Yrast structure of ^{64}Fe

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The level structure of the $N = 38$ isotone ^{64}Fe was studied with the ^{64}Ni + ^{238}U reaction at 430 MeV. Several new levels were identified and compared to shell model calculations. Results show no evidence for deformation in the ground state, but a possible contribution from intruder orbitals at higher energy and spin.

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I. INTRODUCTION

The structure of ^{68}Ni$_{40}$ and adjacent nuclei has been of considerable interest as neutron number 40 marks the filling of the $N = 3$ oscillator shell. This region has been particularly interesting since the discovery that the 2^+ energy in ^{68}Ni rises to >2 MeV as a result of the sub-shell gap separating the *pf* and $g_{9/2}$ orbitals. This gap, however, seems to disappear or substantially reduce in size when protons are added to or subtracted from ^{68}Ni, making this region of the nuclear chart an important landscape for studying the effects of proton-neutron interactions and the onset of deformation [1].

The 2^+ energies of nuclei in this mass region are given in Fig. 1. The parallel trends exhibited by Zn-Ge, Fe-Se, and Cr-Kr isotones are worth noting, as this can be viewed as a consequence of the interaction between the valence proton orbital and the $g_{9/2}$ neutron orbital. Thus, the 2^+ energies in the $Z = 30$, 32 Zn and Ge nuclides reflect the filling of the $p_{3/2}$ proton orbital, and therefore the trends depicted in Fig. 1 reflect the interaction between $p_{3/2}$ protons and $g_{9/2}$ neutrons. Similarly, the presence of two holes in the $f_{7/2}$ and two particles in the $f_{5/2}$ proton orbitals manifests itself in the $Z = 26$, 34 Fe and Se nuclei, respectively, while the $Z = 24$, 36 Cr and Kr nuclides represent four holes in the $f_{7/2}$ and four particles in the $f_{5/2}$ orbitals.

Recent reports on even-even Cr isotopes indicate a lowering of the 2^+ energies with increasing neutron number. This has been interpreted as an indication that these nuclei belong to a new region of deformation [2] (although this interpretation has recently come into question [3]). This follows the argument set forth by Hannawald *et al*. [1] to explain the downward trend in 2^+ energy observed for ^{64,66}Fe. Drawing on the 2^+ energy parallels outlined above, it is worth mentioning some of the properties of the well-documented $Z > 28$ nuclides following the argument that they can be compared with the analogous $Z < 28$ counterparts. Perhaps the most significant conclusion to be brought forth by such a comparison is the shape-driving nature of the $g_{9/2}$ neutron orbital near $N = 40$. For example, the $N = 38$, 40 Sr isotopes exhibit strong prolate deformation [4], which is reflected in the very low 2^+ energies of Fig. 1. In addition, $^{72}_{36}$Kr has been observed to show characteristics of oblate deformation in its ground state [5], which gives way to shape coexistence in ^{74}Kr as both prolate and oblate energy minima are encountered [6]. Se isotopes have also been reported to possess some degree of oblate deformation and shape coexistence (for example, see Ref. [7]). Although the properties of $Z > 28$ nuclides should not be expected to translate exactly into their $Z < 28$ analogs, because of the complex interactions involved, they may serve as a useful guide when assessing the less well studied neutron-rich nuclides below Ni.

Continuing progress on the odd-*A* Cr isotopes has given indication for the presence of prolate rotational bands built on the $g_{9/2}$ states in ^{55,57}Cr [8] and of a structure built on a $g_{9/2}$ isomeric state associated with a small oblate deformation in ^{59}Cr [9]. Low-lying positive parity states in ^{55,57,59}Cr, ^{61}Fe, and isomers observed in ^{65,67}Fe indicate a strong presence of the $g_{9/2}$ neutron orbital in stabilizing the spectral properties of these nuclei [8–11]. This has been experimentally confirmed with a g-factor measurement of the $9/2^+$ isomer in ^{61}Fe [12]. Fewer data are available, however, for the even-*A* nuclides. In fact, nothing has yet been reported beyond the 2^+ levels for the $N = 38$ and $N = 40$ isotones below Ni. Hence, the purpose of this study is to extend the known level structure of ^{64}Fe to higher energy and spin so that a more detailed description of the structural characteristics of this transitional region can be obtained. This is accomplished by measuring the γ rays emitted following complex reactions between ^{64}Ni and ^{238}U and by, subsequently, comparing the results with shell model calculations.

