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Abstract. We have measured the ^{72}Zn(d,^{3}He)^{71}Cu proton pick-up reaction in inverse kinematics at 38 MeV/u. A dedicated set-up was developed to overcome the experimental challenges posed by the low cross section of the reaction and the low energy of the outgoing ^{3}He particles. The excitation-energy spectrum was reconstructed and spectroscopic factors were obtained after analysis of the angular distributions in the finite-range Distorted-Wave Born Approximation (DWBA). The results show that unlike for the $\pi f_{5/2}$ orbital, the $\pi f_{7/2}$ single-particle strength is not appreciably affected by the addition of neutrons beyond $N = 40$.

1. Introduction

With a long and fruitful history to its credit, the shell model still accounts for much of our understanding of nuclear structure at low excitation energy [1]. The bulk of the interaction within the nuclear many-body system is well represented by a mean field, the potential of which gives rise to a shell structure, from which in turn well-known magic numbers appear that define the closed shells. These magic numbers, however, are not absolute and universal but are subject to a slow evolution as one moves away from the valley of stability into the realm of exotic isotopes, where the numbers of protons and neutrons are out of their ordinary balance. The fate

of a presumed doubly magic nucleus like ^{78}Ni therefore carries much interest, as its closed-shell character comes under scrutiny. While the ^{78}Ni isotope has been observed for the first time two decades ago [2], only its half-life is known so far [3] and direct spectroscopic information is not yet available.

The neutron-rich copper isotopes are characterised by one proton outside the nickel core and present an ideal opportunity to probe the movement of a single proton in the field of a closed-shell nucleus. In particular, the $Z = 28$ closure is the first shell gap that originates from the spin-orbit interaction and its evolution away from stability gives insight into the isospin dependence of the spin-orbit force. Proceeding along the copper isotopic chain, one is able to explore the influence of the occupation of the neutron orbitals on the nuclear structure. Of particular interest is the transition at $N = 40$. Because the first excited state in ^{68}Ni is located at a rather high energy and moreover shows a spin and parity of 0^+, the existence of a subshell gap at $N = 40$ was rapidly acknowledged [4]. Much experimental work has been done since, revealing a third 0^+ state at 2511 keV [5] and readjusting the energy of the second 0^+ state to 1604 keV [6]. This has in turn spurred new theoretical activity, leading to a richer interpretation that advances the coexistence of spherical and strongly deformed shapes in ^{68}Ni in the frame of the Monte-Carlo Shell Model (MCSM) [7].

In the β decay of ^{71}Cu, it was observed that the first excited state of spin and parity $5/2^-$, which is situated in a stable manner at an energy between 1 and 1.2 MeV in the ^{63,65,67,69}Cu isotopes, suddenly comes down to 534 keV [8]. This distinctive feature coincides with the addition of neutrons beyond $N = 40$. Because of the high spectroscopic factor of $C^2S = 1.5$ in the ^{70}Zn(d,^{3}He)^{69}Cu proton pick-up reaction [9], the level was interpreted as chiefly corresponding to the $\pi f_{5/2}$ single-particle state. For the level at 1190 keV in ^{71}Cu, seen in the $E2$ cascade that desexcites a $19/2^-$ microsecond isomer, a $7/2^-$ assignment was made [10, 11]. Based on lower limit for the log ft value of 5.9 in the β decay of ^{71}Ni, the ground state of which is conjectured to consist of a $9/2^+$ configuration, and the similarity of the γ branching pattern between ^{69}Cu and ^{71}Cu, a spin and parity of $7/2^-$ was suggested for the level at 981 keV. This was corroborated by calculations within the particle-core coupling model (PCM) that linked the state to the $f_{7/2}^{-1}$ proton hole, onto which a 2p–1h quasiband would dwell in the same manner as for ^{69}Cu [12]. The Coulomb excitation of ^{71}Cu accordingly revealed a value of 10.7(12) Weisskopf units for the 1190-keV level, while the 981-keV state remained unobserved [13].

In the present work, we set off to measure the spectroscopic factors of the $7/2^-$ levels with the aim of obtaining the strength function of the $\pi f_{7/2}$ single-particle state. We chose to do so in the ^{72}Zn(d,^{3}He)^{71}Cu proton pick-up reaction, as it should selectively populate the hole states in copper.

