Observation of ^{46}Cr and Testing the Isobaric Multiplet Mass Equation at High Spin

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The ground state band in ^{46}Cr and the isospin $T = 1$ band in ^{46}V have been delineated up to $I^\pi = 10^+$ (tentatively 12^+). These observations complete the highest spin $T = 1$ isospin triplet known. Following the isobaric multiplet mass equation, a combination of level energies in ^{46}Cr, ^{46}Ti, and ^{46}V are taken to highlight the angular momentum dependence of the isovector and isotensor parts of the interaction. The results are compared with full-fp-space shell model calculations. The influence of the one-body and two-body contributions to the isovector energy difference are investigated.

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The charge independence of the nuclear force has been a central concept in nuclear physics for more than 60 years. Once account is made for the Coulomb interaction, which is very weak compared to the strong nuclear interaction, charge independence states that the nucleon-nucleon force for the same relative state of motion and spin does not depend on whether one considers protons, neutrons, or a combination of the two. This symmetry, together with the fact that proton and neutron masses are nearly identical, prompted the isospin formalism wherein the two types of nucleon are treated as different states of the same particle that are distinguished by the projection of isospin (t_3) onto a quantization axis. In reality, the nucleon-nucleon interaction may have an isovector contribution (i.e., the $nn \neq pp$ interaction) on the order of 1% and an isotensor contribution (the average of the nn and pp interactions $\neq$ the np interaction) on the order of 2% of the strength of the isoscalar interaction [1,2]. Because of the weakness of the isospin nonconserving terms, and assuming that the nuclear Hamiltonian contains only one- and two-body interactions, the binding energies for members of an isospin multiplet of mass A and isospin T can be obtained from the isobaric multiplet mass equation (IMME) [3–5]:

$$BE(A,T,T_3,i) = a(A,T,i) + b(A,T,i)T_3 + c(A,T,i)T_3^2, \tag{1}$$

where i refers to all other common quantum numbers, such as angular momentum, state number, etc. The coefficients a, b, and c depend on the isoscalar, isovector, and isotensor components of the Hamiltonian, respectively. (There is a weak contribution to a from the isotensor interaction from the $\frac{1}{12}S_0^{(2)}V_0$ term; see Eq. (15) in Ref. [5]. This affects the value of a on the order of 0.3%.) The IMME has seen widespread application to nuclei for over 40 years (see, e.g., Refs. [3,4,6]), and was used recently in the mapping of the proton drip line over a wide range [5], important in determining the rp-process path (the radiative capture of protons believed to be responsible in the stellar medium for the production of many elements beyond the iron group) and to identify candidates for two-proton emission [5]. In addition, the IMME is used to constrain models for the isospin breaking correction factor needed for CKM matrix unitarity tests [see, e.g., Ref. [7]].

The IMME has never been thoroughly tested as a function of angular momentum. Coulomb energy differences (CED), the differences in excitation energies for states of the same isospin T and angular momentum I, have been extracted for $T = 1/2$ mirror pairs up to high spin [8,9]. These studies are sensitive to the isovector nature of the interaction only, and have been used as a probe of the spatial correlations of the valence protons. In a $T = 1$ triplet, the lowest isospin where the isotensor contribution can be investigated, the IMME has never been studied above $I^\pi = 6^+$ (in the $A = 42$ system [6]).

Since the level schemes of ^{46}Ti [10] and ^{46}V [11–13] were well established, ^{46}Cr remained as the only missing link in the completion of the $A = 46, T = 1$ triplet. The neighboring $T = 1/2$ CED's were explained by considering proton angular momentum alignment [8,9], and it was of interest to examine if the experimental ^{46}Cr-^{46}Ti CED agreed with recent predictions from the cranked shell model (CSM) [14]. Furthermore, much of the information on isobaric multiplets has been obtained [4,6] from the sd shell. The higher Z available in fp-shell nuclei increases the degree of isospin mixing caused by the Coulomb interaction that is proportional to Z^2.