II. EXPERIMENT AND RESULTS

Excited levels in ^{64}Fe were populated in collisions between a ^{64}Ni beam and a ^{238}U target in an experiment performed with the Argonne Tandem Linear Accelerator System (ATLAS) at Argonne National Laboratory. The adopted 430-MeV beam energy corresponds to a value ∼25% above the Coulomb barrier in the entrance channel. The beam was incident upon a 55 mg/cm^2 isotopically enriched target centered within

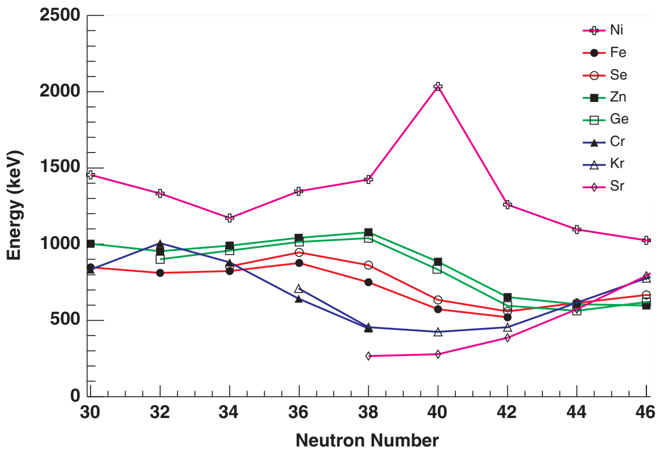

FIG. 1. (Color online) The 2^+ energy trends for selected nuclides near ^{68}Ni.

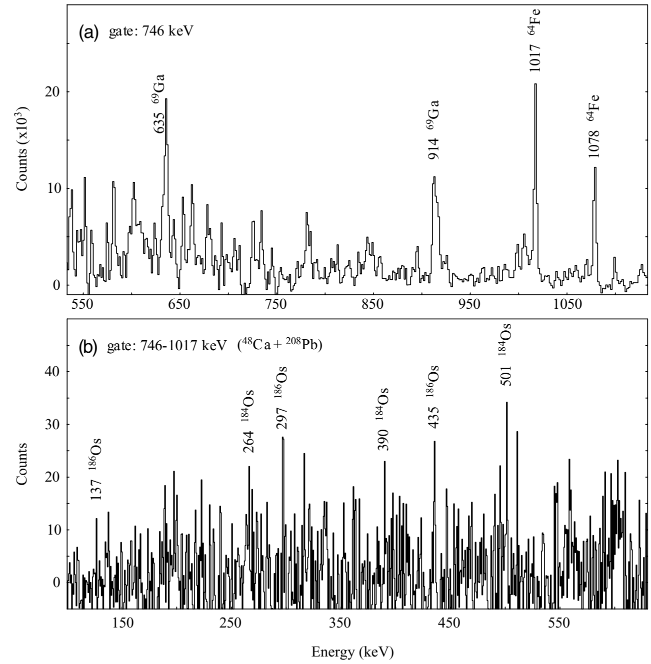

FIG. 2. (a) The γ-ray spectrum obtained by setting a single gate at 746 keV in the data from the deep-inelastic reaction of ^{64}Ni and ^{238}U. (b) The spectrum obtained from a double gate on 746- and 1017-keV γ rays in data from the deep-inelastic reaction of ^{48}Ca and ^{208}Pb [18].

the Gammasphere array, which consisted of 100 Compton suppressed HPGe detectors [13]. A beam current of $\sim 4 \times 10^8$ ions per pulse was maintained for approximately 5 days. Beam bursts were separated by 410-ns intervals so that the presence of short-lived isomers could be identified. Events were recorded on the basis of threefold or higher coincidences. This enabled the distinction between prompt events, which arrived during the beam bursts and decay events, which came from buildup of reaction products within the target. Thus, the coincidence requirement that three detectors fire during a beam pulse (prompt coincidence) produced clean spectra in which longer cascades were enhanced with respect to background. Similarly, spectra could be generated in which three γ rays were required in coincidence between beam pulses (delayed coincidence). Data requiring both prompt and delayed events were analyzed as well in order to study deexcitations across isomers, for example.

