Weak coupling and near spherical shell-model structures in Fe isotopes

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Decay of Neutron-Rich Mn Nuclides and Deformation of Heavy Fe Isotopes

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Yrast structure of ^{64}Fe

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This study started 10 years ago here at ISOLDE with the identification of the 2+ energies for $^{64,66}Fe$ populated in the decay of $^{64,66}Mn$ selectively ionized by RILIS. Until we started the new study at Argonne for high-energy levels in ^{64}Fe with the deep inelastic reactions, NO OTHER DATA WERE AVAILABLE FOR any other excited levels in $^{64,66}Fe$.

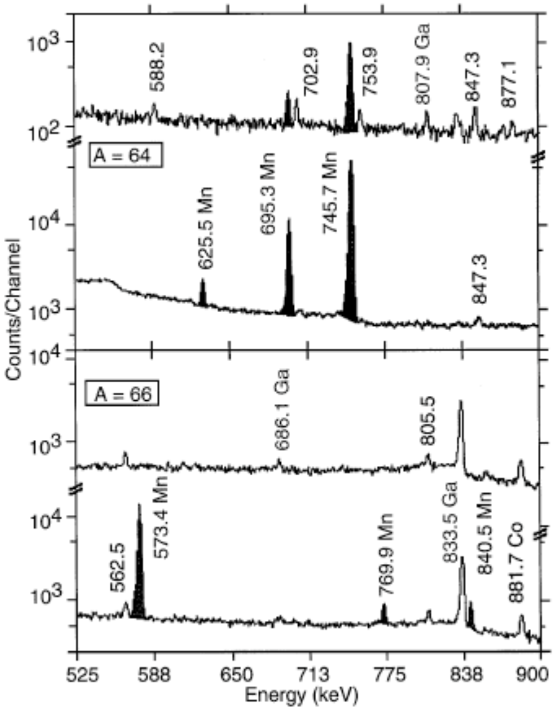
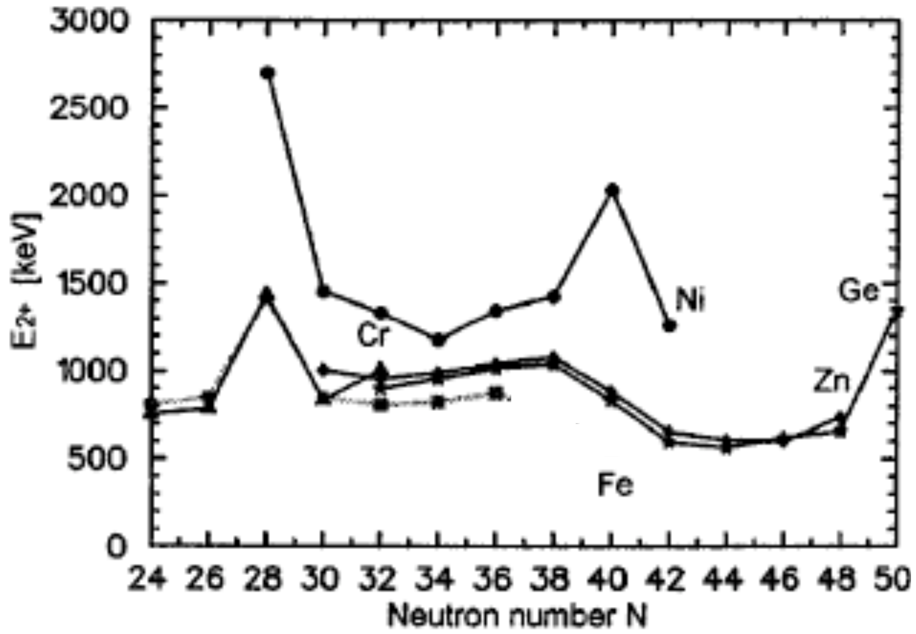
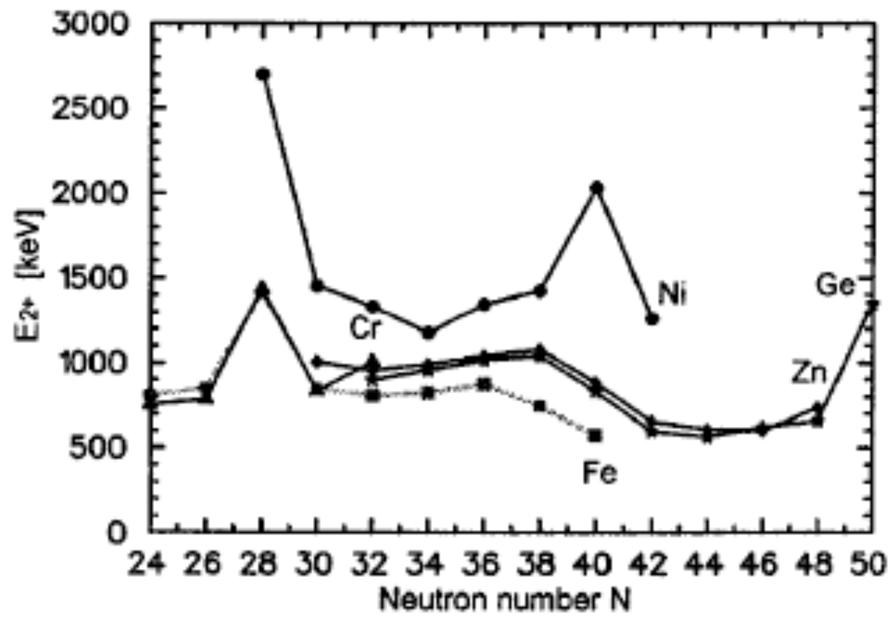


FIG. 2. Partial γ-ray spectra taken at $A = 64$ (upper part) and $A = 66$ (lower part), one for the time period from 40 to 140 ms after the PSB proton pulses, and a second for the time slice from 800 to 900 ms after bombardment.





$^{63}Ni_{35}$ [9]. Because of the lowered position of the base $\nu g_{9/2}$ orbital, it can be seen by reference to Fig. 12 in [10] or Fig. 7 in [5] that, as the neutron number increases beyond 36, the down-sloping $\nu[440]1/2^+$ and $\nu[431]3/2^+$ orbitals are more likely to be occupied than the spherical orbitals, thus generating increased deformation at $N = 40$. This collectivity increase beyond $N = 36$ can be seen to correlate with the difference between the masses calculated with a spherical model and the measured values shown by Richter *et al.* [12] in their Fig. 1. From the trends in that figure, it can be expected that $^{64}Cr_{40}$ may be even more deformed than $^{66}Fe_{40}$.

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THE EUROPEAN PHYSICAL JOURNAL A

New region of deformation in the neutron-rich $^{60}_{24}Cr_{36}$ and $^{62}_{24}Cr_{38}$

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Four years later, support was published from both MSU and GANIL for our suggestion of larger deformation for the Cr isotopes that included new 2+ energies for $^{58,60,62}Cr$ that did show rapidly dropping 2+ energies as N = 40 was approached. And, it was found that shell-model calculations were not able to reproduce the observed drop in energy as N increased from 36 to 38.

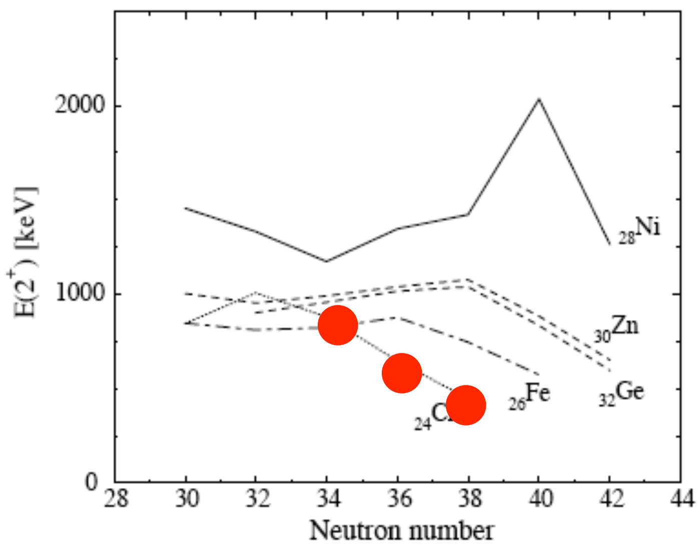


Fig. 4. 2^+ energies in the Ca, Cr, Fe and Ni isotopic chains around $N = 40$. Experimental values of ^{58}Cr and in the neutron-rich $^{64,66}Fe$ have been taken from refs. [17] and [3], respectively.

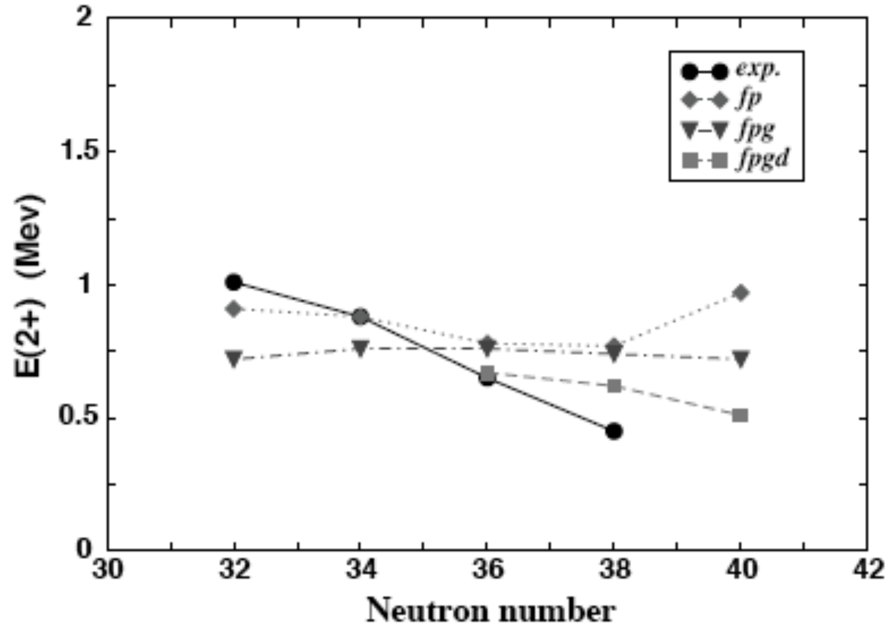
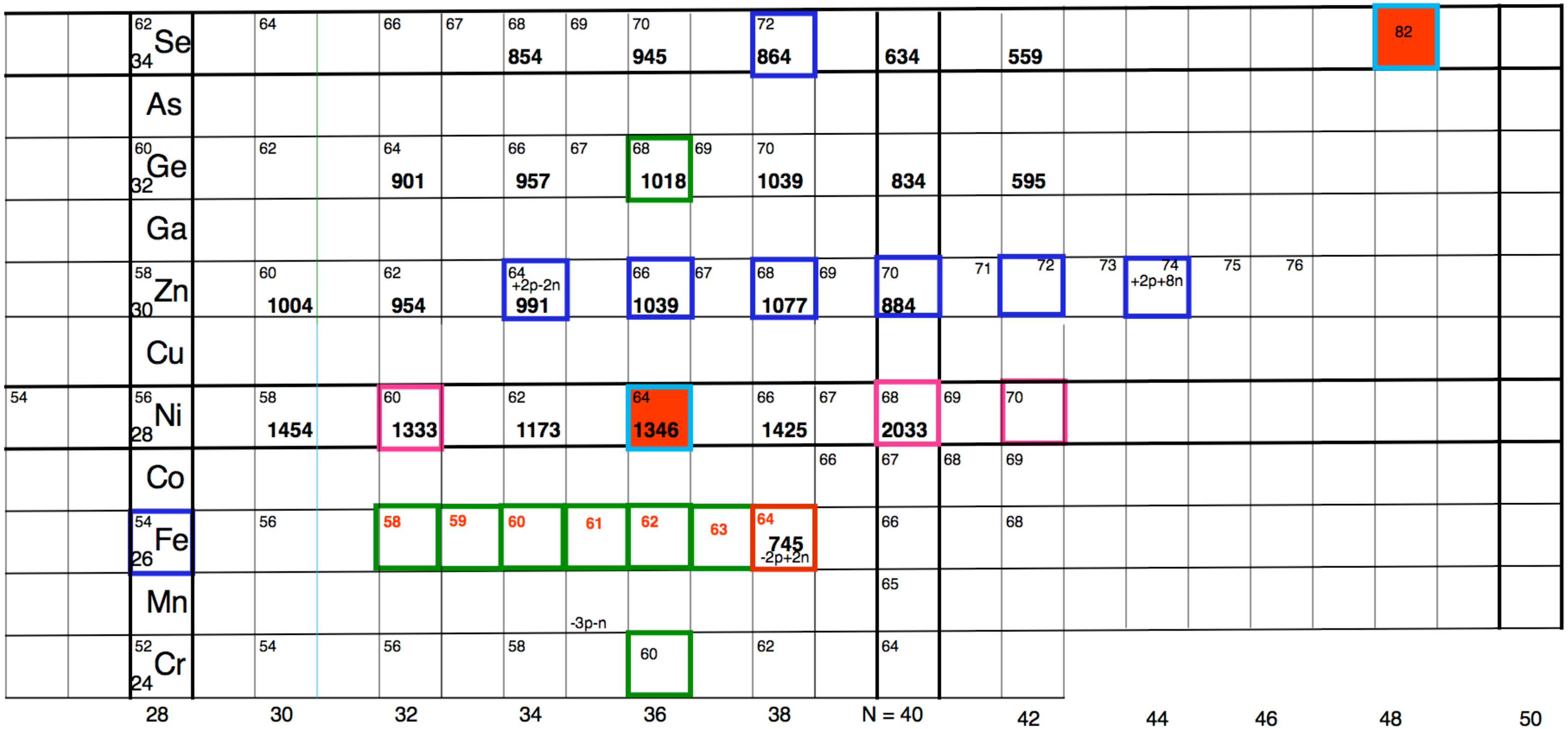
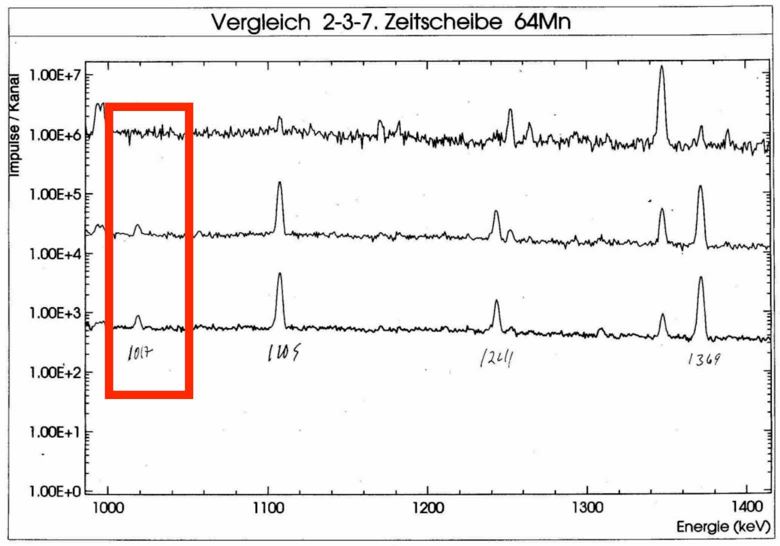