The experiment to study ^{46}Cr was performed at the ATLAS facility of Argonne National Laboratory. Beams of ^{36}Ar, at an energy of 105 MeV, bombarded three different targets of ^{12}C that were 200, 567, and 602 μg/cm^2 thick. ^{46}Cr was produced via the (^{36}Ar, $2n$) reaction. The reaction products were analyzed with the fragment mass analyzer (FMA) [15] that separates them at the focal plane according to their A/q (mass/charge state) values. For the present experiment, only one A/q value, corresponding to 46/15, was accepted at the focal plane. The focal plane position was determined from multichannel plate detectors and Z identification was achieved from ionization chamber (IC) data that consisted of two energy loss ΔE (ΔE_1 and ΔE_2) signals and a total energy E signal. The γ rays from the reaction were detected with 101 large volume, Compton suppressed HPGe detectors of the GAMMASPHERE array [16]. From the recorded data, γ-ray events were selected by placing conditions $\Delta E_1 + \Delta E_2$ vs E and ΔE_1 vs ΔE_2. Shown in Fig. 1a is a two-dimensional histogram of the $\Delta E_1 + \Delta E_2$ vs E data obtained with the 200 μg/cm^2 target. The regions corresponding to Ti, V, and Cr ions are labeled, and separating them is straightforward. Also shown are γ-ray singles (b) and coincidence (c) spectra after selection of the $Z = 24$ (Cr) events. Minor contributions from the ^{46}Ti and ^{46}V channels, created by gating on the $Z = 22$ and $Z = 23$ reaction products, have been subtracted from the γ-ray singles spectrum. The most prominent features in Fig. 1b are transitions from ^{49}Cr (reaching the focal plane due to A/q ambiguities since $49/16 \simeq 46/15$) from the ^{16}O(^{36}Ar, $2pn$)^{49}Cr reaction on oxygen target contamination. After accounting for ^{49}Cr (only the strongest transitions are labeled on the figure), the remaining lines are candidates for transitions in ^{46}Cr. The results of $\gamma\gamma$ coincidences indicate that the transitions labeled by their energies form a cascade. From intensity relationships, and the expected similarity with the ground state cascade in ^{46}Ti, these transitions are assigned as the yrast band in ^{46}Cr as presented in Fig. 2. (The remaining lines are weaker transitions in ^{49}Cr or have been assigned as off-yrast transitions in ^{46}Cr.) The levels are established firmly up to the 6177-keV 10^+ state; the 1983-keV transition is highly speculative as it was observed in the $Z = 24$ gated γ-ray singles spectrum only and its placement is based solely on its similarity with the 1974-keV, $12^+ \rightarrow 10^+$ transition in ^{46}Ti. Angular distributions of the γ rays assigned to the ground state band are consistent with the expected stretched $E2$ character. A large amount of data was also collected for ^{46}V and the $T = 1$ band is firmly extended to $I^\pi = 10^+$, and tentatively to 12^+. The 8^+ and 10^+ states are newly observed, while the other $T = 1$ states are in agreement with previous studies [11–13].

The variation of the isovector and isotensor contributions as a function of angular momentum can be isolated by taking the following combinations of excitation energies $E_{\rm ex}$:

$$E_{\rm ex}(T_3 = 1, I^\pi) - E_{\rm ex}(T_3 = -1, I^\pi) = -2\Delta b(I), \quad (2)$$

$$E_{\rm ex}(T_3 = 1, I^\pi) + E_{\rm ex}(T_3 = -1, I^\pi) - 2E_{\rm ex}(T_3 = 0, I^\pi) = -2\Delta c(I), \quad (3)$$

which removes the sensitivity to the ground state masses. The experimental CED values are given by the filled points in Fig. 3a for the $T = 1$ bands up to $I^\pi = 12^+$. This is the first time that both the isovector *and* isotensor CED's have been extracted beyond spin 6 for a $T = 1$ system. In both cases, a very smooth dependence as a function of angular momentum is observed.

