the 366, 1129, and 1495 keV transitions must form decays from the $9/2^-$ and $11/2^-$ yrast states in ^{51}Co. The calculations confirm that these two states should be strongly populated. In addition, the calculations show that we expect to see a strong transition from the $15/2^-$ state. Of the remaining (unassigned) transitions in Fig. 1(c), only the 862 keV transition is a candidate for this transition, from intensity arguments. This, along with the obvious mirror symmetry, is sufficient to confirm this assignment. For the remaining two transitions, at 953 and 682 keV, it is tempting to assign
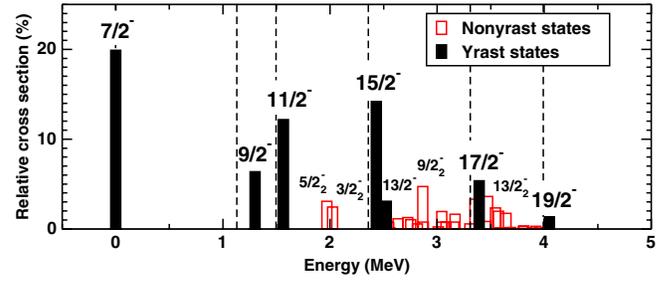
these to the next two members of the yrast sequence, the $17/2^-$ and $19/2^-$ states, based on mirror-symmetry arguments and measured intensities. However, the predicted relative cross sections in Fig. 3 do not indicate a strong population of these states and so these two assignments remain tentative in Fig. 2. For all states identified in this work, the spins and parities are inferred, rather than directly measured, and so they are indicated in Fig. 2 as tentative.

The resulting MED for the ^{52}Ni/^{52}Cr and ^{51}Co/^{51}Cr mirror pairs are shown in Figs. 4(a) and 4(b), respectively [calculated as $\mathrm{MED}(J) = E^*_{J,T,-T_z} - E^*_{J,T,T_z}$, where E^*_{J,T,T_z} is the excitation energy of a state with spin J, isospin T, and isospin projection T_z]. The observed rise in the MED is easily explained [9] as due to the recoupling of angular momentum with increasing spin for neutron pairs in ^{52}Ni and protons pairs in ^{52}Cr. Such recoupling reduces the overlap of nucleons and, hence, for protons, also the Coulomb energy. This yields a positive MED, typically of around 100 keV for nucleons in the $f_{7/2}$ shell [9]. For the $A = 51$ mirror pair, which can be viewed as a proton (neutron) hole in ^{52}Ni(^{52}Cr), we see a similar trend in the MED, Fig. 4(b), suggesting that the same structural effects are occurring.

Large-scale shell-model calculations using the full fp shell have been performed using the ANTOINE code [27] with the KB3G [12] interaction. Previous work [12] shows that in this upper part of the $f_{7/2}$ shell, and in the $A = 51$ and 52 isobars in particular, the agreement with data on excitation energies and transition strengths is excellent. In order to calculate the isospin-breaking effects and their contribution to the MED, an identical approach to that described in Ref. [9] has been employed. The model has four components that contribute to the MED. (a) The Coulomb multipole effect (V_{CM}) accounts for the recoupling effect described above, and is accounted for by the addition of the Coulomb energy to the two-body matrix
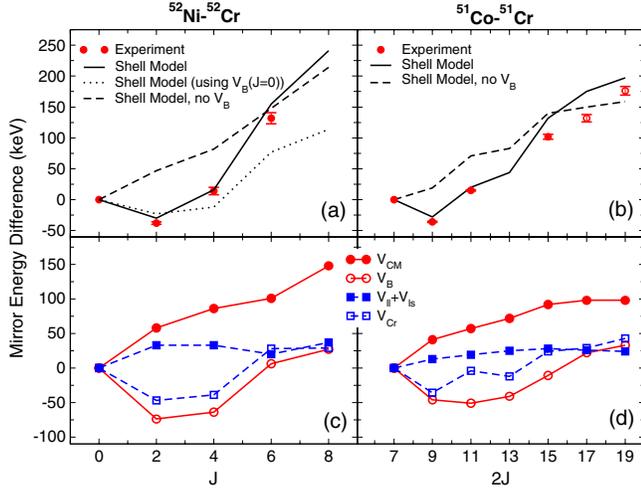
FIG. 4 (color online). (a),(b) Comparison of the experimental
MEDs with the predictions from shell-model calculations (solid
line), using the formalism described in the text which includes
the V_B term (for $J = 2$). Calculations without the inclusion of V_B
are shown by the dashed line. Additionally, in (a) the dotted line
shows calculations where the usual V_B term (for $J = 2$) is
replaced with a term of opposite sign for $J = 0$ couplings; see
text for details. (c),(d) The four isospin-breaking components of
the shell-model calculation (see text), the total of which sum to
give the solid line in (a) and (b).

elements for protons. (b) The radial term (V_{Cr}) is a mono-
pole term that accounts for the Coulomb energy of changes
in nuclear radius, according to the prescription of [8].
(c) The V_{ll} and V_{ls} terms are monopole terms that account
for Coulomb [8] and electromagnetic [3] shifts to single-
particle levels. (d) The final term (V_B) accounts for the
$J = 2$ effect described earlier—which is found to be nec-
essary for a successful MED description in the shell
[7–9,13]. It is included in the model by adding a single
repulsive interaction of 100 keV to the proton two-body
matrix elements for $f_{7/2}$ protons. This shell-model pre-
scription has been shown to be extremely successful in
describing the J dependence of MED for $T = 1/2$ and 1
states, but has yet to be tested in detail for such a large
difference in T_z, where the monopole terms (which scale
with difference in proton number) will become large. In
addition, for states far above the proton separation energy
(i.e., the excited states in ^{51}Co), the effects of coupling to
the continuum may become more important [28].