The 746-keV $2^+ \rightarrow 0^+$ transition, which was first reported by Hannawald *et al.* [1] and later confirmed by Sorlin *et al.* [14] and Matea [15], was used as a starting point for the identification of new transitions associated with ^{64}Fe. The spectrum obtained from this single coincidence gate is presented in Fig. 2(a). Four strong peaks can be clearly distinguished from the more complex background, typical for the selectivity of such a simple coincidence requirement. Upon further investigation, two of these γ rays could be easily associated with known transitions in ^{69}Ga, a nucleus where the $13/2^+ \rightarrow 9/2^+$ yrast transition lies at 745.6 keV [16]. The two remaining peaks could not be placed in any other known γ cascade and were, therefore, assumed to be candidates for higher-lying transitions in ^{64}Fe. In fact, the peak at 1017 keV could be retrospectively identified in a spectrum measured at ISOLDE following the β decay of ^{64}Mn [17]. Furthermore, a double-coincidence gate placed on the 746- and 1017-keV transitions in the data set from a previous experiment with ^{48}Ca and ^{208}Pb produced weak, but discernible, lines corresponding to yrast transitions in the Os isotopes, as shown in Fig. 2(b) (for experimental details, see Ref. [18]). This is a clear indication that the γ rays belong to Fe because, for this particular colliding system, Fe and Os are produced simultaneously as reaction partners. Therefore, transitions in the Fe and Os isotopes will appear in coincidence with one another. The assignment to ^{64}Fe then follows because the 746-keV $2^+ \rightarrow 0^+$ transition has been measured previously. A similar γ-ray cross-correlation analysis could not be performed with the current data because the target-like nuclei are expected to mostly undergo prompt fission.

The spectrum from a double-coincidence gate on the 746- and 1017-keV transitions is presented in Fig. 3. New lines are observed at 781, 1005, and 1078 keV. These are found to be in mutual coincidence with each other and with the 746- and 1017-keV γ rays. Additional lines are observed at 582 and 687 keV that are in mutual coincidence with the 746-, 1017-, and 1078-keV lines, but not with each other. A noticeable energy broadening of the 1078-keV γ line gave indication for a possible doublet consisting of similar intensity components with an energy difference in the range of 1 keV. Indeed, the double-coincidence gates placed on the 746-keV line and correspondingly lower- and higher-energy parts of the 1078-keV peak resulted in clearly different spectra. Careful examination confirmed the presence of two closely spaced transitions with the lower-energy component being in coincidence with the 582-keV line and the higher-energy component forming an yrast cascade with the upper 781- and 1005-keV transitions. This is illustrated in the inset in Fig. 3, where selected portions of the 582-746 (upper panel) and 781-746 (lower panel) double-gated spectra are given. Besides the 1005-keV line appearing only in the lower spectrum, one observes a shift in the position of the 1078-keV peak. The centroids obtained from these spectra determined the 1077.8- and 1078.9-keV energies for the corresponding

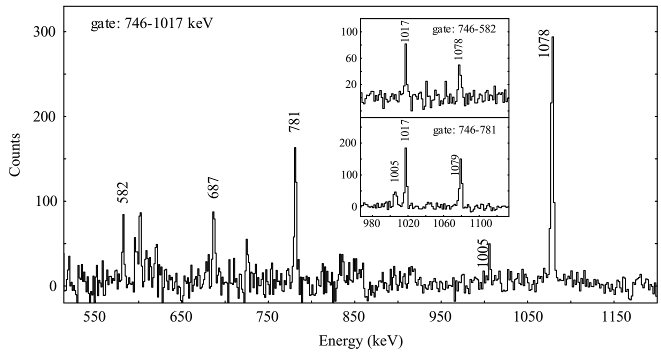

FIG. 3. The γ-ray spectrum obtained by setting a double gate on 746- and 1017-keV γ rays. The inset shows portions of spectra obtained from 746-582 (top) and 746-781 (bottom) double gates.

components of the doublet. The proposed level scheme obtained from these data is provided in Fig. 4.