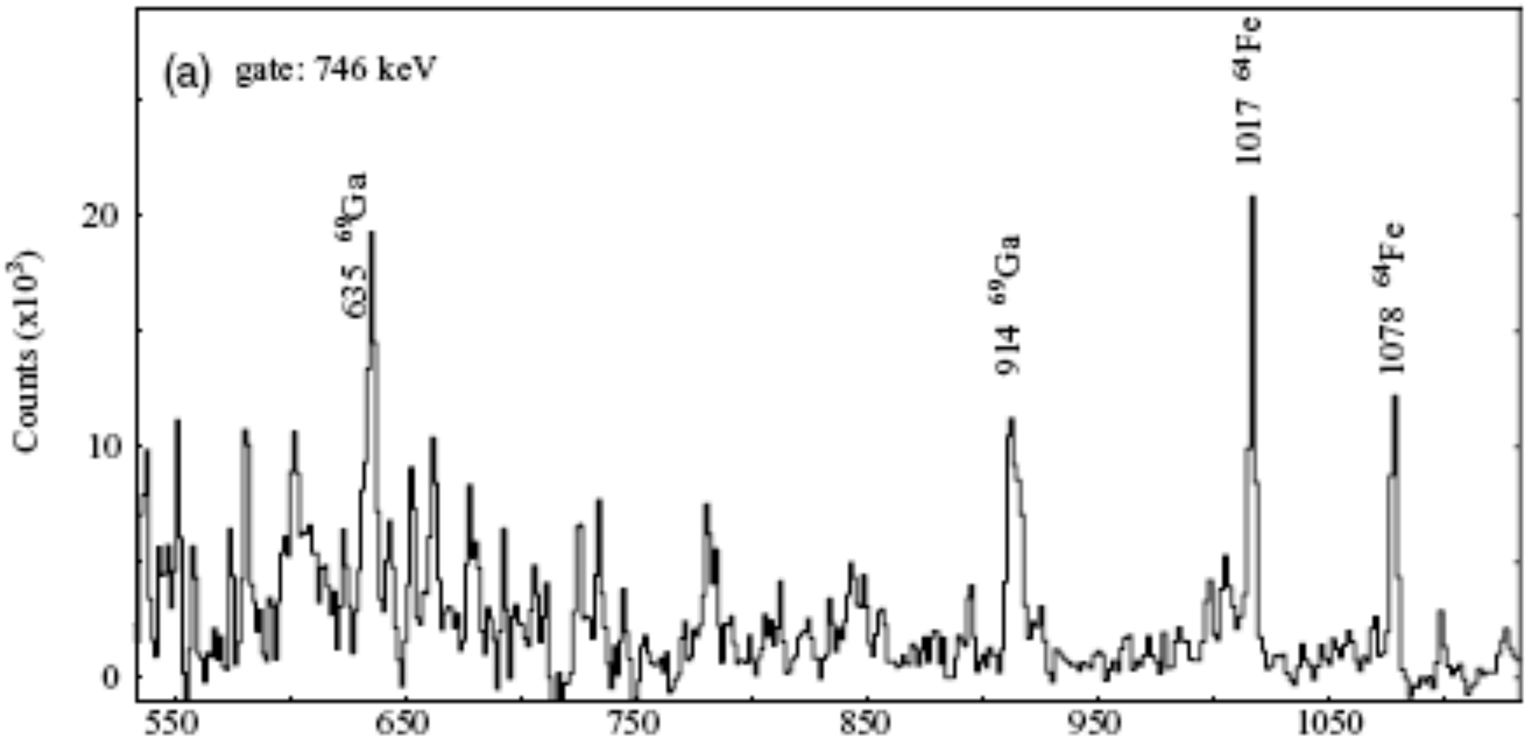
Fig. 5. Excitation energy of the 2^+ state for Cr isotopes (*pf*, *pfg* and *pfgd* calculations *versus* experimental values).

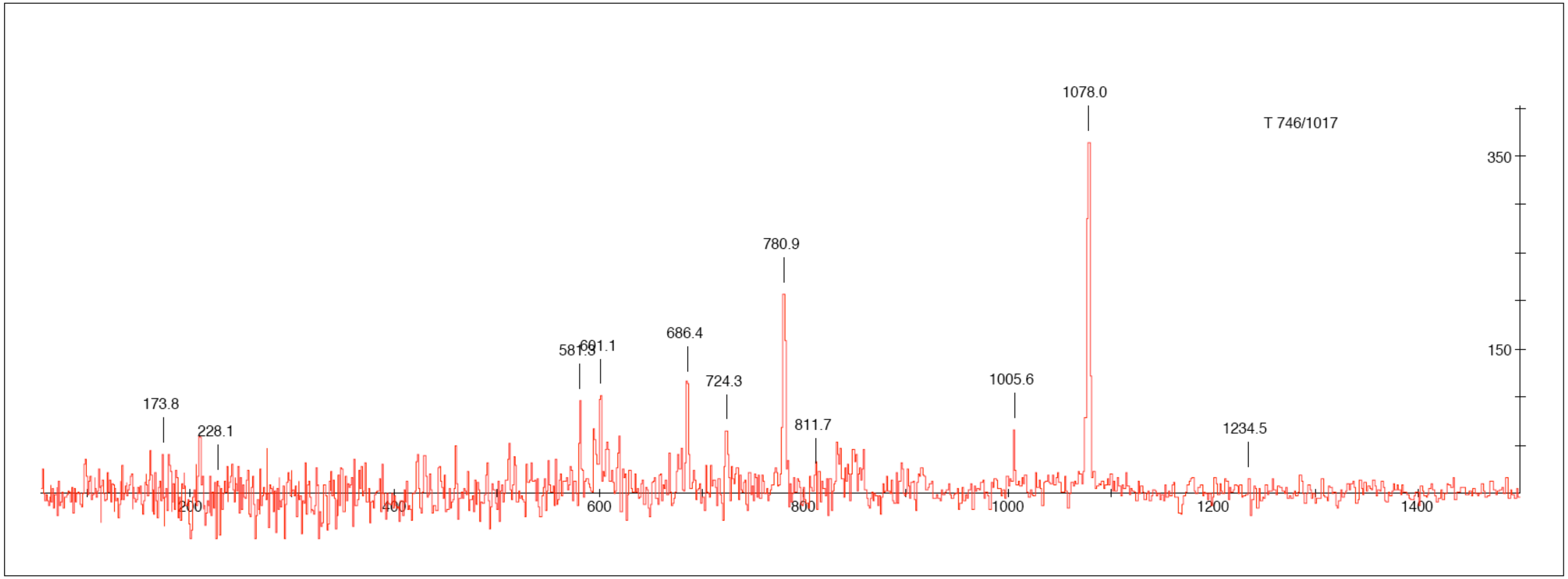


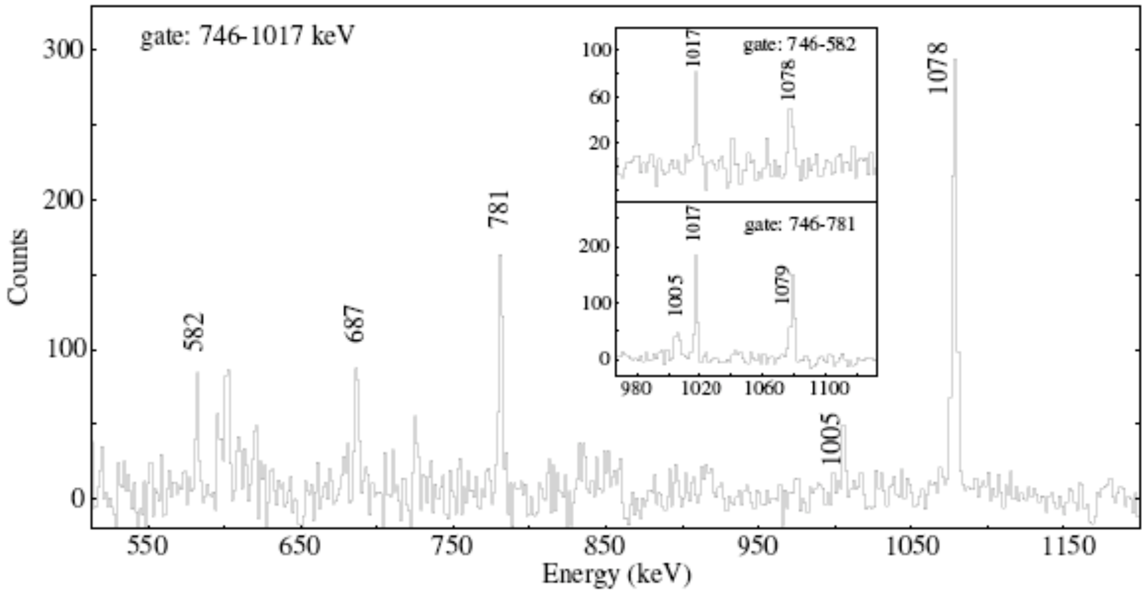
At ATLAS at Argonne, we performed a reaction gamma-ray study with GAMMASPHERE using a 430-MeV ^{64}Ni beam that was about 25% above the Coulomb barrier for ^{238}U. Three gamma rays were required for an event to be recorded. The beam was pulsed at 410-ns intervals. Data were sorted into four Cubes, PPP where three prompt events were required within 10 ns of each other and the beam pulse, PPD, where two prompt events were required within 10 ns of each other and the beam, while the third event could come within the next microsecond, PDD, 1 prompt gamma, 2 delayed, allowed the study of cascades both above and below isomers, and DDD which would be sensitive to longer cascades in both nano- and microsecond isomers as well a decay events from radioactivity.

Below is the single-gated spectrum for the 746-keV gamma ray. Nearly every other gate shown will be a double gate as these GAMMASPHERE data were taken with a 3-gamma coincidence requirement. But, at the time, we had ONLY one gamma, so below is the gate. Two intense lines emerged at 1017 and 1078 keV. We returned to the ISOLDE data and, sure enough, there WAS a weak line at 1017 keV that was populated in the beta decay of what is now known as the 1+ ground state for ^{64}Mn.





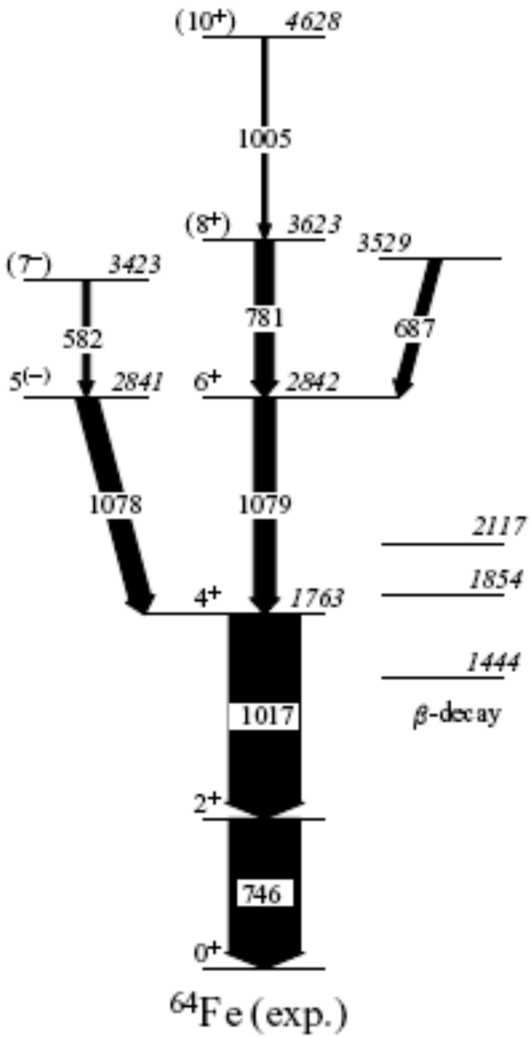


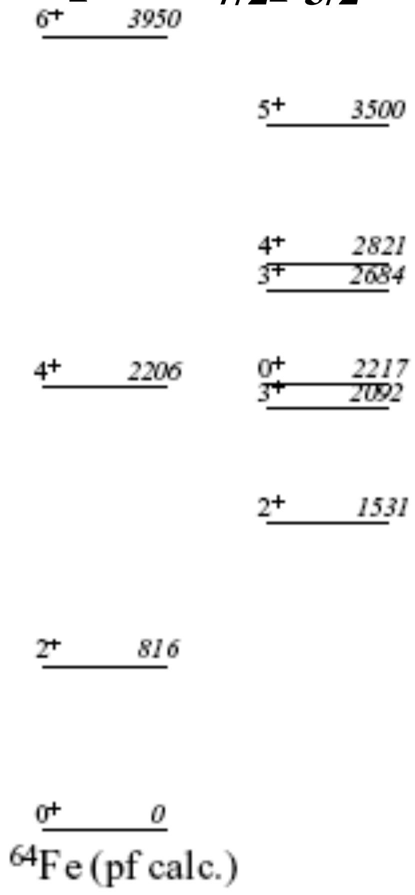


Above is the much cleaner double gate on the 746- and 1017-keV gamma rays that shows the lines that we have been able to place in the high-spin level scheme for ^{64}Fe. The large line at 1078 keV turns out to be a doublet whose components could be isolated in other properly set gates.

