PARTICLE-CORE COUPLING AROUND ^{68}Ni

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The single-particle spectrum of nuclei with large neutron excess is predicted by some approaches [1] to become similar to that of a harmonic oscillator with a spin-orbit term (no additional $\vec{l}^2$ term) and thus reinforce some of the harmonic oscillator magic numbers. This is the case of N=40, and indeed experimental results accumulating in the past few years [2,3] indicate the presence of a subshell closure in ^{68}Ni. Although ^{68}Ni is only modestly far from stability (the last stable Ni isotope has A=64), understanding the properties of the nuclei around ^{68}Ni is one important step towards understanding the structure of the more exotic ^{78}Ni. In addition, the existence of a good subshell closure at N=40 is expected to have a significant impact on the properties of the nuclei in the region. Furthermore, a good subshell closure at N=40 in ^{68}Ni might develop into a real shell closure for nuclei with smaller proton numbers and larger neutron excess. Pursuing the evolution of the N=40 subshell gap in the very neutron-rich nuclei towards ^{60}Ca, while being a very difficult experimental task, would give rich information about the evolution of the nuclear spin-orbit term for large neutron excess.

We studied the influence of the subshell closure at N=40 on nuclei adjacent to ^{68}Ni in the framework of the Particle-Core Coupling Model (PCM). A detailed description of the model can be found in Refs. [4,5]; calculations on nuclei in the region of ^{68}Ni have been reported in Ref. [6]. The aim of the particle-core coupling study is to (i) investigate if ^{68}Ni is a good core for the adjacent nuclei; and (ii) extract information about the neutron and proton single-particle energies around N=40, Z=28 and their behavior with increasing neutron excess. The model space for the odd-mass Ni and Cu nuclei around ^{68}Ni, described herein, consists of single-hole or -particle states coupled to collective quadrupole and octupole vibrational excitations of the underlying even-even core. It is assumed that the core does not change whether a proton or a neutron particle or hole is coupled to it. In addition to the "natural" configuration space consisting of collective excitations in ^{68}Ni coupled to single-hole or single-particle excitations, an additional subspace has been included, which accounts for neutron or proton excitations of the type two-particle one-hole (2p-1h) or one-particle two-hole (1p-2h). This latter part of the model space can be approximated by hole or particle excitations coupled to the collective excitations of $^{68\pm2}$Ni for the odd-neutron Ni isotopes, or of the corresponding Zn isotopes for the odd-proton Cu isotopes.

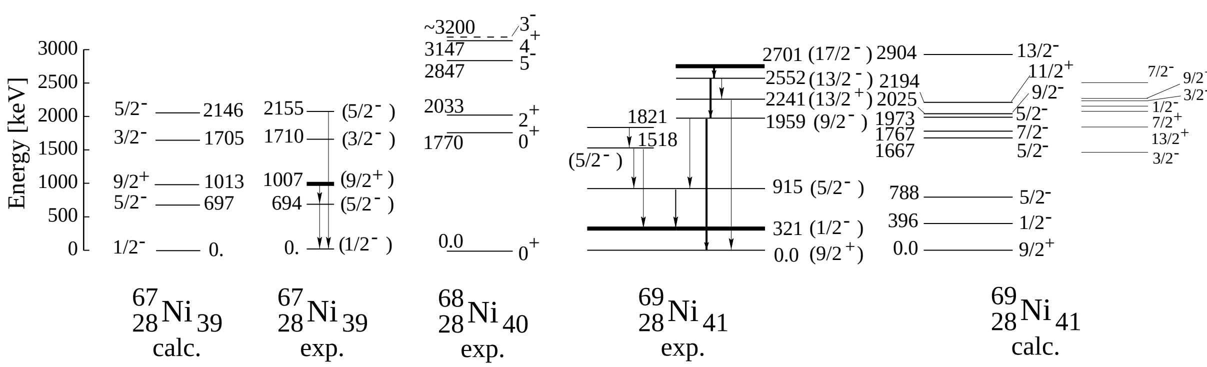

Figure 1: Experimental and calculated states in ^{67}Ni and ^{69}Ni. Selected states (experimental and extrapolated) in the core ^{68}Ni are shown in the middle part of the figure. The experimental levels are taken from Refs. [3,7-10].