Angular correlations were used to determine the multipolarity of several γ-ray transitions identified from this experiment. For this analysis, a ten-point curve was fit to the data from which customary a_2 and a_4 correlation coefficients were determined. Each point represents the angle between two Gammasphere detectors and is given on the x axis of the plots in Fig. 5. To determine the angular correlation coefficients, a two-γ cascade is selected in which the area of one peak is determined from a coincidence gate placed on the other. The expected a_2 coefficient for a pure quadrupole-quadrupole sequence is $\sim$0.1, whereas the corresponding value for a pure quadrupole-dipole cascade is ~ -0.7. With this procedure, the 1017-746 cascade, displayed in Fig. 5(a), is determined to be of $E2$-$E2$ character, providing the spin-parity assignment of 4^+ to the 1763-keV state. The two members of the 1077.8/1078.9 doublet exhibit a stark contrast in their respective angular correlations, depending on which γ ray is measured in conjunction with the 746- or 1017-keV transition, as illustrated in Figs. 5(b) and 5(c). The curve produced from a coincidence gate on the lower-energy component strongly resembles that of a quadrupole-dipole transition, whereas the curve produced from a similar gate on the higher-energy component is suggestive of a sequence of quadrupole-quadrupole character. This fact not only reinforces the concept that this peak is,

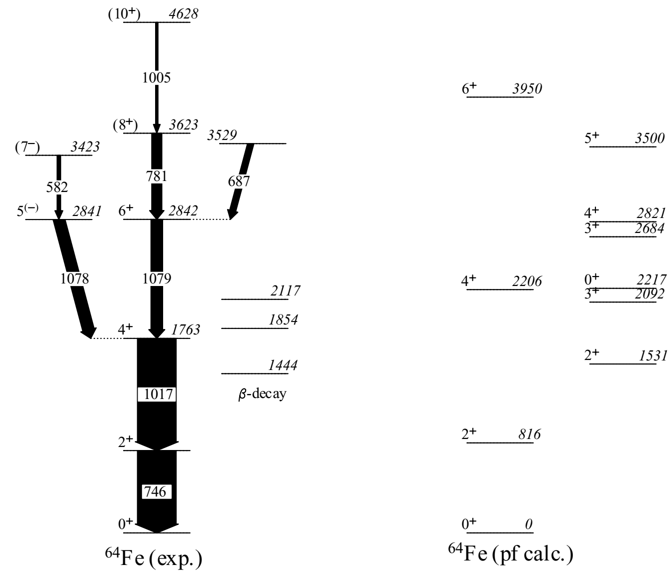

FIG. 4. The proposed level scheme for ^{64}Fe compared with shell model calculations (see text for details). Included with the experimental levels are three low-energy levels reported by Hannawald [20].

indeed, a doublet, but, given the quadrupole nature of both the 746- and 1017-keV transitions established above, also supports spin assignments of 5 and 6 for the levels at 2841 and 2842 keV, respectively. Although parity assignments cannot be unambiguously made from this type of angular correlation analysis, a positive parity is assigned to the $J = 6$ level at 2842 keV because it seems to be naturally part of the main yrast cascade. The 781-keV peak is too weak in intensity to obtain a reliable fit in any single coincidence gate, but the summation of 1017- and 1078.9-keV gates does produce a curve that supports a quadrupole character and, therefore, the level at 3623 keV is tentatively assigned $J^\pi = 8^+$, with the parity assignment following the same argument that was used for the 6^+ level. The level at 4628 keV is tentatively assigned a spin and parity of 10^+, because it appears to represent the extension of the yrast cascade toward higher angular momentum. All relevant a_2 and a_4 coefficients are given in Table I as well as the gate from which each was determined.