Oslo CD Bonn

$\nu pf \;\; \pi f_{7/2} p_{3/2}$





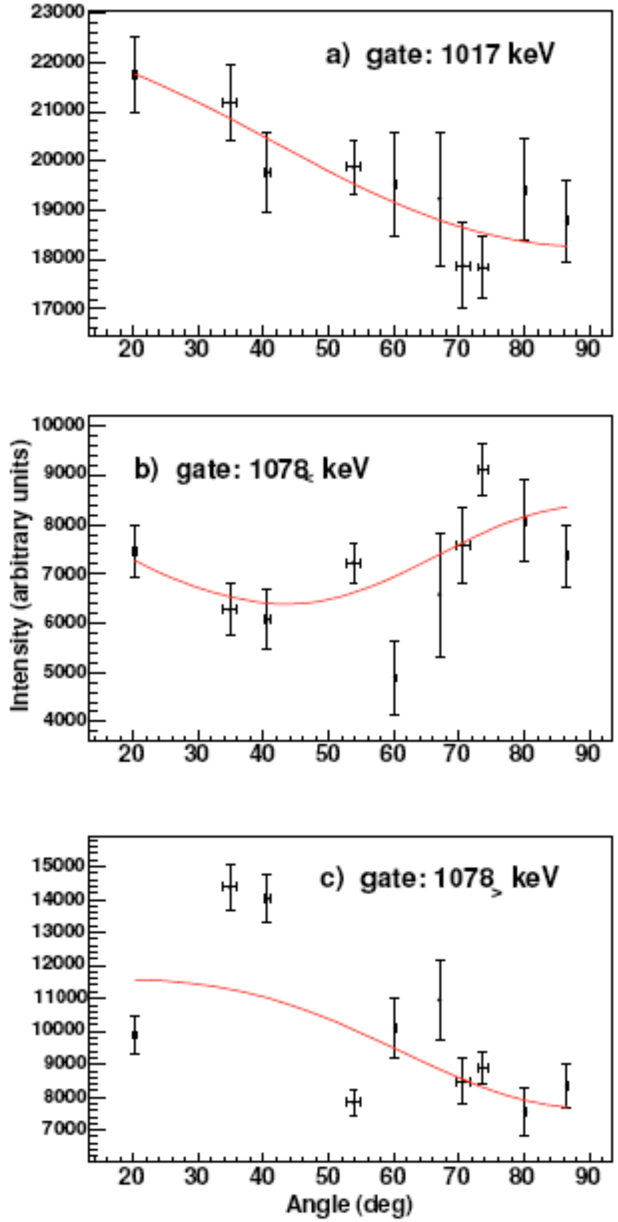
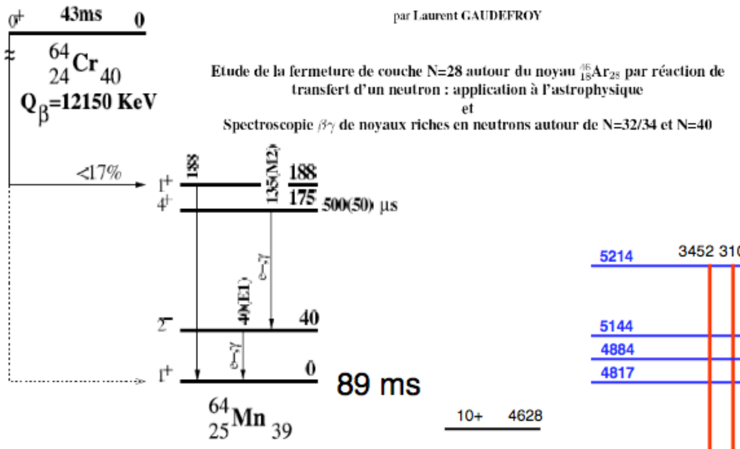
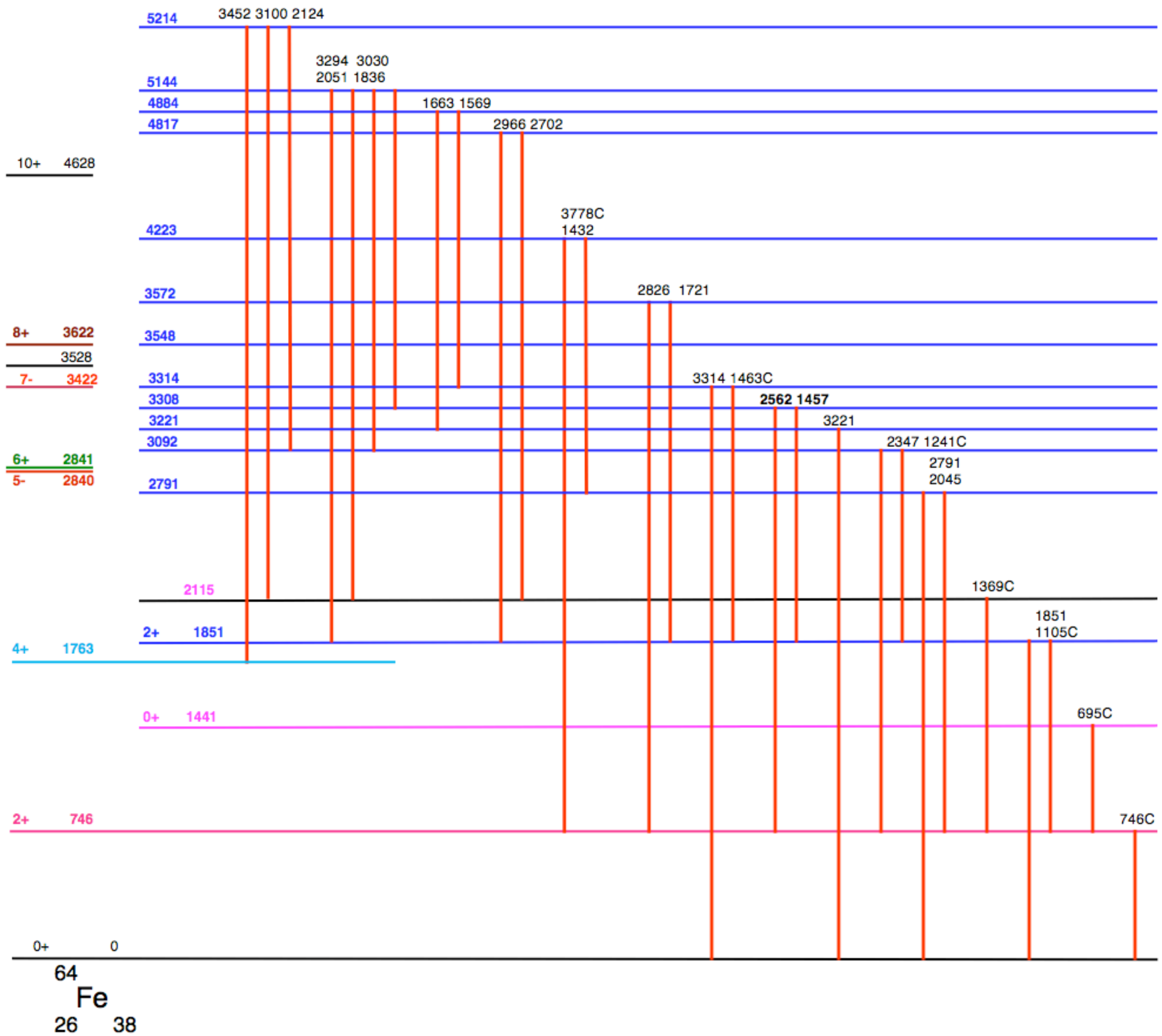


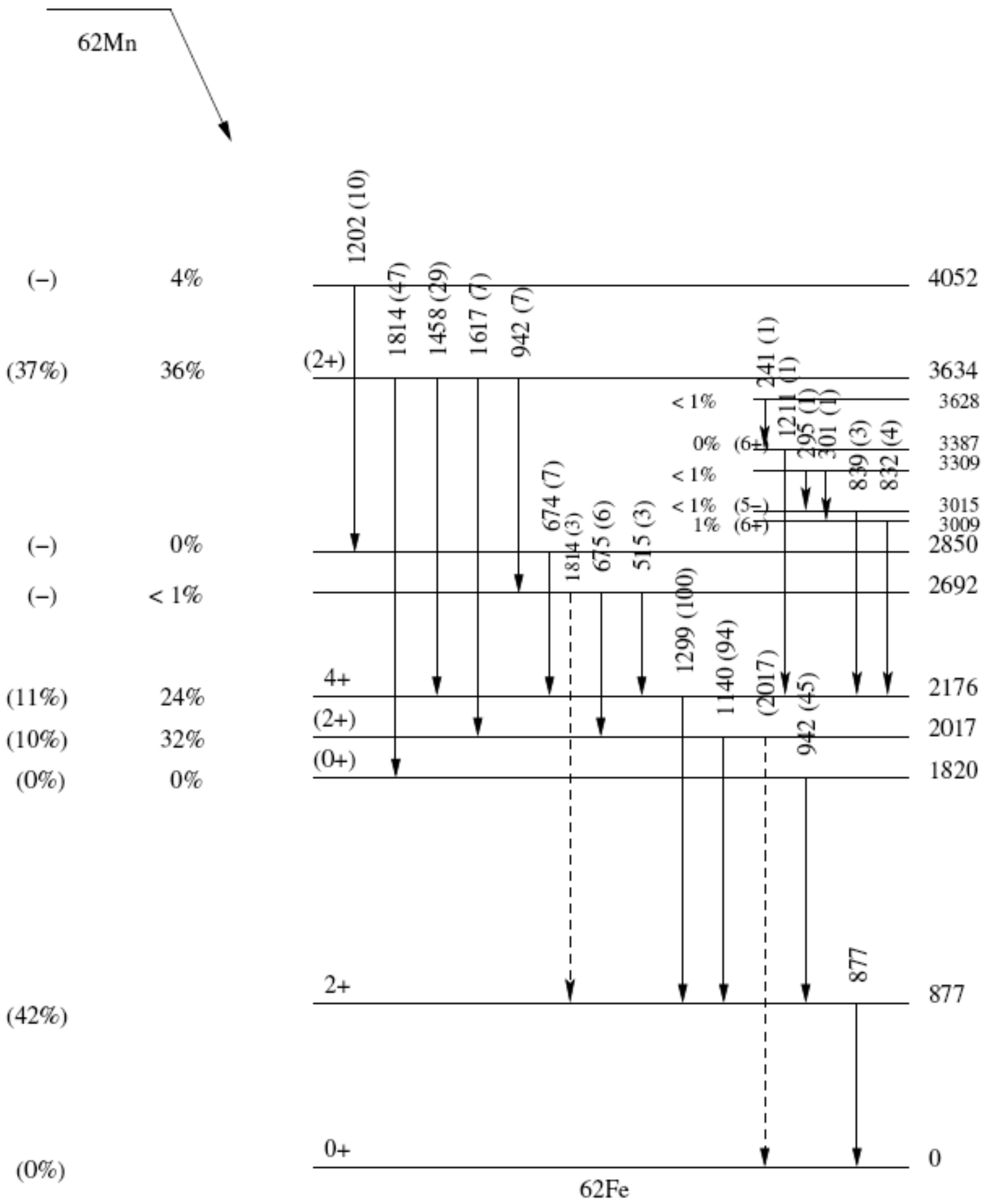
FIG. 4. The proposed level scheme for ^{64}Fe compared with shell model calculations (see text for details). Included with the experimental levels are three low-energy levels reported by Hannawald [20].

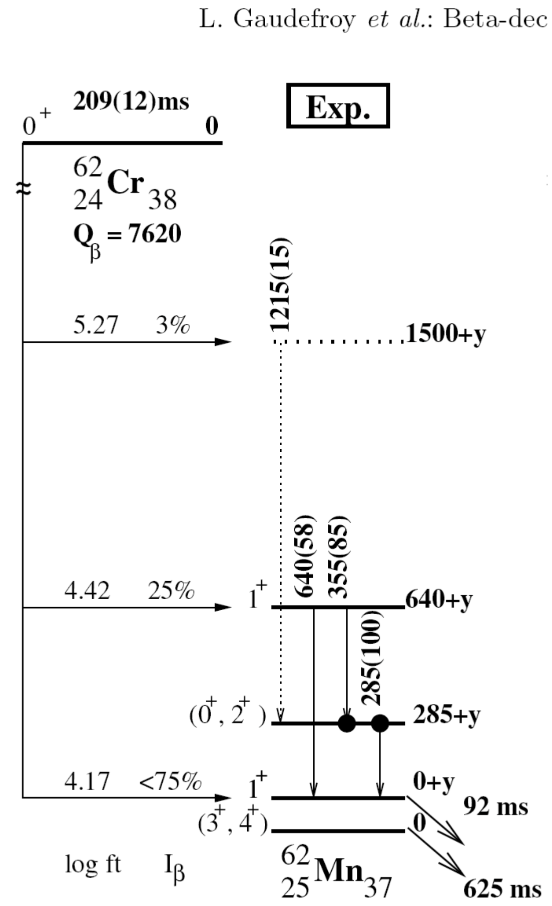
One important feature of this data set is the ability to determine angular correlations and distinguish between E2-E2 cascades and E2-E1 and E2-nonE2 cascades.

Now, we have returned to the initial ISOLDE data set and extracted the decay scheme shown below for ^{64}Mn decay to ^{64}Fe and also for ^{62}Mn to ^{62}Fe.

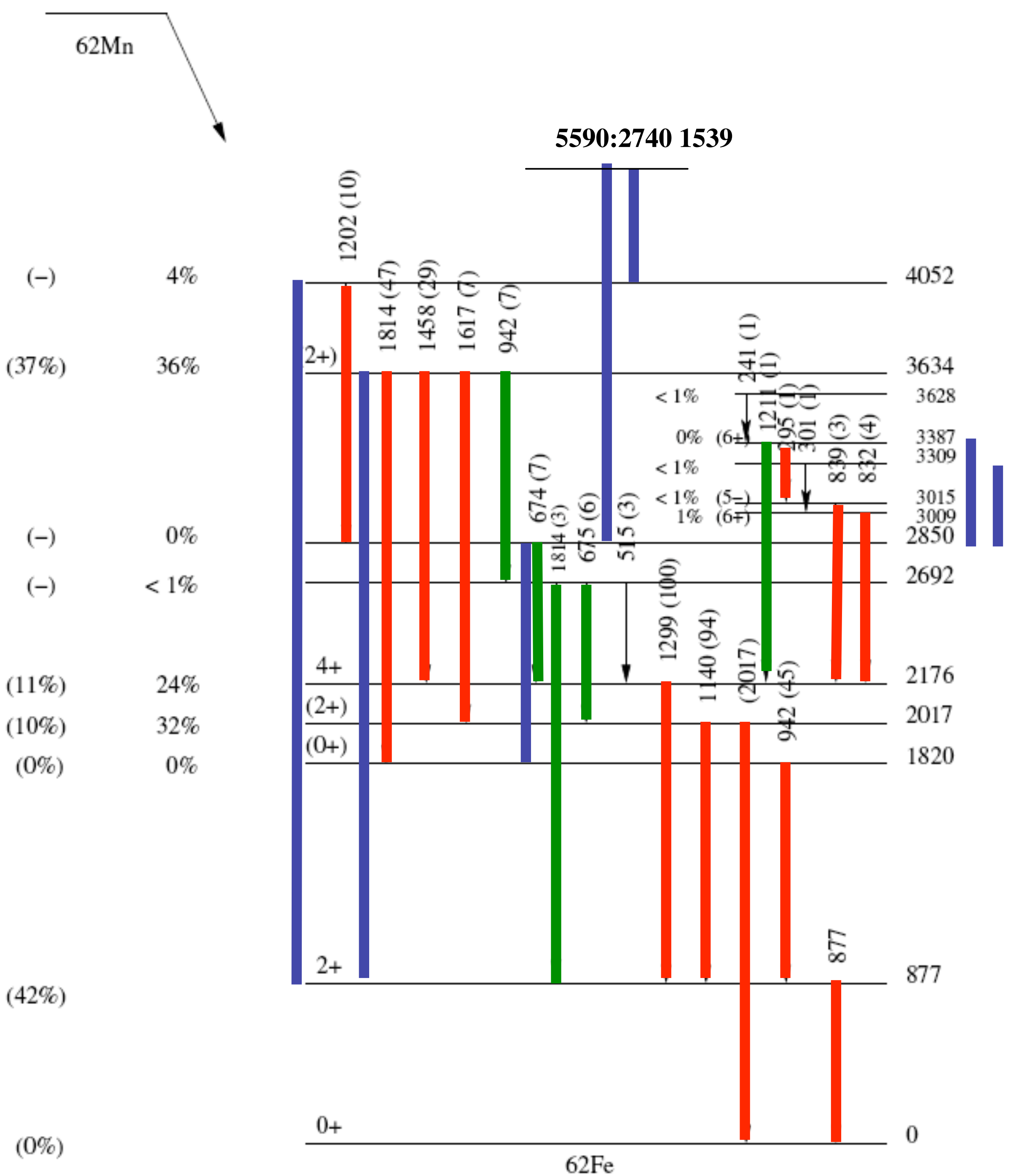








This is the decay scheme for ^{62}Mn isomers constructed from Gammasphere triples data. As there are KNOWN low-and high-spin isomers, a wide range of spins are populated.