The energy levels of the odd-A Ni isotopes in the immediate vicinity of ^{68}Ni can provide evidence for a significant subshell closure at ^{68}Ni. For an open shell odd-mass nucleus A, an average core composed from the even-even A-1 and A+1 nuclei would be needed. In the case of a strong subshell closure, distinct excitations corresponding to a dominating ^{68}Ni core should exist in the odd-neutron nuclei. The results of the calculations for ^{67,69}Ni and ^{69,71,73}Cu are compared to the available experimental data in the following. We will only emphasize the interesting physical aspects to which the model calculations provide a better insight, rather than aim at a level-by-level discussion.

The known experimental levels of ^{67}Ni and ^{69}Ni are shown in Fig. 1, along with the levels calculated in the particle-core model and selected experimental states in the core ^{68}Ni. The particle-core model provides an overall good description of the known levels in the odd-mass ^{67,69}Ni isotopes adjacent to ^{68}Ni. In each isotope, a member of the quadrupole multiplet was identified at an energy close to that of 2^+_1 in ^{68}Ni. The (5/2$^-$) level at 2155 keV in ^{67}Ni and (13/2$^+$) at 2241 keV in ^{69}Ni are well reproduced by the calculations, and their energy is close to that of the 2^+ state in ^{68}Ni, at 2033 keV, providing direct evidence that ^{68}Ni is a good core for the two "one-neutron" nuclei. The fact that the low-energy spectrum of ^{69}Ni is dominated by negative-parity levels of 2p-1h structure does not contradict this conclusion. The high density and low energy of these levels can be explained in terms of (i) gain in pairing energy in the 2p-1h as compared to the 1p configuration; (ii) stronger particle-vibration coupling and lower energy of the 2^+_1 state in the subspace of ^{70}Ni (^{68}Ni+2p), and (iii) higher density of single-hole, as compared to single-particle, orbitals.

The experimental levels for ^{69}Cu, ^{71}Cu and ^{73}Cu, along with the results of the PCM calculations, are shown in Fig. 2. An excited "quasi-band" of 2p-1h character, built on the lowest 7/2$^-$ state at 1711 keV in ^{69}Cu, has been observed by Ishii et al. [11] and is shown in Fig. 2(a). As noted earlier, the particle-core model can account for proton 2p-1h excitations, and describes well the states in ^{69}Cu belonging to this category. In particular, the decay within the "quasi-band" built on the $7/2^-_1$ state is well reproduced [6]. In a similar way, the calculated dominant structure of the lower (7/2$^-$) state at 981 keV in ^{71}Cu is a 2p-1h excitation with the hole in the $\pi 1f_{7/2}$ orbital. The structure assignment is supported by the experimental decay mode. Combining the model predictions and the experimental data, it is likely that the sequence of levels in ^{71}Cu, at energies of 1972 keV, 1452 keV and 981 keV form an 11/2$^-$, 9/2$^-$, 7/2$^-$ "quasi-band" built on the 7/2$^-$ state of 2p-1h character. A rather striking energy lowering of this 2p-1h quasi-band can be seen between ^{69}Cu and ^{71}Cu, possibly indicating that proton 2p-2h excitations might play an important role in the structure of the even nuclei around ^{68}Ni.

Levels with main single-particle component have been identified in all three Cu isotopes from comparison of the calculations with the experimental energies, decay modes and feeding in beta-decay, and show a very interesting behavior with mass number. As discussed by Franchoo et al. [13], the energy spacing between the states with dominant single-particle character $\pi 1f_{5/2}$ and $\pi 2p_{3/2}$ decreases rapidly after N=40. This "monopole shift" has been attributed to the monopole interaction of the proton in the orbital $\pi 1f_{5/2}$ with neutrons in $\nu 1g_{9/2}$, which is stronger than the corresponding interaction when the proton occupies the reference orbital $\pi 2p_{3/2}$. The monopole shift of the *single-particle energy*, deduced from model calculations, of the $\pi 1f_{5/2}$ orbital relative to $\pi 2p_{3/2}$ in the heavy Cu isotopes is as pronounced as the drop in the energy of the (5/2$^-$) state. The $\pi 1f_{5/2}$ single-particle energies needed to reproduce the spectra of ^{69}Cu, ^{71}Cu, and ^{73}Cu are 0.9, 0.25, and -0.30, respectively, all energies given relative to that of $\pi 2p_{3/2}$. If this effect is attributed entirely to the occupancy of the $\nu 1g_{9/2}$ orbital, the $\pi 1f_{5/2}$ orbital is expected to be around 2 MeV lower than $\pi 2p_{3/2}$ in ^{78}Ni. Nevertheless, additional mean-field effects must be taken into account in order to predict the evolution of the relative energy of $\pi 2p_{3/2}$ and $\pi 1f_{5/2}$ towards ^{78}Ni.