TABLE I. Levels and γ rays identified from the deep-inelastic reaction of ^{64}Ni and ^{238}U. Also included are the angular correlation coefficients, where they could be determined.

E_{level} (keV)	J^π	E_γ (keV)	I_γ (rel.)	a_2	a_4	Gate[a]
746	2^+	746.4(1)		0.14(3)	0.01(4)	1017
1763	4^+	1016.7(1)	100	0.14(3)	−0.09(3)	746
2841	$5^{(-)}$	1077.8(2)	58(3) { 12(3)[b]	−0.13(6)	0.22(8)	1017
2842	6^+	1078.9(3)	50(7)[b]	0.31(5)	−0.11(7)	1017
3423	(7^-)	582.0(2)	12(1)			
3528	>6	686.9(2)	20(2)			
3623	(8^+)	781.0(1)	30(2)	0.11(3)	−0.06(5)	1017+1078.9
4628	(10^+)	1005.4(5)	6(1)			

[a]Gate from which the angular correlation coefficients were determined.
[b]The combined intensity, 58(3), of the two transitions is the quantity that can be extracted most reliably from the present data; the values 12(3) and 50(7) are estimated from coincidence relationships and feeding and decay intensity patterns.

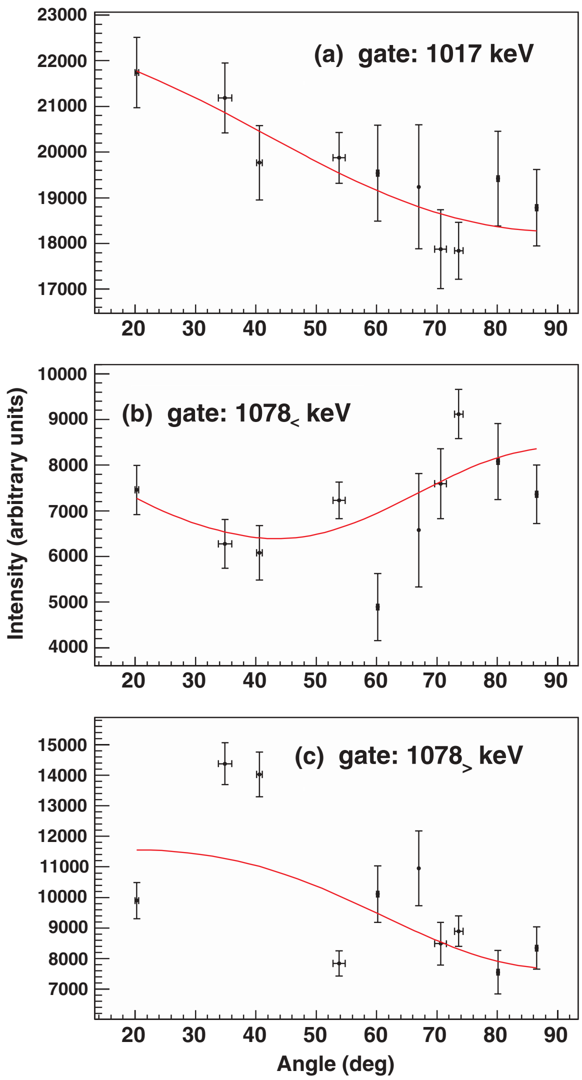

FIG. 5. (Color online) Angular correlation curves for the 1017-keV transition and high- and low-energy components of the 1078-keV doublet. Each point was determined by fitting the 746-keV peak in the respective gates denoted in each plot.

The new level at 3529 keV appears to feed the 6^+ yrast level and not the lower-energy 4^+ state and, therefore, is assigned a spin of 6 or greater. As the new level at 3423 keV depopulates only to the spin 5 level at 2841 keV, and not to the 6^+ level at 2842 keV, a negative parity assignment for the 2841-keV level is favored and a tentative spin and parity of 7^- is favored for the 3423-keV state.