The calculated and experimental MED are compared in
Fig. 4(a) for ^{52}Ni/^{52}Cr and Fig. 4(b) for ^{51}Co/^{51}Cr. The
solid line shows the prediction of the MED including
all four effects as described above, and each of the four
individual components to the MED are plotted in Figs. 4(c)
and 4(d). A number of points become apparent in this
comparison. Firstly, the overall agreement is extremely
good for both sets of nuclei, the greatest deviation between
calculation and data being the tentatively assigned highest
spin states in ^{51}Co. Secondly, it can be seen that the two

monopole components V_{ll}/V_{ls} and V_{Cr} [dashed lines in
Figs. 4(c) and 4(d)], which scale with difference in Z, are
large—and comparable with the multipole terms at low
spin. Finally, by comparing the two multipole terms it is
clear that at low spin V_B (open circles), which represents
the $J = 2$ anomaly, is of comparable magnitude to the
Coulomb multipole term V_{CM} (closed circles) and of oppo-
site sign. This has the effect of virtually canceling V_{CM} for
both the 2^+ and 4^+ states.

The clear need for the additional $J = 2$ isovector inter-
action is demonstrated in Fig. 4(a), where the dashed line
shows the effect of not including the V_B term. V_B will
contribute strongly wherever there is a significant change
in the $T = 1$, $J = 2$ component of the wave function for
protons in *one* nucleus (and hence neutrons in its mirror).
An example is the mirror pair ^{54}Ni/^{54}Fe [29,30] (expected
to have a $f_{7/2}^{-2}$ structure), where V_B was found to be
significant for the 2^+ state. In the case of ^{52}Ni(^{52}Cr),
with four neutron (proton) holes in doubly magic ^{56}Ni,
the effect is amplified by the bigger difference in proton
number, and the wave functions of both the 2^+ and 4^+
states are expected to have significant $J = 2$ components.
This is shown very clearly by the open circles in Fig. 4(b),
and Fig. 4(a) provides the most convincing evidence to
date that the anomalous $J = 2$ isovector component of the
two-body interaction for the $f_{7/2}$ shell must be used to
obtain agreement between the shell model and experiment.
For the ^{51}Co/^{51}Cr case, the $J = 2$ strength is distributed
among a wider range of states, and so the effect is less
clear. Nevertheless, as Fig. 4(b) shows, the need for V_B in
this case is equally compelling.

Since these MED are normalized to the ground state, the
analysis presented here is sensitive to the J dependence of
these effects. Thus, one might expect that, rather than a
repulsive $J = 2$ component being added (for protons), one
could include an attractive $J = 0$ component instead. This
was first investigated in Ref. [30], which showed that the
$J = 0$ approach did not have the required effect at higher
spins. This is confirmed in Fig. 4(a), where the dotted line
shows the effect of including an attractive $J = 0$ compo-
nent for protons. This obviously fails to follow the data for
the 6^+ state. It is worth stressing that this region of nuclei is
very well described by large-scale shell-model calculations
in the fp valence space, and yet the evidence for the need
for inclusion of this additional isovector term within this
shell-model description is overwhelming.

It is timely to consider possible origins. If the anomaly
can be genuinely associated with a multipole phenomenon,
as seems to be likely, then the source can only be Coulomb
or nuclear (i.e., charge-symmetry breaking) in origin. The
observed spin dependence of the additional effect (increas-
ing from $J = 0$ to $J = 2$) rules out a simple two-body
Coulomb term alone, as the wave-function overlap of the
pair must *reduce* with increasing J. Of course, we cannot
rule out other Coulomb-induced effects, and attempts have

been made [31] at a renormalization of the Coulomb matrix elements to account for these, but the required J dependence could not be reproduced. In terms of CSB, it has long been recognized that accurate calculations of nuclear masses (e.g., to predict location of the proton drip line) require inclusion of CSB effects in order to correctly determine the CDE. However, the numerical values needed are not known, and usually *effective* isovector matrix elements have been determined by fitting experimental CDE (e.g., Ref. [32]). A recent study from Kaneko *et al.* [33], parallel to the work presented here, is an example of this. In that work, an isospin nonconserving isovector term of 100 keV (attractive for protons in the $J = 0$ channel) was used as it was found necessary in order to reproduce the detailed behavior of the CDE. Thus, there are some indications that the two observations—one concerning ground state energies, the other MED—may have the same origin in this region. However, associating these effects with the nuclear interaction is possibly not safe at this point, and, clearly, some theoretical effort is needed to understand the origin from both a nuclear structure and a fundamental interaction perspective.

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