2. Experimental set-up

The experiment took place at the Ganil laboratory in Caen, France. A radioactive beam of ^{72}Zn at 38 MeV/u and a rate of $1.5\ 10^5$ particles per second was obtained from the fragmentation of a primary ^{76}Ge beam on a beryllium target of 733 μm thickness. The reaction products were selected in the Lise spectrometer, resulting in a beam purity of 55 % with ^{74}Ga as main contaminant. After travelling through two Cats beam-tracking detectors [14], the beam arrived at a deuterated polypropylene target of 0.26 mg/cm^2 thickness.

The target was surrounded by four Must-2 telescopes [15], covering forward angles of 8 to 50° in the laboratory. The energy of the ^{3}He particles coming out of the reaction, however, was less than 20 MeV for laboratory angles lower than 46°. Since they would have been stopped already in the first stage of Must-2, a double-sided silicon strip detector (DSSSD) of 300 μm, four silicon strip detectors with nominal thickness of 20 μm were therefore added in front of the Must-2 array. From transmission measurements with an α source it appeared that the actual thickness deviated in places with up to 25%. Only after a pixel-by-pixel mapping on a 1 mm^2
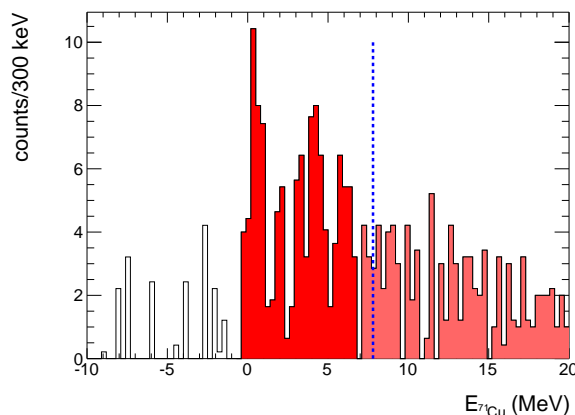
Figure 1. Excitation-energy spectrum of ^{71}Cu. In red we show the part of the spectrum that was assigned to particular levels and for which angular distributions were extracted. The area in pink is statistically not conclusive. The counts below 0 were excluded from the ^{71}Cu spectrum on grounds of energy. The dotted blue line indicates the threshold for neutron emission.

grid was carried out to correct for the variation in energy loss, the necessary resolution for particle identification could be achieved. Two Must-2 telescopes were installed at a forward angle of 85° to measure also elastic scattering.

At 0°, a ionisation chamber filled with CF_4 gas at a pressure of 100 mbar and followed by a NE 104 plastic scintillator of 2 cm of depth allowed for the identification of the outgoing heavy ions. In spite of the high count rate a resolution of $Z/\Delta Z \approx 30$ could be realised, which was sufficient for the present purpose. The signal in the ionisation chamber was digitised at a sampling rate of 40 MHz and was also used for pile-up rejection. The electronic dead time was kept at 15% throughout the experiment.

3. Results

The ^{3}He particles of interest were identified by combination of their time of flight, ΔE signal in the 20-μm strip detectors and E deposit in the Must-2 DSSSD. For each selected event, the excitation energy was reconstructed. After the subtraction of background stemming from reactions on the carbon nuclei in the target, five peaks could be distinguished in the spectrum. The width of the first peak is larger than the experimental resolution of 360 keV, indicating the presence of a doublet. From the known level scheme, the doublet can include two or more states among the $3/2^-$ ground state, the $1/2^-$ state at 454 keV and the $5/2^-$ state at 534 keV.

The angular distributions of the emitted ^{3}He particles were fitted with functions calculated within the finite-range Distorted-Wave Born Approximation (DWBA). For the incoming channel, the relativistic Daehnick optical potential was used [16]. For the outgoing channel, we took the Perey and Perey parametrisation [17].