219
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314
368
434
457
539
547
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674
832
839
877
942
1032
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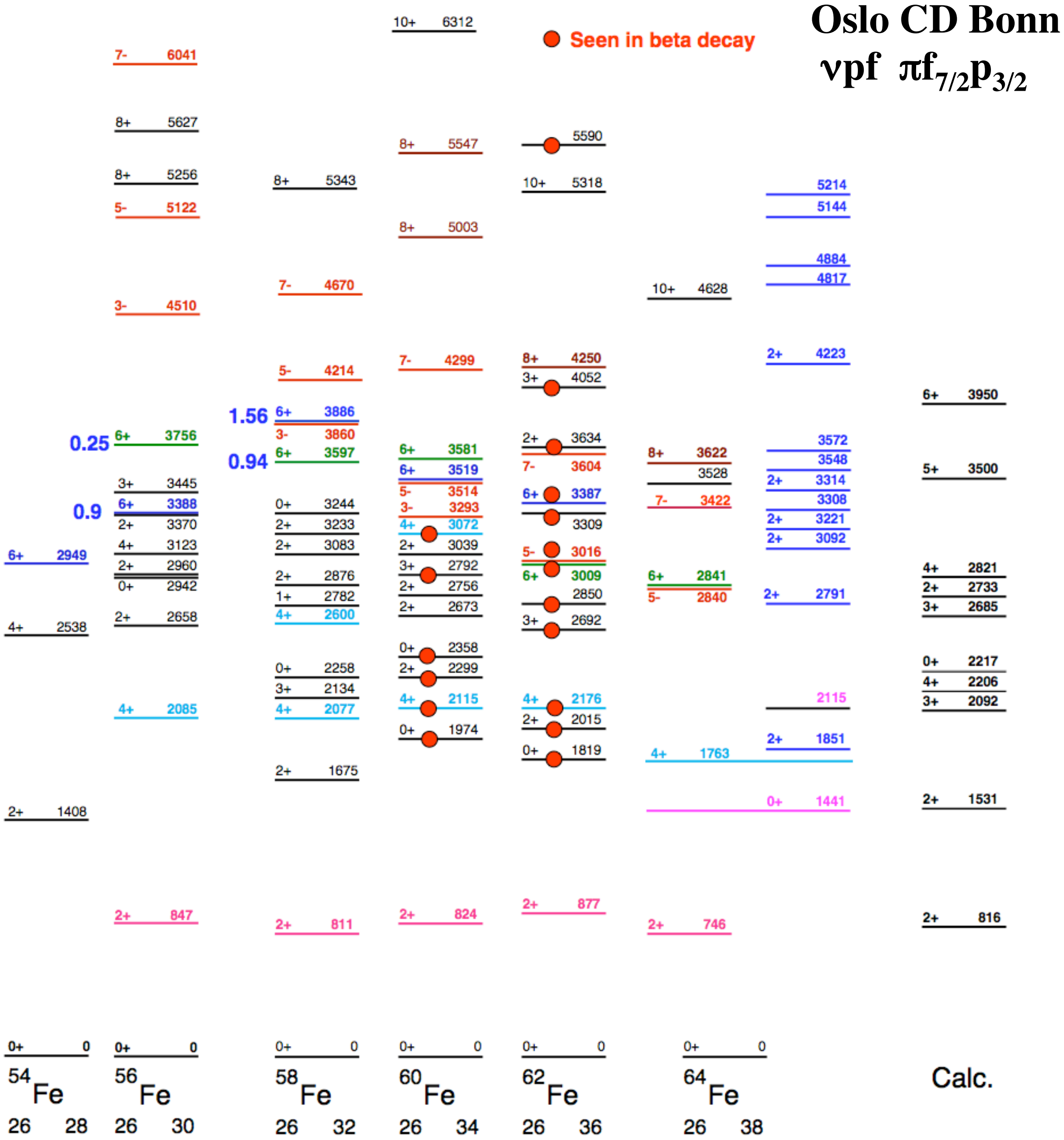
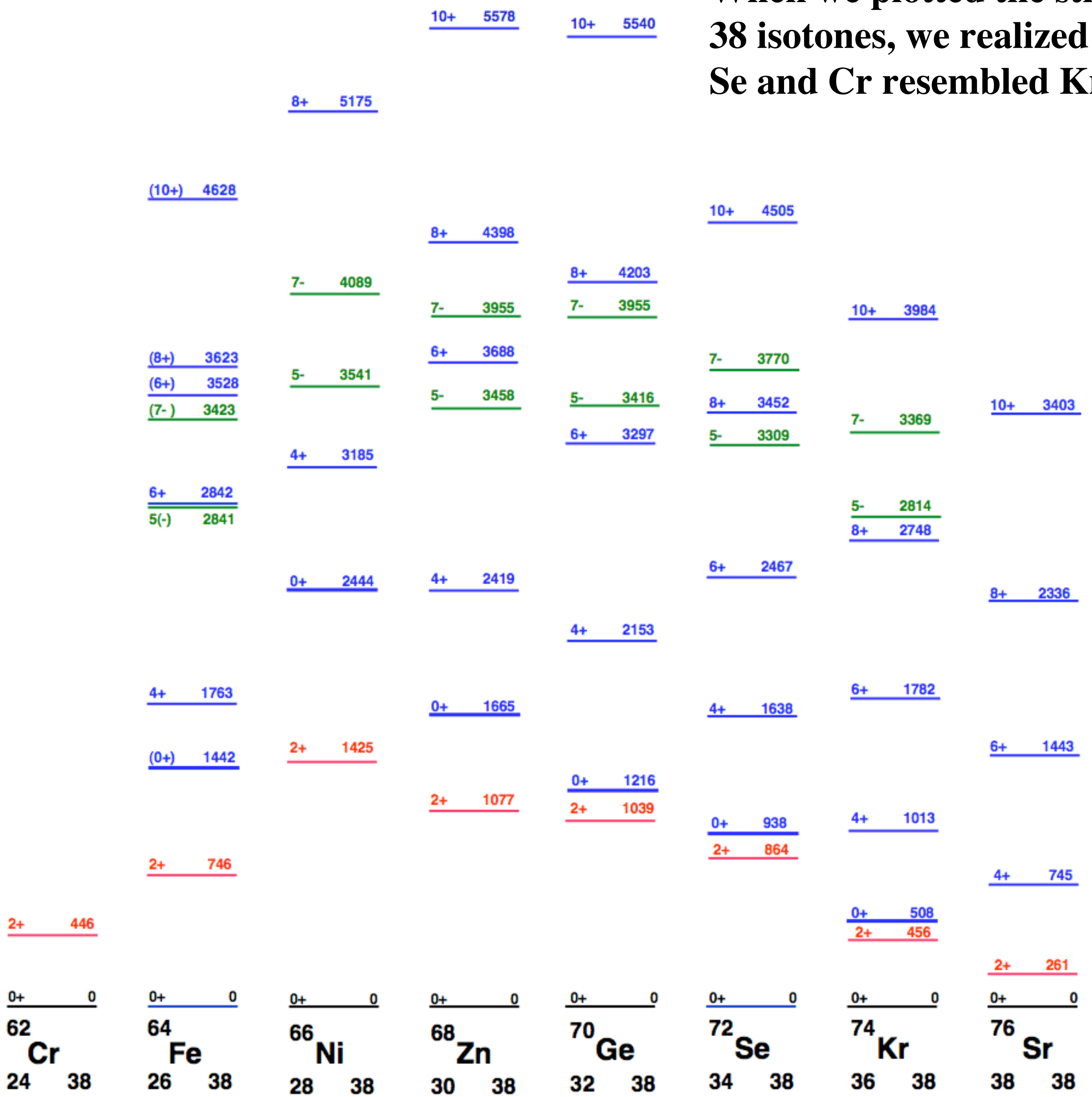
1201
1215
1248
1299
1457
1539
1618
1814
2017
2085
2212
2740
2757
3174

Here are the gamma rays observed at ISOLDE for Mn-62 decay. At ISOLDE with the Mn RILIS we have excellent clean singles spectra, whereas at ATLAS, we have excellent triples coincidence spectra, with angular correlations. In particular, at ISOLDE, the crossover transitions shown as blue lines can be seen that do not appear in triple coincidence gates.

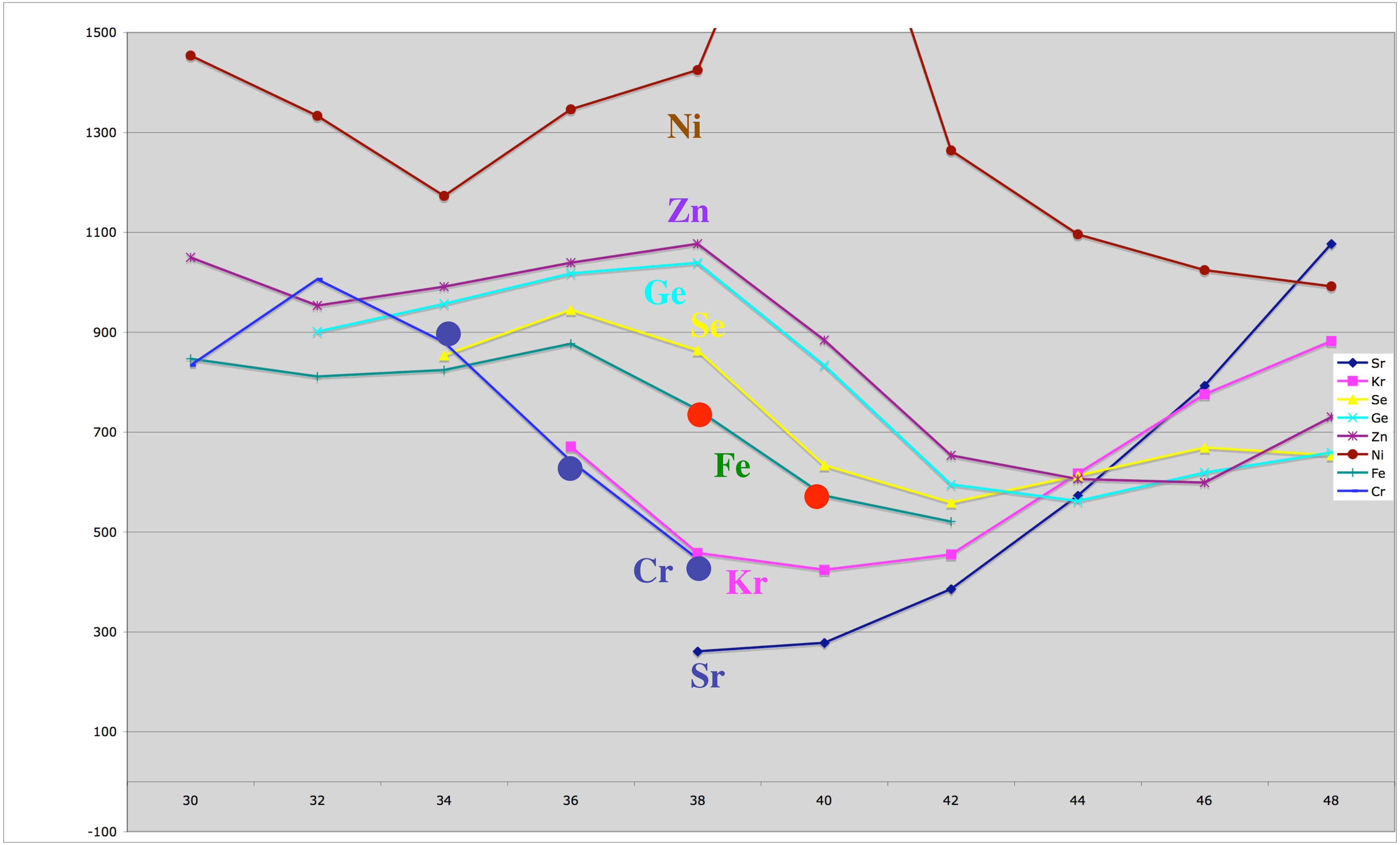


This is a summary that includes the new spins and parities from our work for $^{60,62,64}Fe$. Extensive data are available for ^{60}Fe from (HI,xn) work at GAMMASPHERE by Alick Deacon and Sean Freeman from Manchester. Here we just show what we see along with decay data and literature data, including (t,p) reaction data. They have much better data, but with a thin target, not quite enough resolution to separate the gamma rays coming from the 3514 and 3519-keV levels. Note how well our calculations fit ^{58}Fe.

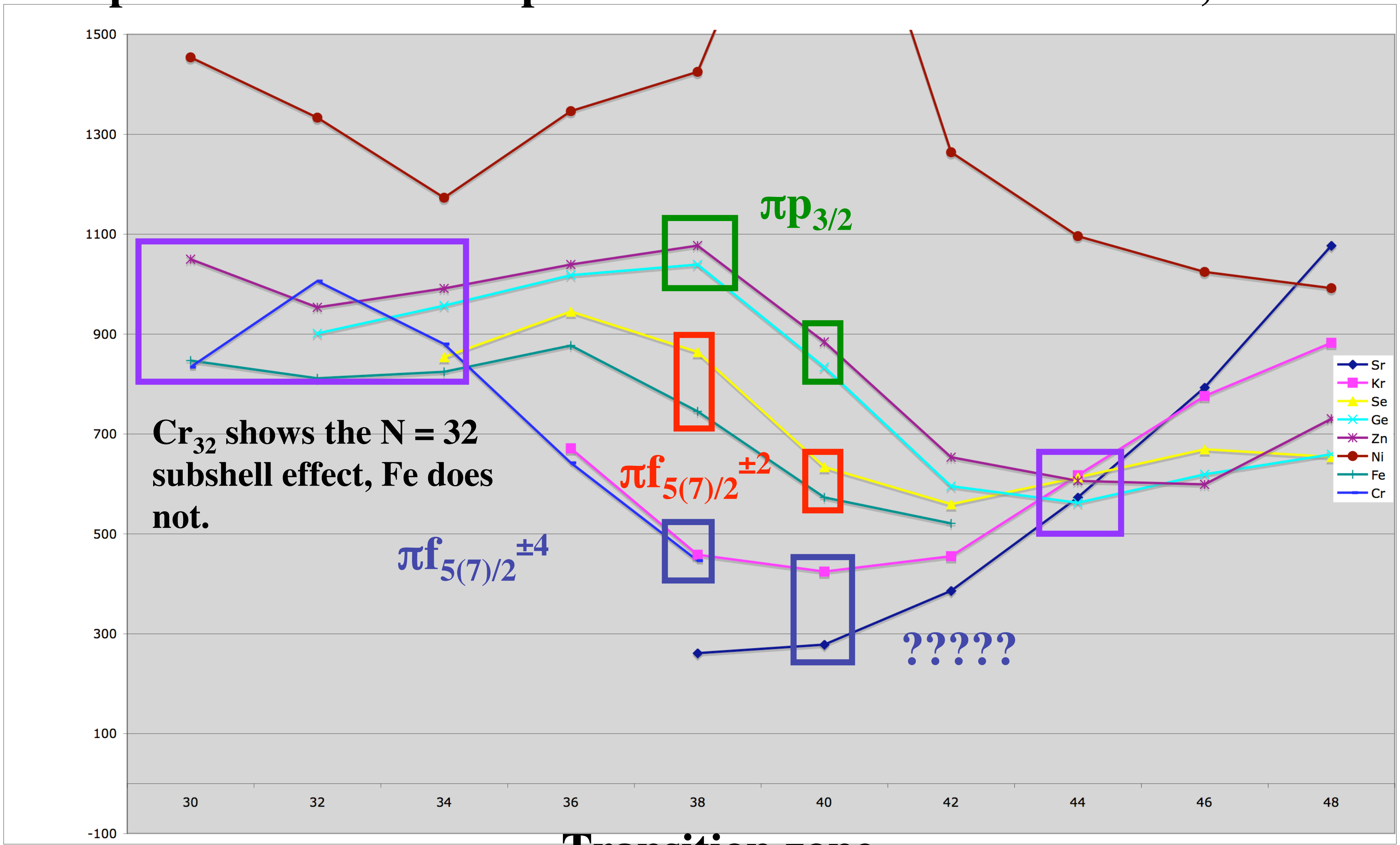
When we plotted the structures for the N = 38 isotones, we realized that Fe resembled Se and Cr resembled Kr.