The same strong monopole proton-neutron interaction with the neutrons in the $\nu 1g_{9/2}$ orbital can be expected to affect the $\pi 1g_{9/2}$ single-particle state. The experimental data from which the single-particle energy of the orbital $\pi 1g_{9/2}$ can be extracted are unfortunately not as clear as for the case of $\pi 1f_{5/2}$. The lowest-energy level assigned ($9/2^+$) in ^{69}Cu (at 2551 keV) and ^{71}Cu (at 1786 keV), should have a significant $\pi 1g_{9/2}$ component.

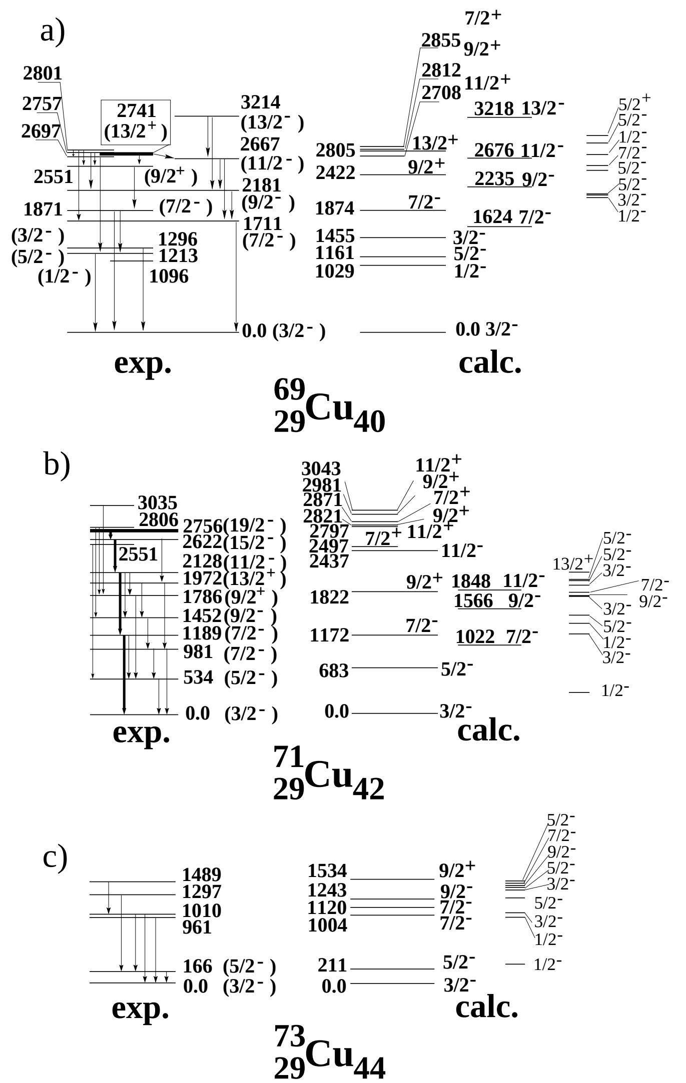

Figure 2: Calculated and experimental levels for (a) ^{69}Cu, (b) ^{71}Cu and (c) ^{73}Cu. The experimental levels are taken from Refs. [7,11-13] for ^{69}Cu, from Refs. [3,12] for ^{71}Cu and from Ref. [13] for ^{73}Cu. For each isotope, known isomeric states are plotted with thick lines. The calculated states suggested to correspond to the experimental levels are plotted with long lines and the remaining calculated states are plotted with short lines.

