Particle-hole intruder levels in $^{67}$Cu, collectivity, monopole shifts, and the hockey-stick behaviour of $\ell - \frac{1}{2}$ $5/2^-$ levels in neutron-rich odd-mass Cu nuclei

W B Walters $^1$ and C J Chiara $^{1,2}$

$^1$University of Maryland, College Park, MD 20742 USA

$^2$Argonne National Laboratory, Argonne, IL 60439 USA

E-mail: wwalters@umd.edu

Abstract. A new sequence of gamma rays with energies of 572, 499, 585, and 674 keV has been identified in $^{67}$Cu populating the $7/2^-$ level at 2362 keV. Owing to the strong population of the 2362-keV level via an $\ell = 3$ proton pickup reaction, that level is assigned to be an $f_{7/2}$ 2-particle-1-hole “intruder” proton configuration, and the new levels are found to form a sequence consistent with intruder sequences in the adjacent odd-mass Cu isotopes and in the odd-mass Sb isotopes. The changing position of the intruder sequence in the odd-mass Cu isotopes is discussed and related to the onset of collectivity associated with the presence of $g_{9/2}$ neutrons beyond $N = 40$. The increase in collectivity is also discussed for a number of isotonic and isotopic chains as more protons or neutrons, respectively, are added beyond an oscillator shell boundary. For most of these systems, the $\ell - \frac{1}{2}$ levels show a systematic “hockey-stick-like” behaviour with a sharp decrease in energy with the addition of the first protons or neutrons, owing to both the added collectivity and the tensor interaction, and then a lower slope when collectivity changes are diminished and only the tensor interaction is influencing the changes in level positions.

1. Introduction

Following the identification of the lowered energies of the $5/2^-$ levels in $^{71,73}$Cu [1], many other studies have been undertaken to obtain additional information for the levels of other odd-mass Cu levels [2,3,4,5,6,7]. Moreover, a number of theoretical studies have also been undertaken that pertain to the systematic changes in these levels, and, in particular, the rapid downward movement of the $\ell - \frac{1}{2}$ $5/2^-$ levels as $\ell + \frac{1}{2}$ $g_{9/2}$ neutrons are added [8,9,10]. In this work, new level structure has been determined for $^{67}$Cu from which level sequences associated with coupling to the $^{66}$Ni core are readily identified [11]. The recent identification of an unexpected $K = \frac{1}{2}$ 1-particle-hole intruder level at 493 keV in $^{66}$Co$_{\text{en}}$ has led to keen interest in intruder levels in Cu and Co for the even-even closed shell Ni isotopes [12,13].

2. Experimental measurements

These new data for the levels of $^{67}$Cu were obtained by determining the gamma rays following the reaction of a 430-MeV $^{64}$Ni beam with a $^{238}$U target using the ATLAS accelerator and Gammasphere at Argonne National Laboratory. The data sorting has been described in recent papers by Hoteling et al. [14,15]. No isomers with half lives in the range from 20 ns to 10 $\mu$s were observed. An $f_{7/2}$ 2-particle-1-hole state was identified at 2362(30) keV by Zeidman et al. in the $(d,^3He)$ reaction with an $\ell$ value of 3 and a spectroscopic factor of 3.1 [16]. A number of additional levels in $^{67}$Cu were identified by Nybo et al. in the $^{68}$Ni$(\alpha,p)^{67}$Cu reaction [17]. The systematic behaviour of particle-hole intruder levels was surveyed by Heyde et al. [18]. Such levels are of interest as, although their behaviour is sensitive to the overall collectivity changes in a particular isotopic sequence, they appear to reflect, in particular for protons, the occupancy of the valence high-$j$ neutrons.

3. Results and discussion

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A partial level scheme for $^{67}\text{Cu}$ showing the four new transitions and four new proposed levels that populate the $\frac{7}{2}^{-}$ 2-particle-1-hole intruder level at 2362 keV is shown in Fig. 1. This figure includes the collective levels populated in Coulomb excitation by Stefanescu et al. [3] The approximately equally spaced levels connected by strong dipole and weak quadrupole crossover transitions are quite similar to those identified for the odd-mass Sb nuclei whose low-energy levels are shown in Fig. 2a [19]. In particular, all of the levels shown for the odd-mass Sb nuclei drop in energy, “in parallel” beyond the N = 4 oscillator-shell boundary at N = 64 up through N = 70. Beyond N = 70, the 2-particle-1-hole $\frac{9}{2}^{+}$ intruder level rises rapidly in energy, while the “tensor-interaction-induced” energy reduction for the $\frac{5}{2}^{-}$ proton state continues to drop in energy, but at a somewhat lesser rate.