Which led to this plot showing the crucial importance of the L value for the protons!!!!!!! The starting point of all of this was the two new Fe 2^{+} energies that were not like Zn and Ge.



The prediction from this plot is that ^{64}Cr will look like ^{76}Kr, not ^{78}Sr.



N = 3 pf region 30-36 **Transition zone 36 - 40** **N = 4 $g_{9/2}$ region 42-48**

This plot shows that the L = 3 $f_{7/2,5/2}$ protons interact more strongly with the L = 4 $g_{9/2}$ neutrons than do the L = 1 $p_{3/2}$ protons.

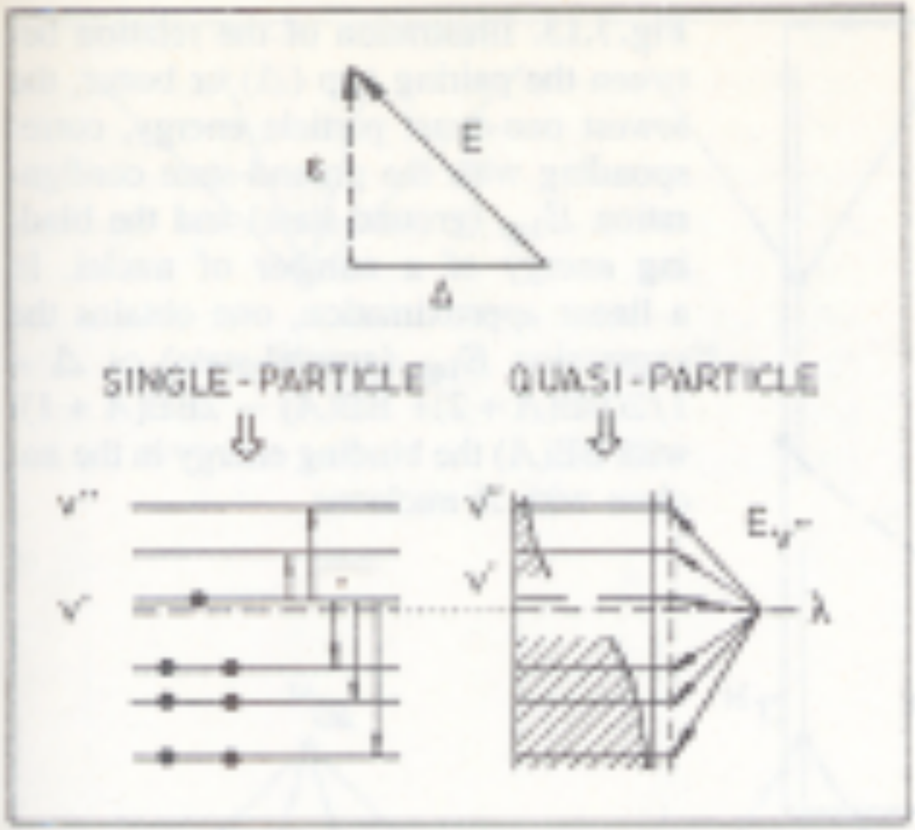
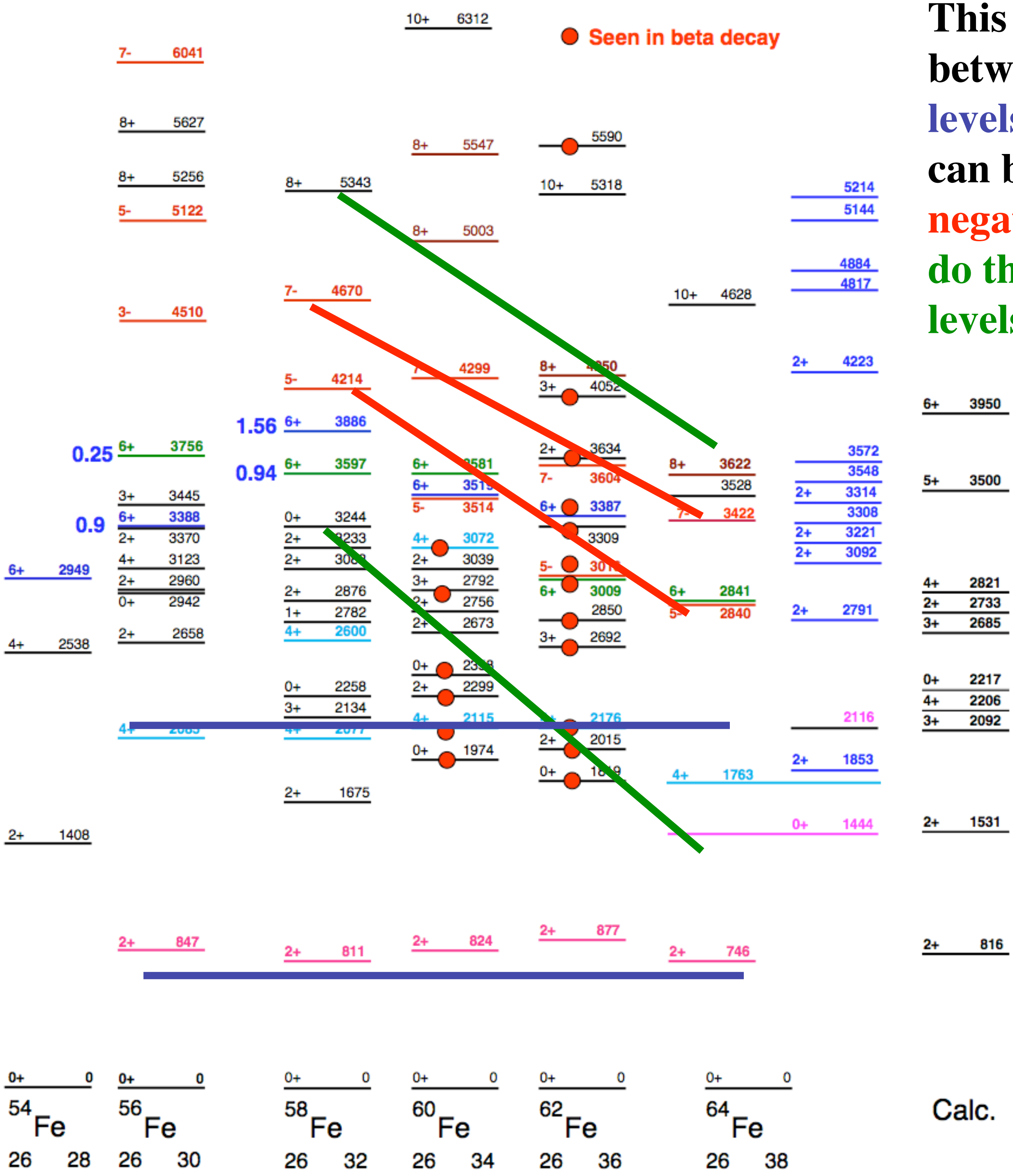


Fig. 7.11. The difference between single-particle excitations ($\varepsilon_{\nu''} - \varepsilon_{\nu'}$) and one-quasi particle excitations $E_{\nu''} - E_{\nu'}$, illustrated in a schematic way. The Fermi level λ is also given. The single-particle energy difference is measured by the distance between two given single-particle configurations. The one quasi-particle energy difference follows from a geometrical construction since $E_\nu = \sqrt{(\varepsilon_\nu - \lambda)^2 + \Delta^2}$ (see the insert in Fig. 7.11)

I call this the "quasiparticle crunch", the stronger pairing is, the easier it is to move particles over the N = 40 boundary. With no protons in Ni, there is a nice subshell in ^{68}Ni, the larger the proton pairing interaction becomes, the more quickly neutrons shift into the g-9/2 orbitals.



This drawing shows the contrast between the collective pf 2+ and 4+ levels and the particle-hole levels. As can be seen, both the 1-particle-1-hole negative parity levels drop smoothly as do the 2-particle-2-hole 0+ and 8+ levels.

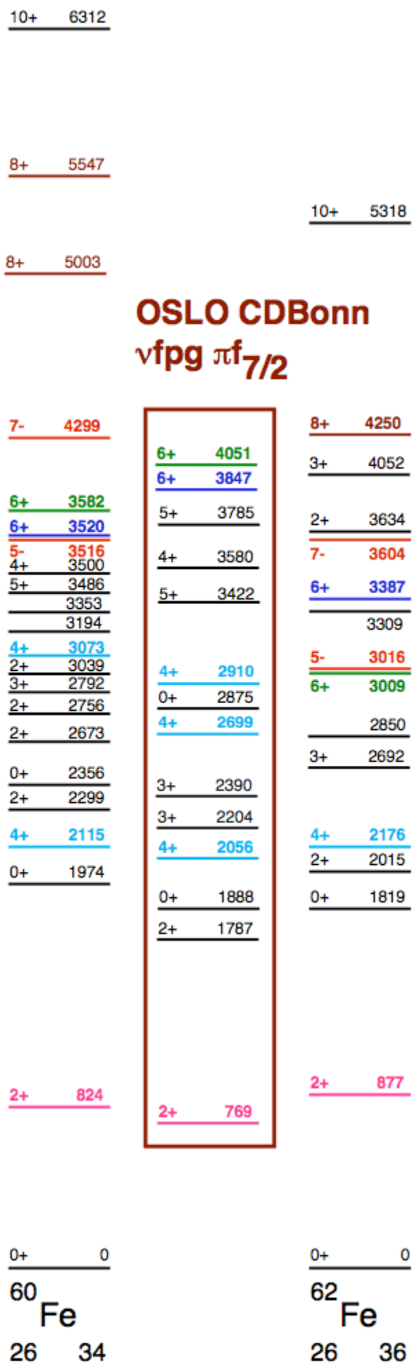
$(g_{9/2})^2{}_{8+}$

$(f_{5/2}g_{9/2})_{7-}$

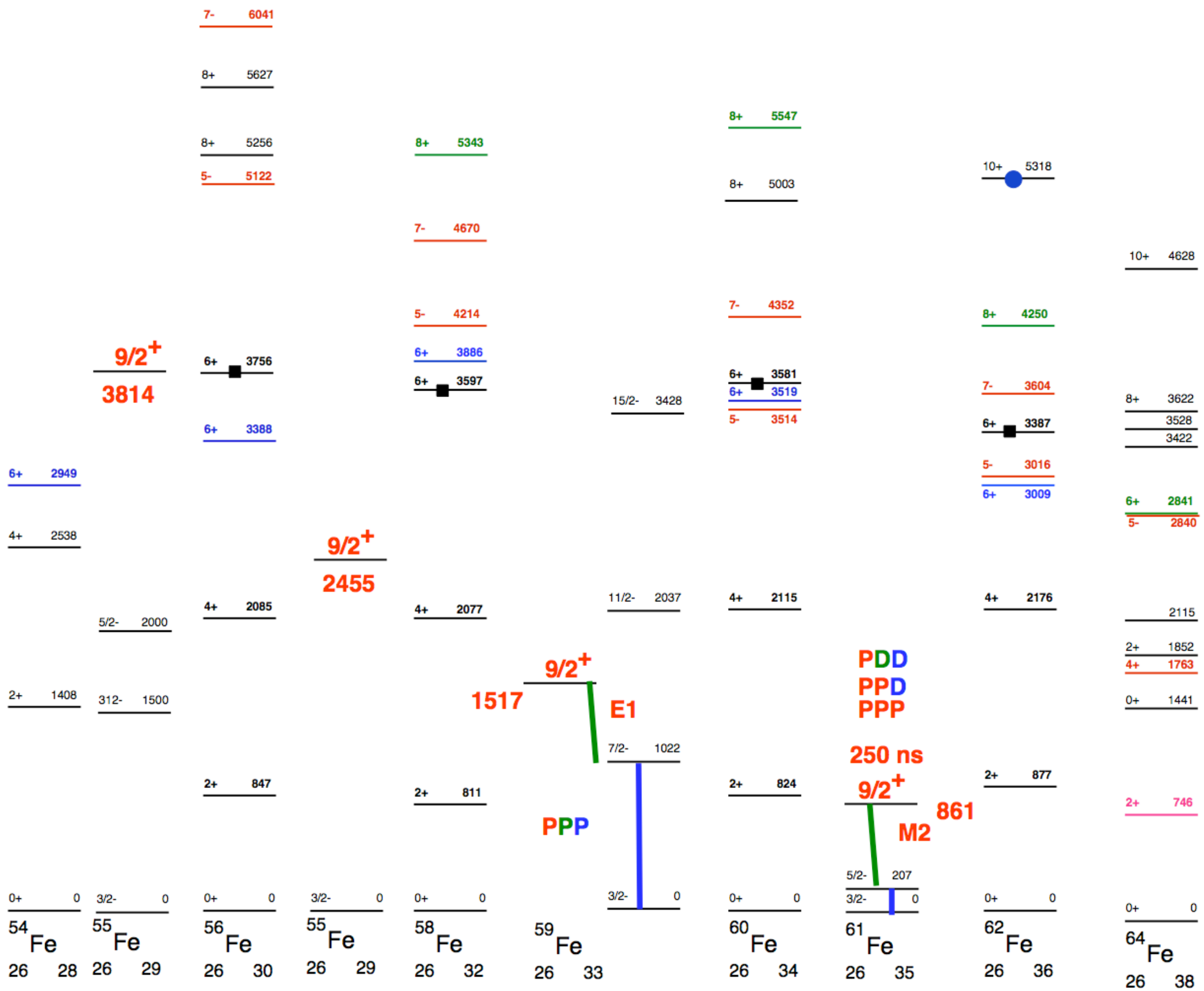
$(p_{1/2}g_{9/2})_{5-}$

$(g_{9/2})^2{}_{0+}$

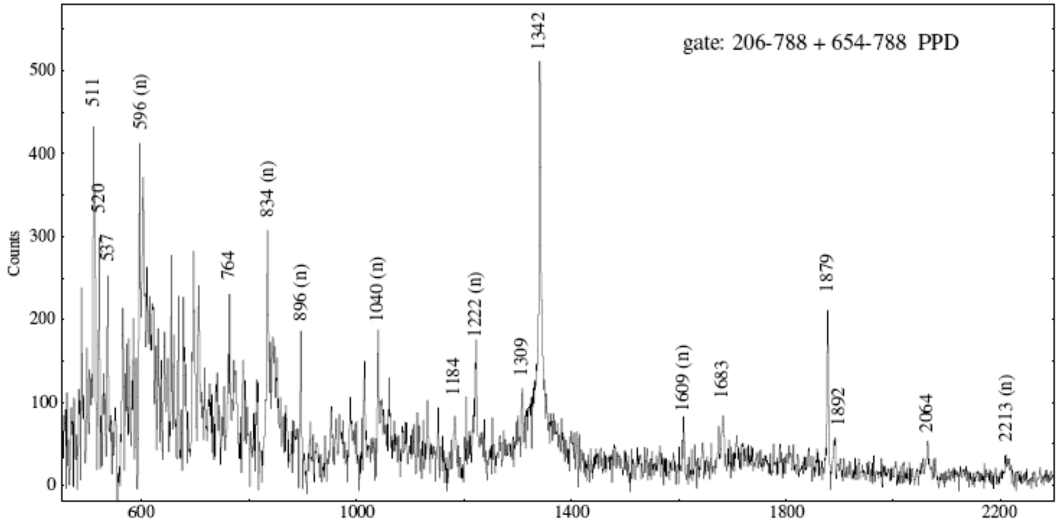
As the calculation does not include the $g_{9/2}$ orbitals, the differences for the 4+ and 6+ levels can be taken as an indication of their contributions.