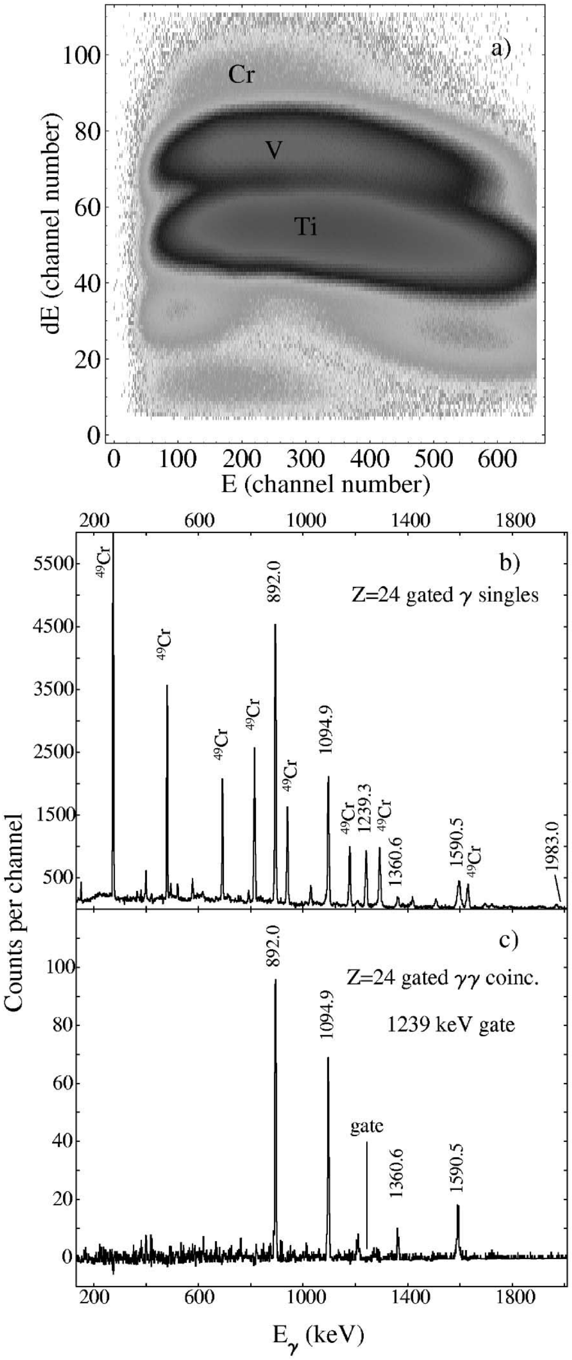

FIG. 1. ΔE vs E plot (a) from ionization chamber data used for Z selection. The scale is proportional to log(counts per channel), and the regions associated with $Z = 24$, 23, and 22 are indicated by Cr, V, and Ti, respectively. The γ-ray singles (b) and coincidence (c) spectra were created by placing conditions to select the $Z = 24$ recoil products.

In order to understand the isovector and isotensor CED values, full-fp-space shell model calculations were performed using the OXBASH code [17]. The FPD6

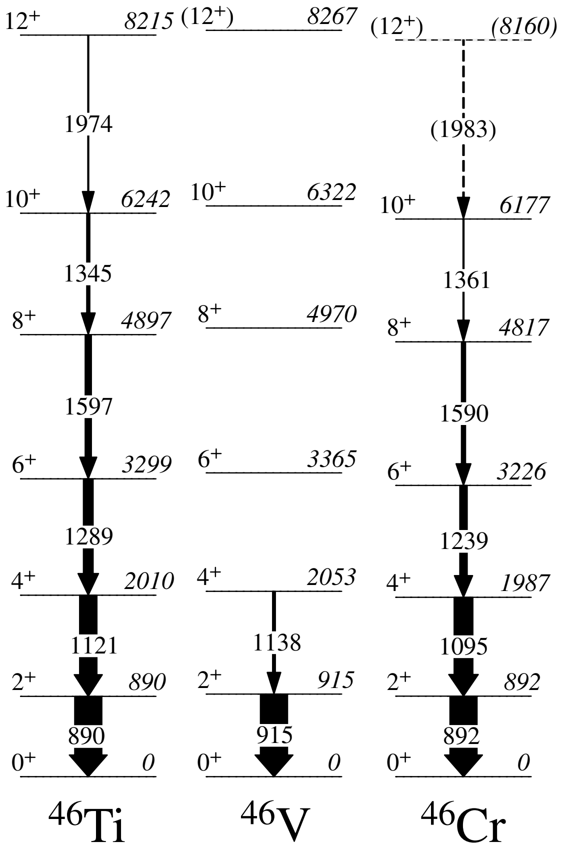

FIG. 2. Partial level schemes, showing only those levels assigned as $T = 1$ states and in-band $E2$ transitions, in ^{46}Ti, ^{46}V, and ^{46}Cr.