The behaviour of “tensor-interaction-induced” energy changes can be seen further in Figs. 2b, 2c, and 2d where the odd-neutron levels are plotted for N = 29, 51, and 53 isotones, respectively. For all three of these sets of levels, protons are being added beyond an oscillator-shell boundary, either Z = 20 or Z = 40: in each case, there is a sharp drop with the addition of the first and/or second pair of protons, and then a gentle drop for additional protons. In Fig. 2b for the N = 29 isotones, the familiar “hockey-stick” shape has been added. In all three cases, the energies of the adjacent $2^{+}$ levels are plotted, along with other levels of interest.

A box has been placed around the region of Sb isotopes comparable to the levels observed in the odd-mass Cu isotopes, namely the region beyond [for Sb] N = 64 where $h_{\frac{1}{2}}$ neutrons are added to the nucleus. The levels shown within that boxed region — the “$\frac{9}{2}^{+}$ and $\frac{1}{2}^{+}$ collective” levels, the “$\frac{9}{2}^{+}$ intruder” levels, and the $\frac{1}{2}^{-} \frac{7}{2}^{+}$ levels—all drop in energy. Similar behaviour is observed for all of the levels in the odd-mass Cu isotopes with N = 38, 40, 42, and 44. For Sb, however, as more neutrons are added, the collective levels and the intruder rise rapidly, and the $\frac{1}{2}^{-} \frac{5}{2}^{-}$ level descends at a lower rate. This comparison supports the notion that beyond N = 46, the collective levels and intruder levels in Cu will rise in energy and the $\frac{1}{2}^{-} \frac{5}{2}^{-}$ level will descend slowly.

A summary of the low-energy levels in the odd-mass Cu isotopes is plotted in Fig. 3. These levels show behaviour similar to those in the odd-mass Sb isotopes. That is, the observed $1/2^{-}$, $5/2^{-}$, “$7/2^{-}$ intruder”, and “$7/2^{-}$ collective” levels drop in energy as N increases from 40 to 42 driven largely by collectivity, as reflected by the sharp increases in B(E2) values reported by Stefanescu et al. for the $1/2^{-}$ and $7/2^{-}$ collective levels [3]. As with the Sb nuclei, the intruders level off at N = 42 and N = 44 and are likely to rise sharply as N approaches 50. The $5/2^{-}$ levels which exhibit much smaller B(E2) values than the adjacent $1/2^{-}$ and $7/2^{-}$ collective levels also drop rapidly for N = 40 and N = 42, and then more slowly for N = 44 and N = 46, exhibiting the “hockey-stick” shaped curve similar to that shown in Fig. 2b for the N = 29 isotones. In contrast, the $9/2^{-}$ level that has relatively large spectroscopic factors in the lighter Cu isotopes exhibits little change in position as N increases from 40 to 42. As the position of this level is not likely to be changed by quadrupole collectivity, the insensitivity to N is not surprising. The positions of the levels of $^{79}\text{Cu}_{50}$ calculated by three different approaches are also shown in Fig. 3, along with the experimental data for isotonic $^{81}\text{Ga}_{50}$, whose ground-state spin has recently been determined to be $5/2$ [20,21,22].
Figure 2a. Plot of the positions of selected low-energy levels in the odd-mass Sb isotopes, including the 2-particle–1-hole 9/2+ intruder levels as described by Heyde et al. [18] The box described by the dashed lines surrounds those levels that are "equivalent" to the odd-mass Cu levels shown in Fig. 1 where the intruder levels come down in energy.

Figure 2b. Plot of the positions of the lowest 1/2+ and 5/2+ levels in the odd-mass N = 29 isotones, along with the position of the lowest 2+ level in the adjacent N = 28 isotones. The boxes associated with the positions of the 5/2+ levels are shown to exhibit the "hockey-stick" shape of 5/2+ levels as described in the text.

Figure 2c. Plot of the positions of the lowest 1/2+ and 7/2+ levels in the N = 51 isotones, along with the position of the lowest 2+ level in the adjacent N = 50 isotones.

Figure 2d. Plot of the positions of the lowest 9/2+ and 7/2+ levels in the N = 53 isotones, along with the position of the lowest 2+ level in the adjacent N = 52 isotones.
including recent values taken from Stefancic et al., that illustrate the rapid rise in $B(E2)$ as $N$ increases beyond 40.\cite{S06}

The filled circles show levels populated in Coulomb excitation reactions. The numbers in the boxes show the $B(E2)$ values for the $3/2^-$ to $1/2^+$ transition.

Figure 3. Summary plot of the energy levels of the odd-mass Cu isotopes, including calculated positions for the levels of $^{68,70}$Cu and observed levels in $^{72,74,76}$Cu.

Levels in odd-proton Cu nuclides.
In conclusion, new levels have been indentified in $^{67}$Cu that populate the 2-particle-1-hole intruder $7/2^-$ level at 2362 keV. These levels now make it possible to observe the behaviour of this intruder sequence for $^{67,69,71,73}$Cu and identify the similarities with analogous intruder levels in odd-mass Sb nuclides. This behaviour highlights the importance of collective effects as neutrons or protons are added beyond oscillator shell boundaries. These results indicate the need to view full systems in developing models to describe nuclei for which few or no results are available.

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