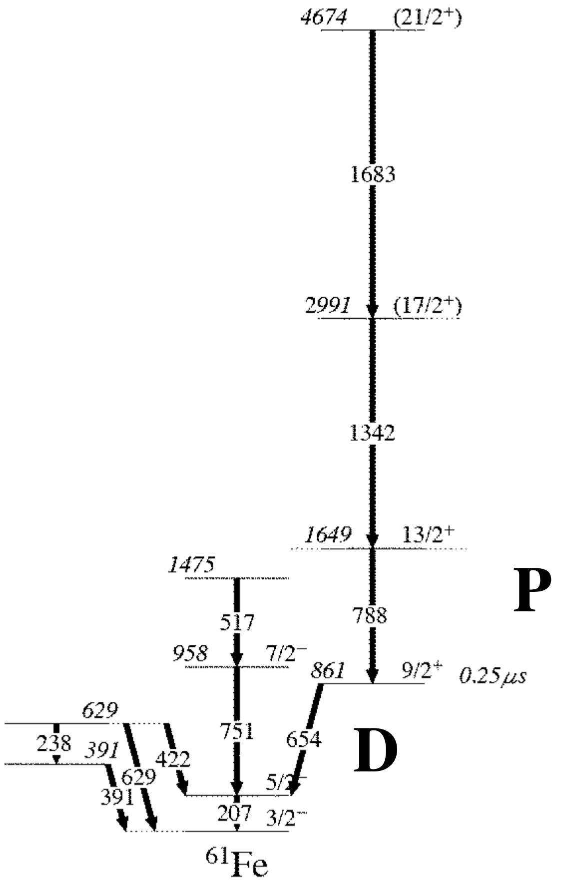


Here we show a reasonable fit for the levels of ^{60}Fe using the CDBonn potential with the OSLO code and a valence space beyond the ^{48}Ca double-magic nucleus that includes the fpg space for neutrons, but only $f_{7/2}$ protons.

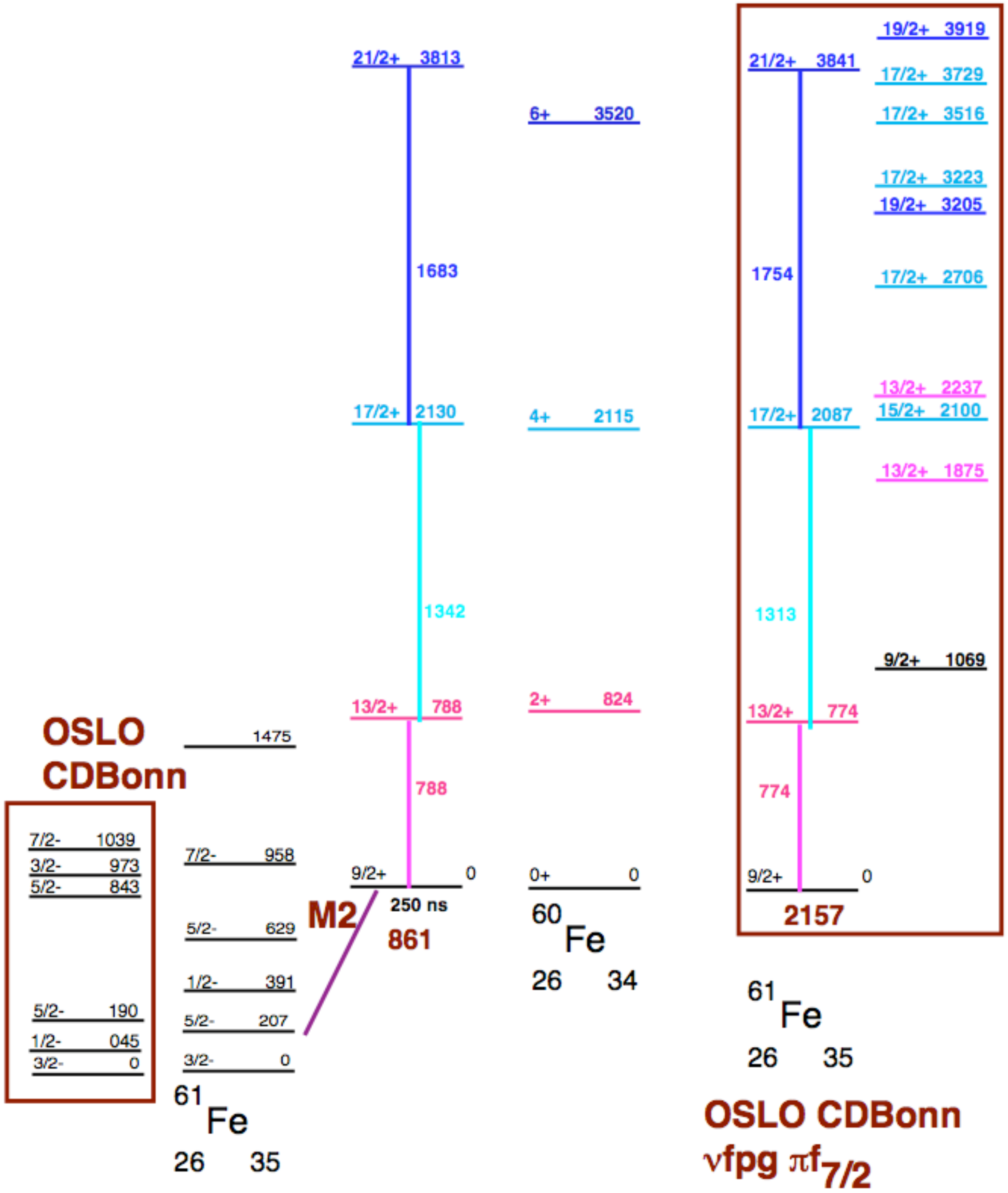


Now, I want to introduce the odd-mass data in a scale drawing. The downward progress of the $g_{9/2}$ neutron orbital can be seen as N increases and the Fermi level moves up. The 9/2+ level decays by a fast E1 transition up through ^{59}Fe and then a 250-ns isomer is known for ^{61}Fe. For ^{59}Fe, we can use PPP gates to identify a high-spin sequence and for ^{61,63}Fe, PDD gates are used. For ^{63}Fe, the progression, 3814, 2455, 1517, 861 indicates a possible low energy for the 9/2+ level, and a 9/2+ ground state for ^{65}Fe





The result is an extensive level scheme with enough data for some angular correlations.



Here is the high-spin sequence associated with the 9/2+ level in ^{61}Fe, along with the rather good fit to the levels from the shell-model calculation. Note, that the absolute energy for the 9/2+ level is high. There are a lot of non-yrast states predicted, and we see many of them. The calculation is also OK for the other low-energy negative-parity levels below ~1 MeV.

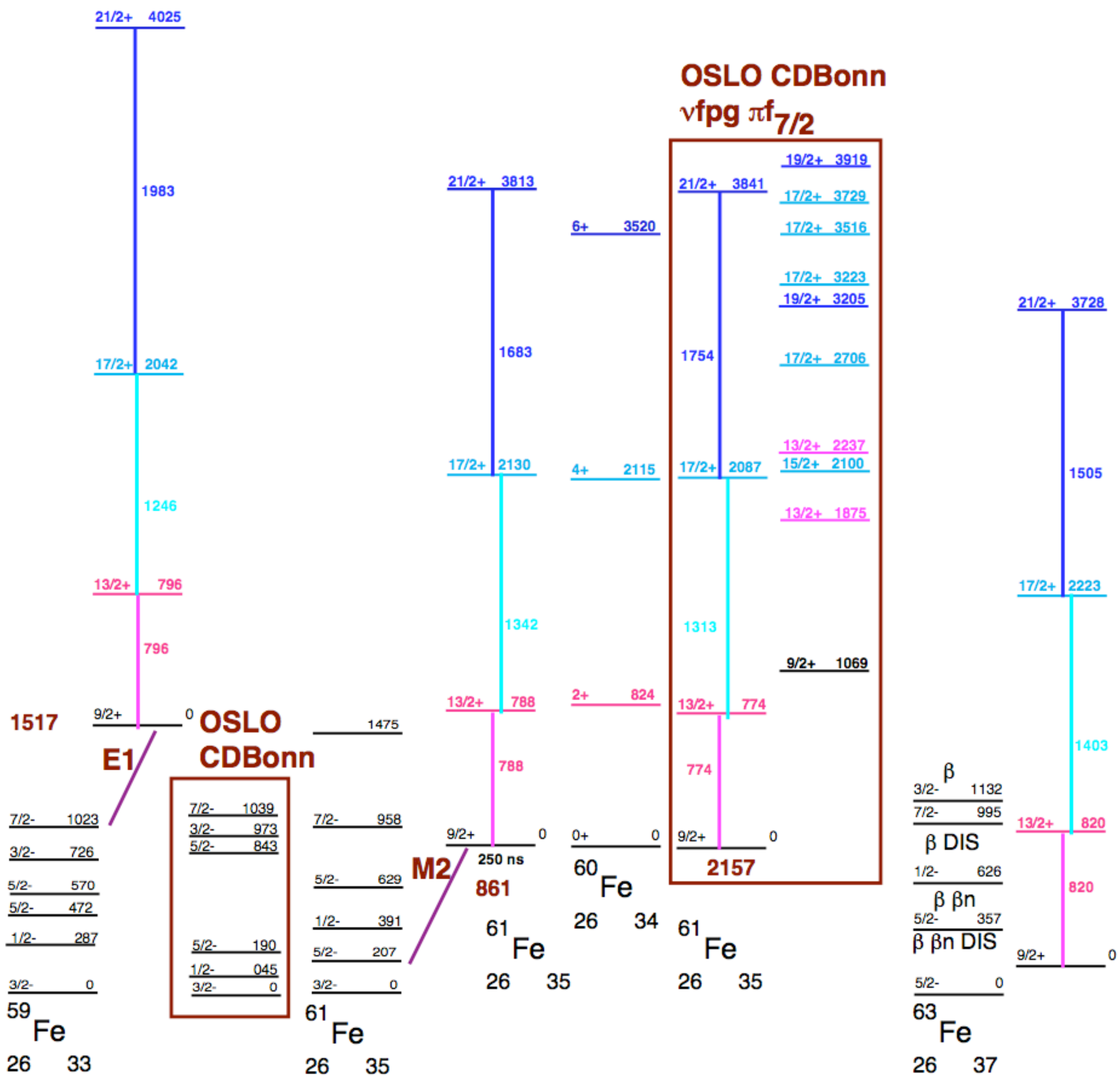
And, note the close relationship between the level spacings in ^{60}Fe and ^{61}Fe.