III. DISCUSSION

The 2^+ energy trends for Fe isotopes, displayed in Fig. 1, show a clear downward trend with increasing neutron number. As alluded to above, this behavior is often correlated with the onset of deformation. In this context, it is worthwhile to note that the 4^+ level energy of 1763 keV results in a 4^+ to 2^+ energy ratio ($E_{4/2}$) of only 2.36, which is significantly lower than the value of 3.33 expected for a perfect rotor. In fact, the systematic trajectory exhibited by the Fe isotopes shows a downward trend in $E_{4/2}$ from 2.57 to 2.48 to 2.36 for $N = 34$, 36, and 38, respectively. This observation is in direct contrast with what might be expected if the neutron-rich Fe nuclei were members of a region of increasing deformation as N approaches 40. Similar findings have recently been reported by Zhu *et al.* for the $N = 34$, 36 Cr isotopes [3]. In this isotopic chain as well, the 2^+ energy is observed to drop precipitously with increasing neutron number, whereas the $E_{4/2}$ ratio remains of the order of 2.4. It is, therefore, proposed that ^{64}Fe is not characterized by a significant ground state deformation and that an interpretation in terms of the shell model is warranted.

^{64}Fe can be viewed as an inert ^{48}Ca core with six protons and ten neutrons occupying the orbitals above magic numbers 20, for protons, and 28, for neutrons, i.e., the $\pi f_{7/2}$ and $\nu(p_{3/2}, p_{1/2}, f_{5/2}$, and $g_{9/2})$ orbitals. The ground and excited states can then be described by the interactions of the valence nucleons in the orbital space above. With this view in mind, shell model calculations were performed with the Oslo shell model code and a ^{48}Ca effective interaction generated from the n3lo *NN* interaction [19] in a model space that included the p and f orbitals only. Neutron and proton single particle energies were obtained from the empirical values derived from available data on ^{49}Ca and ^{49}Sc. Even in such a limited model space, the computed 2^+ energy of 816 keV is quite close to the measured value of 746 keV, indicating that higher-lying orbitals located above the $N = 40$ harmonic oscillator gap do not play a significant role in the configuration of the first excited state. The associated shell model configuration indicates that the six protons above Ca are distributed such that four occupy the $f_{7/2}$ orbital, one occupies the $p_{3/2}$ state, and the last has a wavefunction spread over the $f_{7/2}$ (22.8%), $f_{5/2}$ (18.7%), $p_{3/2}$ (32.9%), and $p_{1/2}$ (25.5%) levels. The ten neutrons outside ^{48}Ca are then represented with four in the $f_{5/2}$ orbital, three in the $p_{3/2}$ state, and one in the $p_{1/2}$ level, with the remaining two distributed over the $f_{5/2}$ (9.2%), $p_{3/2}$ (98.6%), and $p_{1/2}$ (92.1%) orbitals. It is also possible that the agreement between experiment and theory extends to other low-spin levels identified at 1444, 1854, and 2117 keV from β-decay experiments [20], but spin and parity assignments are presently lacking. Finally, it should also be pointed out that Caurier, Nowacki, and Poves [21] have recently reported on calculations in which a partially truncated *pfgd* model space was used. Compared with smaller spaces, this produced only a slight drop in the 2^+ energy for ^{64}Fe, consistent with experiment, suggesting again that the effect of the $g_{9/2}$ intruder orbital is minor for the lowest excitations.

The agreement between the results of *pf* shell model calculations and experiment quickly deteriorates at higher energy and spin, as the 4^+ energy is overpredicted by nearly 450 keV and that of the 6^+ state by nearly 1 MeV. This discrepancy can most likely be attributed to the limited model space used. Here as well, there is an analogy with the work of Zhu *et al.* [3] where a compression in energy of the experimental levels in ^{60}Cr with respect to *pf* shell model calculations was reported and assigned to the impact of the $g_{9/2}$ intruder. This assertion was made on the basis of experimental data on the excitation energy of negative-parity states in the even Cr isotopes and of $9/2^+$ levels in the odd Cr neighbors, backed by preliminary calculations in a *pfg* model space. Unfortunately, inclusion of the $g_{9/2}$ orbital for the shell model calculations employed in this study had the effect of rendering the calculations impracticable owing to memory limitations and available computer power. Furthermore, the work by Caurier, Nowacki, and Poves in Ref. [21] does not report the results of calculations beyond the 2^+ level, but some experimental indications on the location in energy of the $g_{9/2}$ orbital can be gleaned from an examination of the negative-parity states. It is worth noting that the position of the 5^- level drops consistently in energy from 4214 to 3514 to 3016 to 2841 keV from ^{58}Fe to ^{64}Fe. Similarly, the energy of the 7^- state decreases from 4699 keV in ^{58}Fe to 4299 keV in ^{60}Fe with a further reduction to 3604 and 3422 keV in the two heavier isotopes ^{62}Fe and ^{64}Fe. Clearly, further progress in the interpretation requires calculations including the $g_{9/2}$ intruder.