From these experimental data, the excitation energy of the ($9/2^+_1$) state decreases by $\sim$800 keV between ^{69}Cu and ^{71}Cu, similar to the effect noted for the $5/2^-_1$ state. The particle-core model calculations for ^{69}Cu and ^{71}Cu set the single-particle energy of $\pi 1g_{9/2}$ (relative to $\pi 2p_{3/2}$) at 3.4 MeV in ^{69}Cu and 2.15 MeV in ^{71}Cu. If we identify, very tentatively, the state at 1489 keV in ^{73}Cu with the calculated $9/2^+_1$ state, the extracted single-particle energy of $\pi 1g_{9/2}$ will further drop to 1.65 MeV. The behavior of the experimental 5/2$^-$ and 9/2$^+$ states, the single-particle energies of the orbitals $\nu 1f_{5/2}$ and $\nu 1g_{9/2}$, as well as the linear extrapolation to ^{78}Ni, are summarized in Fig. 3(a). We show for a qualitative comparison in Fig. 3(b) the calculated monopole shift in the single-particle energies using a $\delta-$interaction with spin dependence [5].

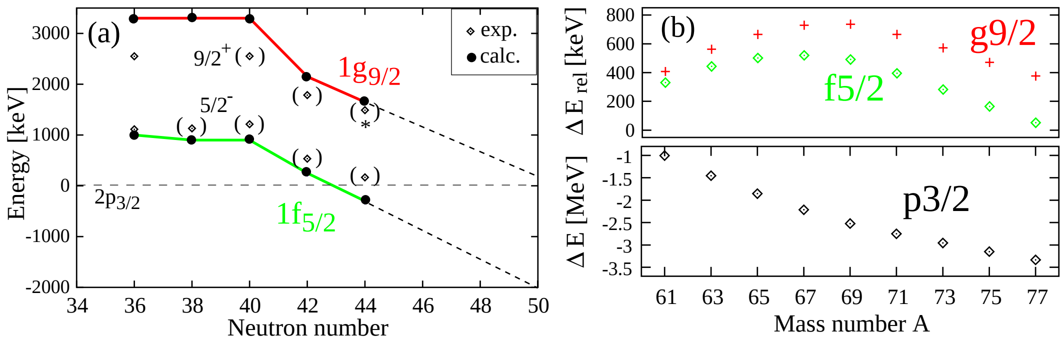

Figure 3: (a) Experimental yrast 5/2$^-$ and 9/2$^+$ states in the odd-mass Cu isotopes and the single-particle energies of the $\pi 1f_{5/2}$ and $\pi 1g_{9/2}$ orbitals relative to the $\pi 2p_{3/2}$ orbital, extracted from the PCM calculations. A linear extrapolation of the $\pi 1f_{5/2}$ and $\pi 1g_{9/2}$ single-particle energies toward ^{78}Ni is shown. The experimental levels are taken from Refs. [12,13]. (b) Calculated monopole shift in the single-particle energies of the orbitals $1f_{5/2}$ and $1g_{9/2}$ relative to $2p_{3/2}$ (upper part) and on the orbital $2p_{3/2}$ (lower part). We use a $\delta-$interaction with spin dependence [5] and parameters V=300 keV and α =0.6

In conclusion, the properties of several nuclei in the region of ^{68}Ni have been studied in the framework of the particle-core coupling model. The calculations suggest that ^{68}Ni is the dominant core for the adjacent odd-mass Ni and Cu nuclei. From the PCM studies, the neutron and proton single-particle energies around N=40, Z=28 have been extracted and the neutron subshell gap at N=40 was estimated to be around 3 MeV. The gap is very similar to that found in the proton single-particle spectrum at Z=40, N=50. The observed "monopole shift" of the proton orbitals $\pi 1f_{5/2}$, and possibly also $\pi 1g_{9/2}$, takes place after N=40 is crossed. This is a strong argument for a nearly zero occupancy of $\nu 1g_{9/2}$ before N=40, indicating a significant subshell closure.

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