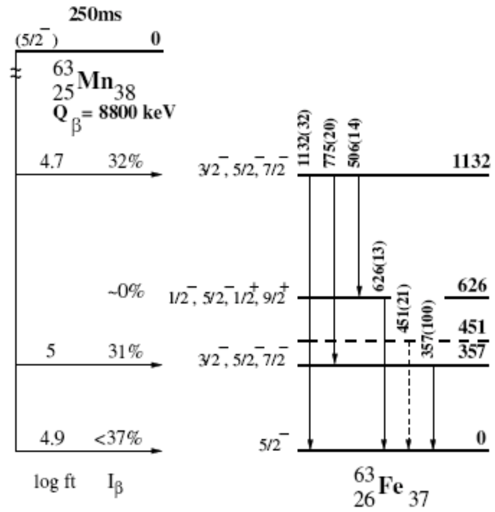
S. Lunardi, ACS Atlanta 2006

GANIL beta-decay data ^{63}Mn | 357, 451, 505, 626, 775, 995, 1132

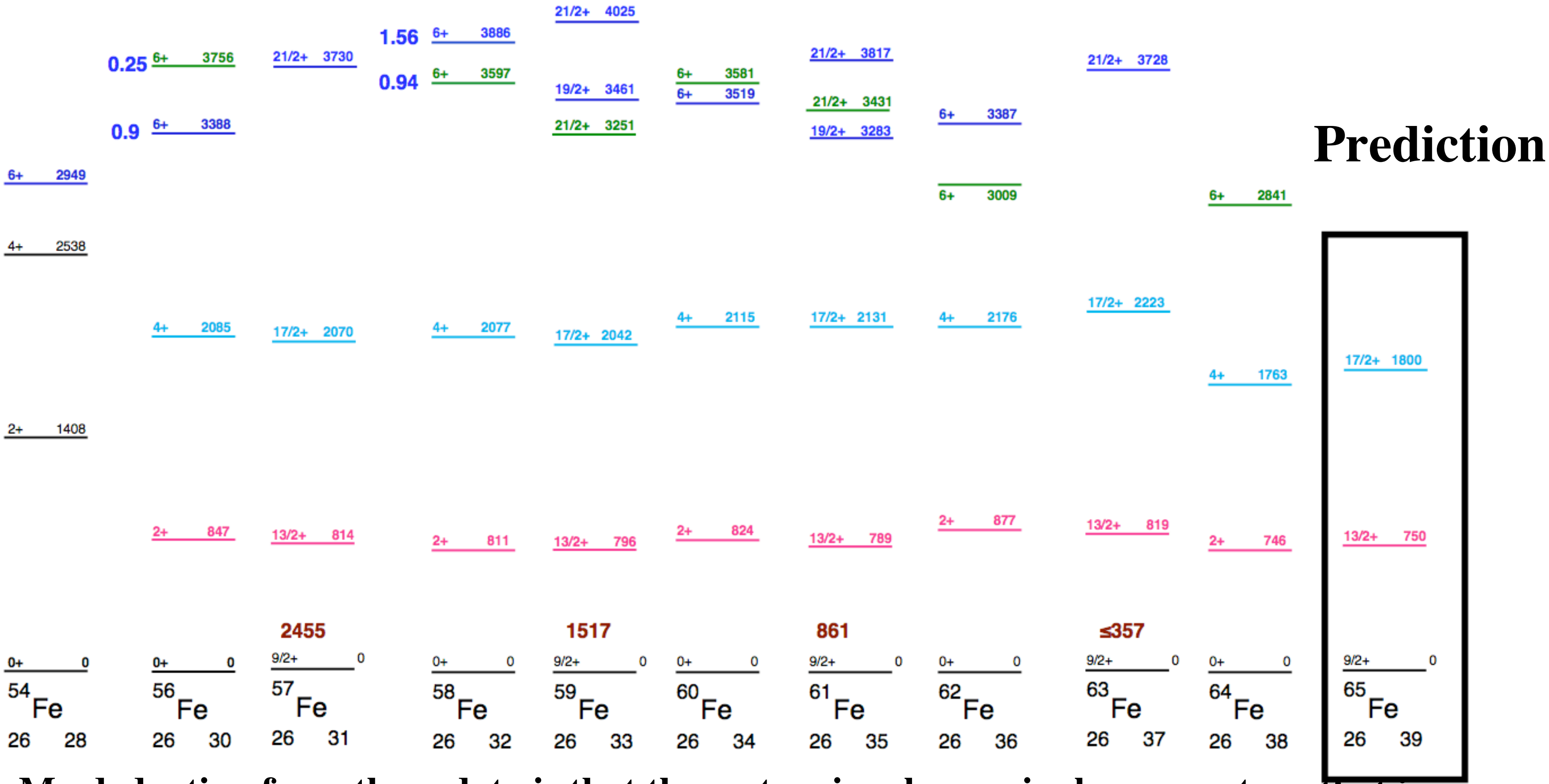
LNL mass-gated DIS data 357 451 820 995 1403

ISOLDE βn data: 357 626





Gaudefroy Thesis



My deduction from these data is that the system involves a single $g_{9/2}$ neutron that is weakly coupled to the adjacent even-even core. The main feature seems to come from the interaction of the single $g_{9/2}$ neutron with the even-even core that is "stabilized" by the pair of $f_{7/2}$ proton holes coupled to 2+ 4+ 6+.

interact with the nucleons of the core and can polarize the core, which is reflected by giving the neutrons an effective charge. Because the nuclear energy is minimized if the overlap of the core nucleons with the valence particle (or hole) is maximal, a particle (respectively hole) will polarize the core towards an oblate (respectively prolate) deformation, as demonstrated in Fig. 1.

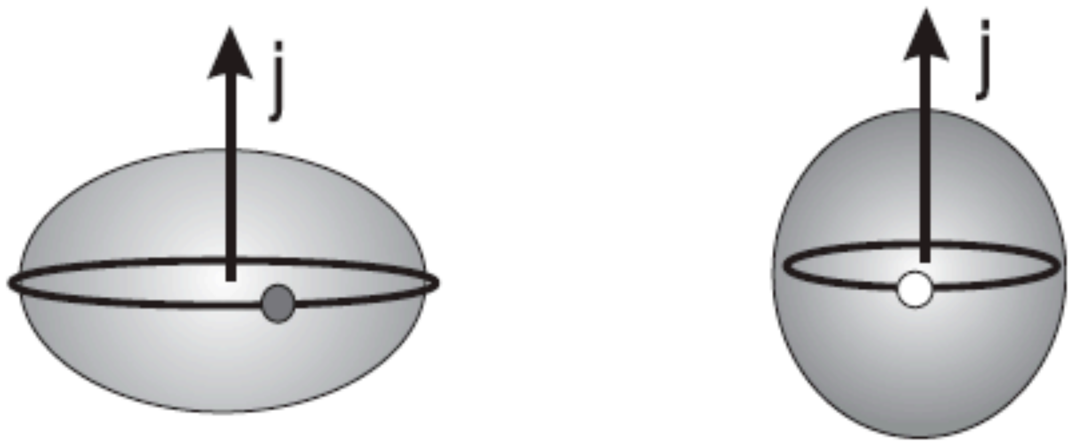
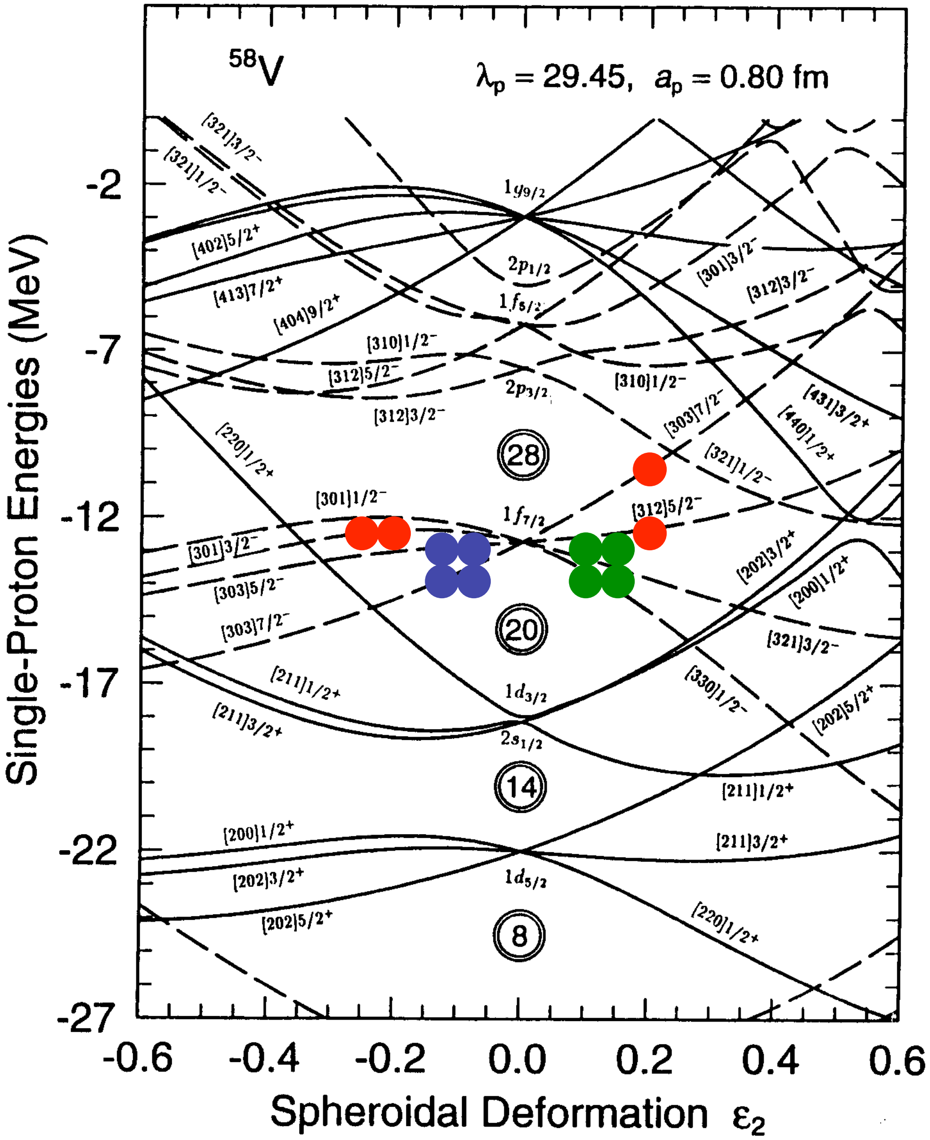


Plate 1. Graphical representation of a particle in a orbital j, polarizing the core towards oblate deformation with a negative spectroscopic quadrupole moment (*left*), and a hole in an orbital giving rise to a prolate core polarization (*right*)

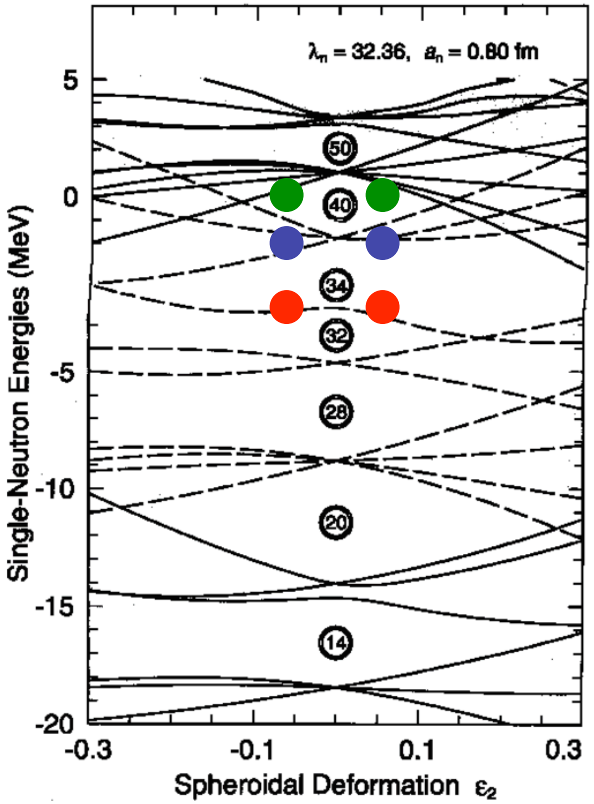


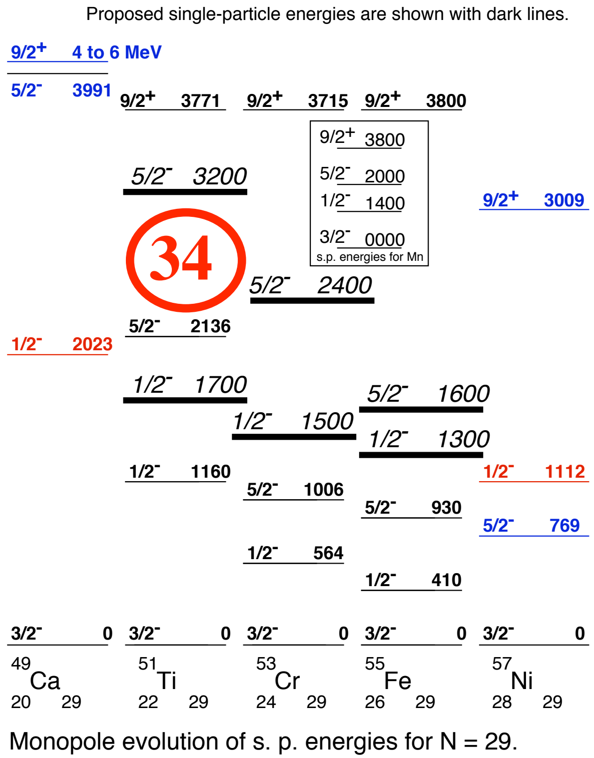
The starting point for shapes in this mass region is to recognize that Cr and Fe are fundamentally quite different.

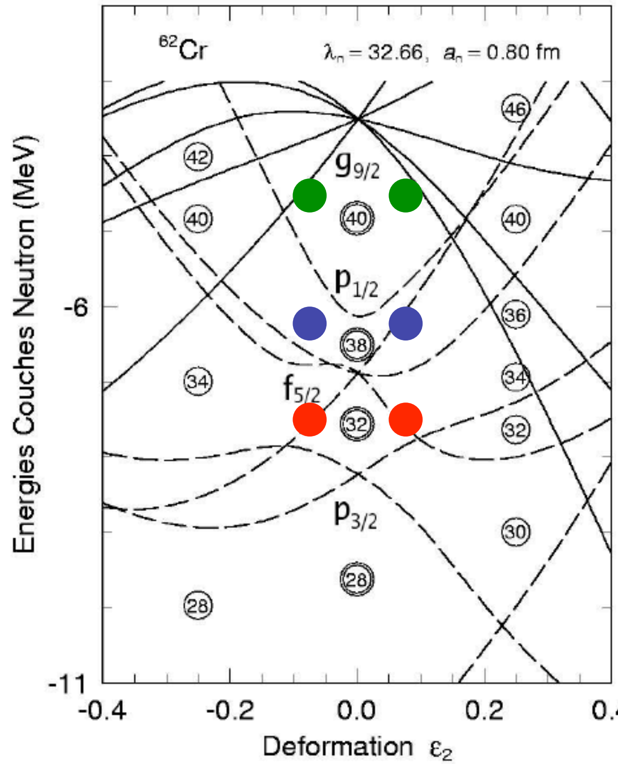
For Cr, with only four protons, either prolate or oblate deformation produces a lowered energy. All options are downsloping.

For Fe, however, the 25th and 26th protons go into the upsloping [312]5/2- orbital that opposes prolate deformation, and any attempt to break a pair requires that the second proton, as shown, must go into an even stronger "upsloping" orbital.