In an attempt to gain further insight into the structure of ^{64}Fe, a comparison of the yrast sequences in all the known $N = 38$ isotones, including new data from the present work, is presented in Fig. 6. The level structure of these $N = 38$ isotones is seen to evolve gradually with the addition of protons from the spherical ^{66}Ni, with a closed $Z = 28$ proton shell and two neutron holes in the $N = 40$ sub-shell, to the structure of ^{76}Sr which is characteristic of a strongly deformed rotor [4,22]. In contrast to this smooth evolution from Ni to Sr, the removal of a single proton pair from ^{66}Ni to ^{64}Fe produces a distinct drop in excitation energy of all the yrast levels, a trend that seems to continue further with the abrupt drop of the energy of the 2^+ level in ^{62}Cr. In fact, the level sequence of ^{64}Fe appears to compare rather well with that of ^{72}Se. The marked similarity between the two isotones was already evident in Fig. 1, where the $E(2^+)$ systematics was shown. The latter similarity can be ascribed, at least qualitatively, to the similarity of the interaction of the two $f_{7/2}$ proton holes with the ten valence neutrons in ^{64}Fe and that generated by the same neutrons with a proton configuration dominated by two $f_{5/2}$ protons in ^{72}Se. It is now evident that not only the 2^+ level but also the 4^+, 6^+, 8^+, and 10^+ levels compare well, with only the 6^+ energy differing by more than 200 keV. This discrepancy can be understood, at least qualitatively, as arising from the fact that the 6^+ level in ^{64}Fe is likely dominated by the maximally aligned two-proton hole configuration from the $f_{7/2}$ orbital, whereas the analogous configuration with $f_{5/2}$ protons in Se can only reach 4^+. Despite this single nonconcurrence, the rather extensive similarity between the