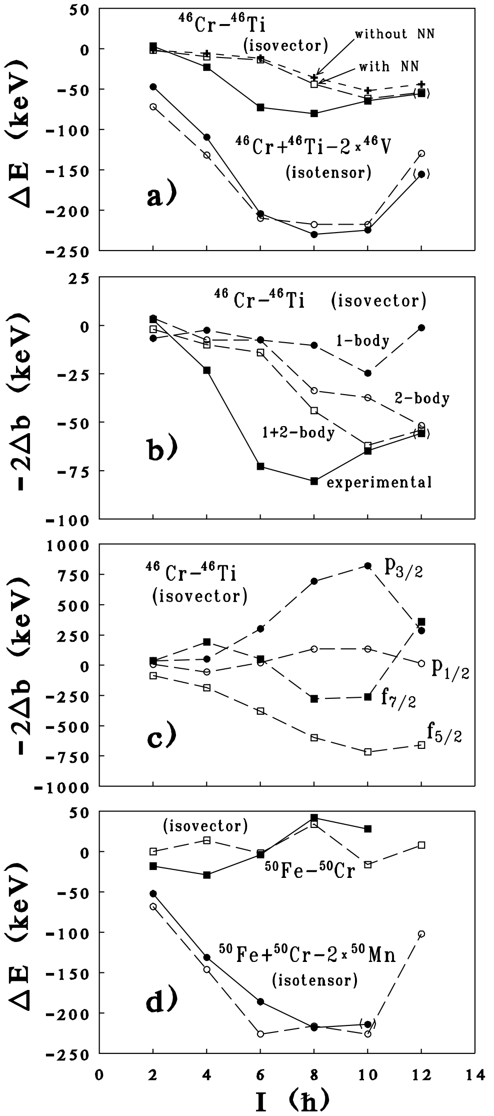

FIG. 3. CED as a function of angular momentum extracted according to Eqs. (2) and (3) highlighting the isovector and isotensor contributions to the energies. In (a), the filled points are the experimental values (those in parentheses are tentative assignments) and the open points are results of fp-shell model calculations (see text for details). The calculated isovector CED without the nucleon-nucleon isovector interaction is also shown (crosses). In (b), the breakdown of the calculated isovector CED into the one-body and two-body contributions is presented. (c) shows how the individual orbitals contribute to the one-body term, and (d) compares data (filled points) for the mass 50, $T = 1$ triplet from Refs. [20,21] with shell model calculations (open points).

Hamiltonian of Ref. [18] was used, with the isospin nonconserving (INC) part consisting of Coulomb plus nucleon-nucleon isovector and isotensor interactions taken from Ref. [19]. The form of the INC Hamiltonian and the procedure determining its parameters are described in Ref. [5]. In previous fp-shell studies, the ground state b coefficients of Eq. (1) were found to be insensitive to the presence of a nucleon-nucleon isovector interaction. Nonetheless, a weak, $\simeq 1\%$, contribution is expected [1,2]. As such, the Coulomb strength parameter was adjusted while including a nucleon-nucleon isovector term that is consistent with scattering data. The strength of the nucleon-nucleon isotensor interaction was also modified slightly to better reproduce the ground-state c coefficient. Along with the single-particle energies of Ref. [5], the values of the parameters used were $S_C = 0.98$, $S_0^{(1)} = -0.01$, and $S_0^{(2)} = -0.05$. These are to be compared with the respective values of 1.006, 0.0, and -0.042 of Ref. [5]. The calculated mass 46 ground-state b and c coefficients of 8.113 MeV and 0.267 MeV are in excellent agreement with the experimental values of 8.109(10) MeV and 0.276(10) MeV.