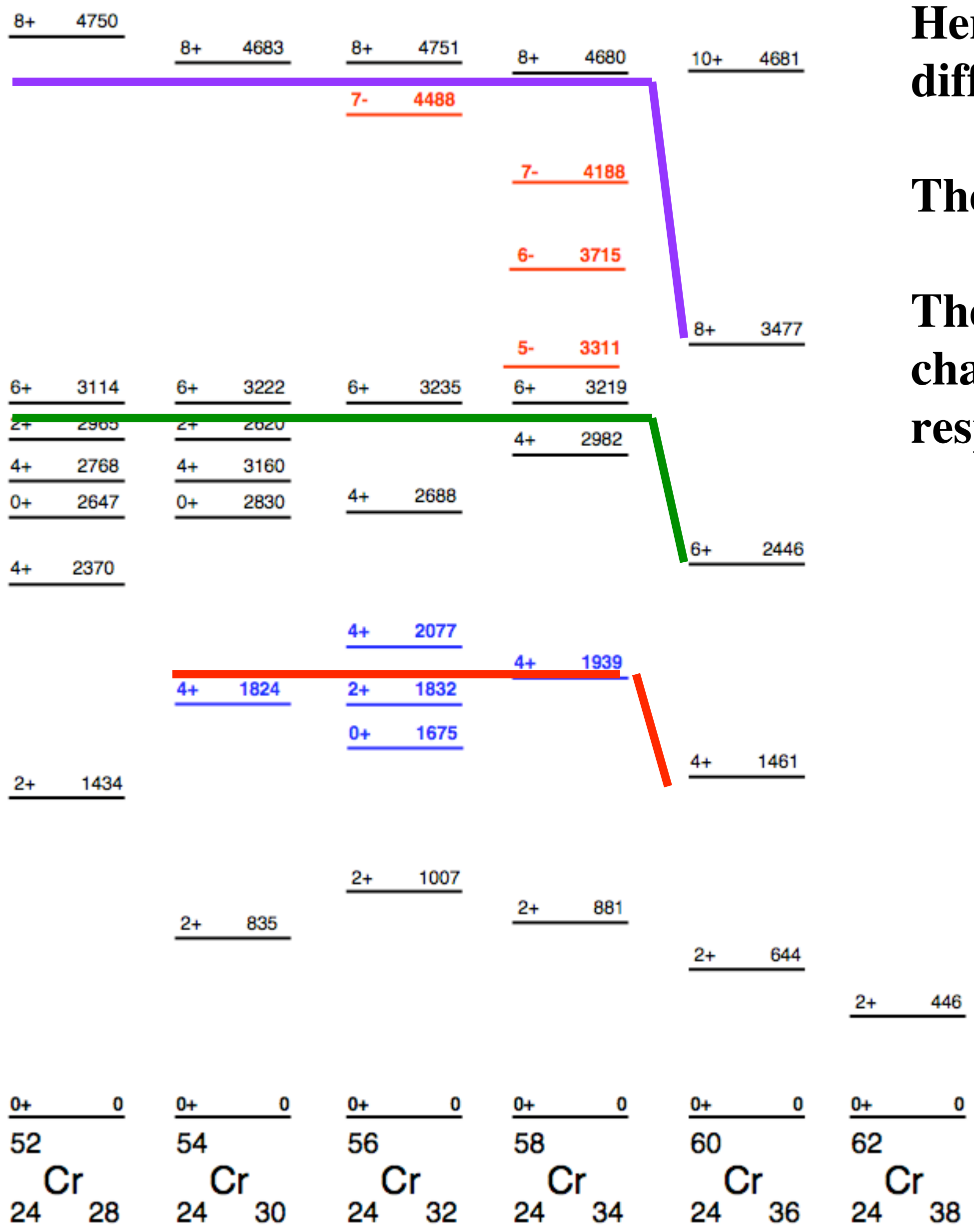
But, for Fe, on the oblate side, the orbitals are more or less deformation neutral.







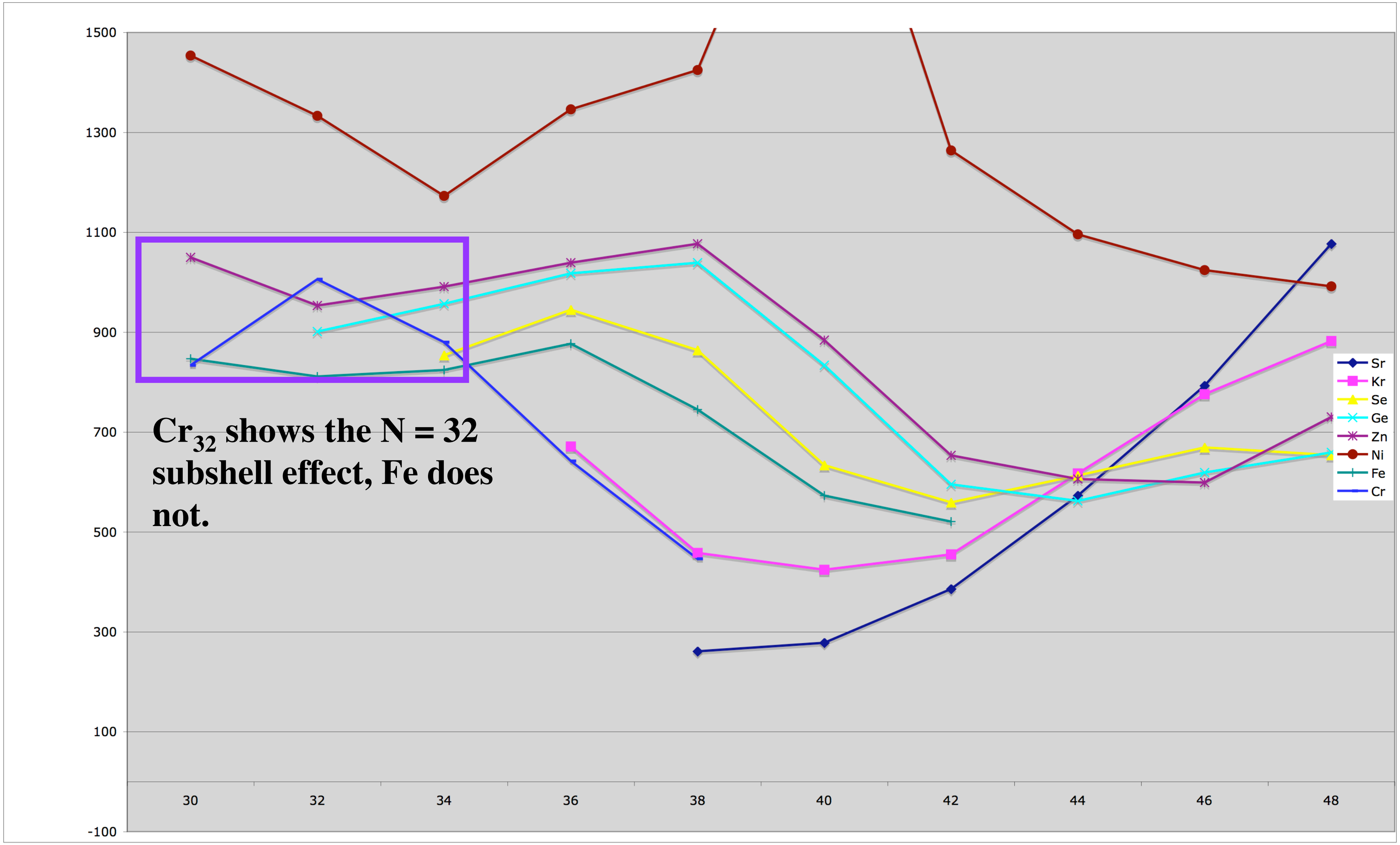
The neutrons show much more interesting possibilities. Above are two different versions of the Wood-Saxon level diagrams, both generated by Bernd Pfeiffer, one for me on the left based on ^{49}Ca single-neutron energies, one for Gaudefroy's thesis on the right is based on ^{57}Ni energies. On the right, the 33rd neutron is in a sharply downsloping orbital for both oblate and prolate deformation, on the left, the neutrons are more or less deformation neutral. But, for the 35th neutron and beyond, neither oblate nor prolate deformation is favored. Also of interest is the behavior of the orbitals associated with the $g_{9/2}$ neutrons. In either setting, the 41st neutron is in a deformation driving orbital. In view of the "resistance" to prolate deformation by the PROTONS, oblate deformation is indicated as the most favored shape for the first neutron promoted across the N = 40 gap in IRON.



Here are the even-even Cr nuclei, is there a difference relative to Fe???

The answer is YES.

The 35th and 36th neutrons show a sharp change in the positions of the yrast levels with respect to the lighter Cr level structures.


1500
1300
1100
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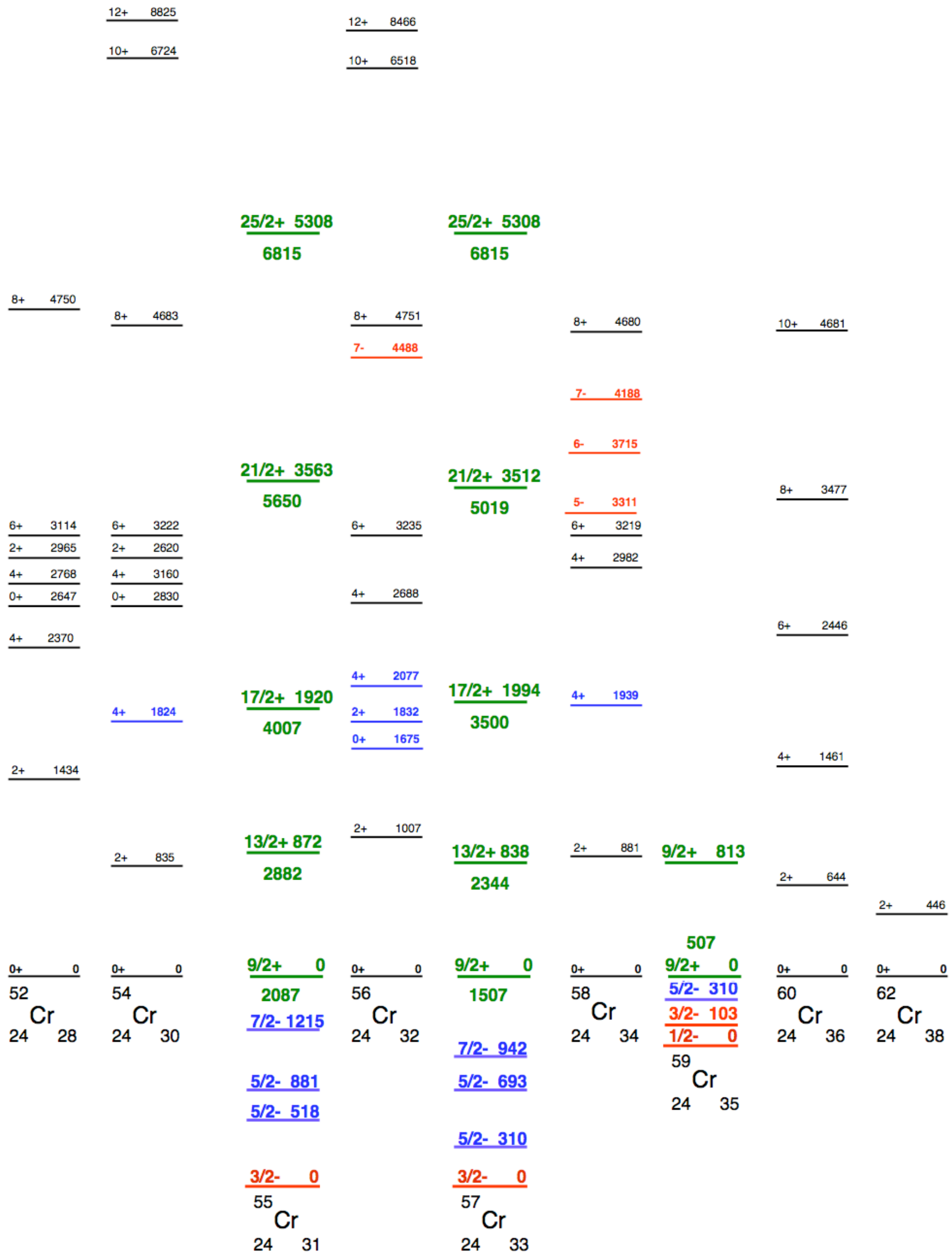
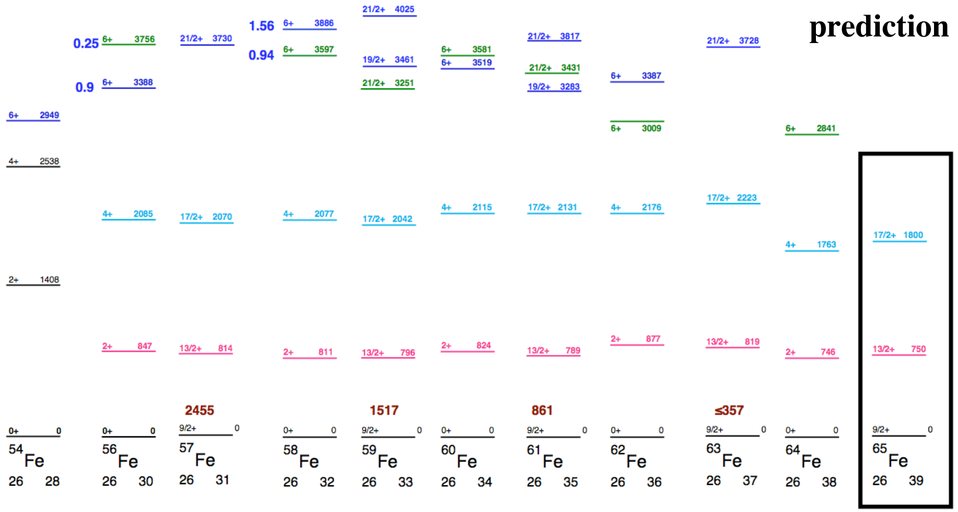
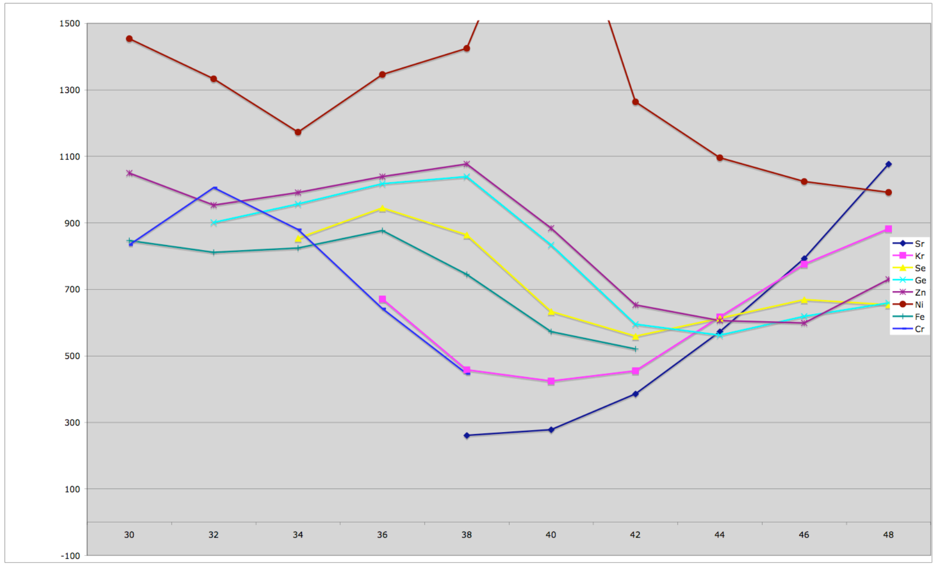
700
500
300
100
-100
30
32
34
36
38
40
42
44
46
48
Sr
Kr
Se
Ge
Zn
Ni
Fe
Cr
Cr$_{32}$ shows the N = 32 subshell effect, Fe does not.



Here, I have added in the odd-mass nuclei. Again, the odd-mass data from Deacon and Freeman at Manchester. The yrast sequences in ^{55,57}Cr are seen to be less well-connected to the adjacent even-even core nuclei. The authors argue for prolate shapes. For ^{59}Cr, they argue for oblate shape!!!

The "quasiparticle crunch" is quite clearly visible in $^{59}Cr_{35}$ where the g-9/2 level is down at 500 keV and falling rapidly. Probably $^{61}Cr_{37}$ will have a g-9/2 ground state





Summary: What have we learned?

I would like to leave you with two ideas, the weak-coupled P + Q view of the Fe nuclei that are rather well described by shell-model calculations and which show little systematic evidence of either strong deformation or noticeable shape change, in contrast to the Cr nuclei.

And, second, added insight into the role that the proton L value plays in the neutron occupancy of the g-9/2 orbital and the transition at N = 40.