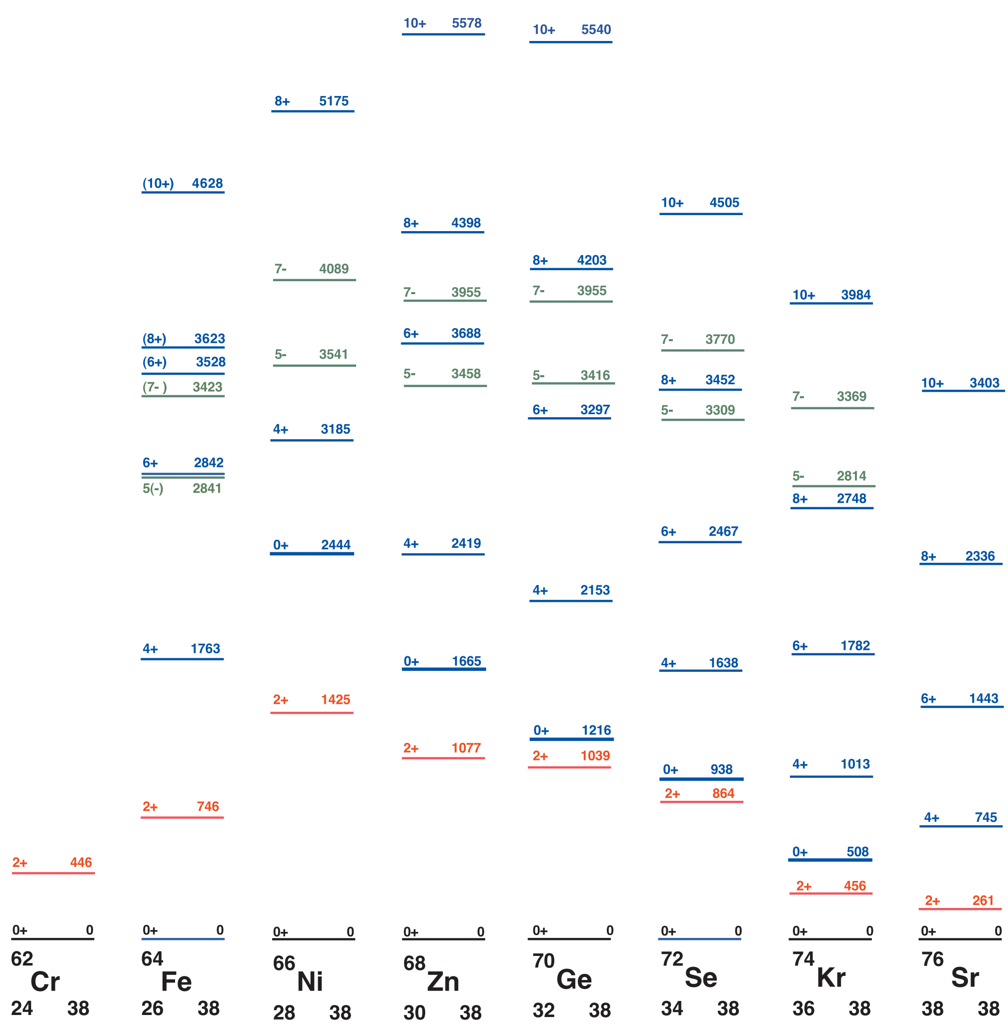

FIG. 6. (Color online) Levels in the $N = 38$ isotones.

yrast states of these two nuclei could be viewed as an indication that the underlying configuration and structural characteristics are comparable, at least to first order. Thus, one might consult the extensive literature associated with the interpretation of ^{72}Se for a possible understanding of the structure of ^{64}Fe (see, for example, Refs. [23–25]). In this context, the degree of collectivity associated with the 0_2^+ and 2_2^+ states [23] in ^{72}Se is particularly intriguing as a shape coexistence picture begins to emerge. Unfortunately, non-yrast states like these are not strongly populated in deep-inelastic processes, and the relevant 0_2^+ and 2_2^+ levels remain to be firmly established in ^{64}Fe.

IV. CONCLUSION

The yrast sequence of ^{64}Fe has been delineated up to moderate spin (10^+) through the study of highfold coincidence data measured with Gammasphere following complex reactions of ^{64}Ni with ^{238}U. The observed $E_{4/2}$ energy ratio is not consistent with expectations for a deformed nucleus, leaving much doubt about the proposed onset of deformation in the Fe isotopes near neutron number $N = 40$. Rather, the 2^+ energy could be well reproduced by shell model calculations in which a *pf* model space is used. However, this rather restricted model space appears to be insufficient at higher energy and spin, an observation that can most likely be attributed to the increasing role of the $g_{9/2}$ neutron intruder orbital. It is hoped that the present data will stimulate further calculations in a more extended shell model space incorporating this intruder state. An intriguing congruency was also noted between the yrast sequences of the $N = 38$ isotones ^{64}Fe and ^{72}Se, presumably reflecting similar interaction strengths for $\ell = 3$ ($f_{7/2}$ and $f_{5/2}$) protons and $g_{9/2}$ neutrons. It is understood that this comparison is solely phenomenological and does not consider the actual complexity of the effective interactions at play. For example, the monopole tensor interaction discussed by Otsuka *et al.* [26,27] should affect differently protons occupying the $f_{7/2}$ and $f_{5/2}$ orbitals and this, in turn, should impact the neutron single-particle spectra involved. It will be interesting to see if other analogies in level structures of this type occur in this region, making such comparisons a useful guide for the understanding of hard-to-reach neutron-rich nuclei.

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