The calculated values from Eqs. (2) and (3) with (open points), and without (crosses) inclusion of the nucleon-nucleon isovector contribution are also presented in Fig. 3a. The agreement with the data is quite satisfactory, although there is a noticeable discrepancy for the isovector values ($2\Delta b$) for spins 6 and 8. The discrepancy is larger than the overall contribution of the nucleon-nucleon isovector interaction. The latter has the effect, increasing with spin, of lowering the $2\Delta b$ values slightly. For the isotensor contribution, the agreement is remarkable, both in magnitude and variation with spin.

The calculated isovector CED was separated into the one-body and two-body contributions, and these are plotted in Fig. 3b. The two-body part, which represents the interactions of the valence protons, shows a steady increase in magnitude with spin. This behavior should be expected because, as angular momentum is generated from the valence particles, the alignment of the protons lowers the Coulomb energy. Since there are more available protons from which to generate the angular momentum in ^{46}Cr than in ^{46}Ti, the Coulomb energy drops more rapidly in the former, resulting in negative CED values. This is, in fact, opposite to the CSM results [14] that predicted the protons in ^{46}Ti to align before those in ^{46}Cr. The plot also shows that there can be a non-negligible effect from the one-body term; indeed, at some angular momentum values the magnitude of the one-body contribution approaches that of the two-body term. The one-body term can be understood by considering a very simplified model with only two orbitals, having single-particle energies $\mathcal{E}_a$ and $\mathcal{E}_b$ and occupation factors $\alpha^I(T_3)$ and $\beta^I(T_3)$. The contribution to the ground state b coefficient is

$$\begin{aligned} -2b &= [\alpha^{I=0}(T_{3=1}) - \alpha^{I=0}(T_{3=-1})\mathcal{E}_a \\ &\quad + [\beta^{I=0}(T_{3=1}) - \beta^{I=0}(T_{3=-1})]\mathcal{E}_b \end{aligned} \tag{4}$$

and, hence, the change with spin is

$$\begin{aligned} -2\Delta b &= [\Delta\alpha(T_{3=1}) - \Delta\alpha(T_{3=-1})]\mathcal{E}_a \\ &\quad + [\Delta\beta(T_{3=1} - \Delta\beta(T_{3=-1})]\mathcal{E}_b \\ &= [\Delta\alpha(T_{3=1}) - \Delta\alpha(T_{3=-1})](\mathcal{E}_a - \mathcal{E}_b), \end{aligned} \tag{5}$$

where $\Delta\alpha$ is the change in the occupancy factor as a function of spin and the last equality expresses the conservation of particles (an increase in the occupancy factor for one orbital must accompany a decrease for the other). Therefore, since in realistic calculations the single-particle energies are not identical, a one-body contribution is generated when there is a difference in the evolution of occupancy factors between the two nuclei. Figure 3c illustrates $[\Delta\alpha(T_{3=1}) - \Delta\alpha(T_{3=-1})]\mathcal{E}$ for each orbital; the sum of all four gives the one-body contribution.

Finally, it is interesting to compare the results for the $A = 46$ triplet with those from the $A = 50$ triplet, shown in Fig. 3d, where the level energies are obtained from Ref. [20] for ^{50}Fe and ^{50}Cr and unpublished data [21] for ^{50}Mn. The isotensor energy difference is remarkably similar and reproduced well by the shell model calculations. The same degree of agreement is not evidenced by the isovector part, which has a completely different behavior with angular momentum. In the $A = 50$ case, the CED values show an overall rise, in qualitative agreement with the CSM predictions [14], which, nevertheless, overestimate the extent of the increase.

In summary, an experiment to observe excited states in ^{46}Cr using the ^{12}C(^{36}Ar, $2n$) reaction with GAMMASPHERE and the FMA has been performed. The yrast band in ^{46}Cr and the $T = 1$ states in ^{46}V have been established up to (tentatively) 12^+, the highest spin $T = 1$ triplet known. Coulomb energy differences are extracted that highlight the change in the isovector *and* isotensor interactions as a function of angular momentum above spin 6 for the first time. The results are used to test fp-shell model calculations, which are in excellent agreement with the isotensor CED but display some discrepancies at low spins for the isovector CED. It is also shown that the nucleon-nucleon isovector contribution is negligible, whereas there can be a significant one-body contribution to the isovector CED.

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