We found that the ground-state doublet could be fitted with a combination of $L = 1$ and $L = 3$ distributions. The $L = 1$ component shows a spectroscopic factor of $C^2S = 0.8(2)$ and encompasses both the $\pi p_{3/2}$ ground state and the $1/2^-$ excited state of $\pi p_{1/2}$ nature. The $L = 3$ contribution yields $C^2S = 1.4(6)$ and we attribute it to the $5/2^-$ level, for which we infer a dominant $\pi f_{5/2}$ configuration. We note that the high spectroscopic factor exhausts the available $f_{5/2}$ proton strength. The next three peaks were best fitted with $L = 3$ functions. Cumulatively they add up to a spectroscopic strength of $C^2S = 6.9(8)$ and we assume that they correspond to
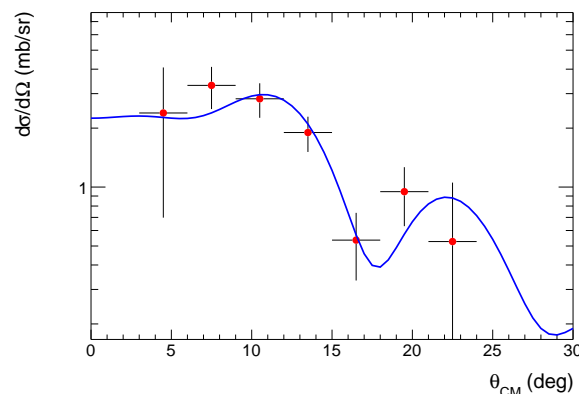
Figure 2. Summed angular distribution for the second, third and fourth peak in the excitation-energy spectrum of ^{71}Cu. The blue line corresponds to a DWBA calculation for $L = 3$.

the $f_{7/2}$ force, of which we thus determined 86%. The experimental centroid of the measured $f_{7/2}$ force is found at 3.8 MeV, which represents a lower limit in as far as part of the strength stays undetected. The fifth peak in the excitation-energy spectrum was fitted with a superposition of $L = 0$ and $L = 2$ distributions and likely originates from hole excitations in the deeper sd shell.

In our experiment, no pick-up strength was detected between 0.9 and 1.7 MeV. The low number of counts in this region is compatible with background. Therefore our data do not support the presence of a strong $L = 3$ component in the wave function of the presumptive $7/2^-$ state at 981 keV.

4. Discussion

The experimental data show that the $f_{7/2}$ proton single-particle strength remains at several MeV of excitation energy in ^{71}Cu. It does not come down appreciably and does not follow the sharp duck of the $\pi f_{5/2}$ state, preventing a rapid closure of the $Z = 28$ gap. It should be kept in mind, however, that the $\pi f_{7/2}$ orbital resides farther away from the Fermi surface and its influence on the nuclear structure at low energy is less immediate. Instead it appears more susceptible to fragmentation and therefore any change in its centroid is less visible than it is for its $\pi f_{5/2}$ spin-orbit partner.

We now come back to the nature of the $7/2^-$ state at 981 keV in ^{71}Cu, for which a single-particle character was proposed in earlier work as mentioned above. We interpret the structure of copper in a weak-coupling scheme of a proton times the excited states in the nickel core and refer to the available data [6, 9] and the MCSM calculations [7]. Of the two $7/2^-$ states at 1.74 and 1.87 MeV in ^{69}Cu, the one at 1.87 MeV with small spectroscopic factor of $C^2S = 0.45$ could correspond to the $\pi p_{3/2}$ ground state coupled to the oblate structure in ^{68}Ni the 0^+_2 bandhead of which is proposed at 1604 keV. For the other one, the $\pi f_{7/2}^{-1}$ broken-core configuration at 1.74 MeV with large spectroscopic factor of $C^2S = 2.7$, there is no immediate counterpart in the calculations. None of both matches the prolate shape that is calculated to prevail in ^{68}Ni near 3 MeV. Since the MCSM now puts forward that it is the prolate shape that would come down in energy in ^{70}Ni to take the place of the 0^+_2 state, there is no indication that the corresponding low-lying prolate structure in ^{71}Cu would correspond to a $f_{7/2}$ proton-hole state. Our data confirm this analysis by showing that within the experimental sensitivity indeed there is no $\pi f_{7/2}$ transfer strength at low energy in ^{71}Cu.

Moreover, we observe that two γ bands are known in ^{71}Cu from experiments that made use of deep-inelastic collisions. The first one shows an $E2$ sequence built on the $3/2^-$ ground state [10, 11]. The second one forms an $\Delta L = 1$ pattern on top of the first $5/2^-$ level at 534 keV [18]. The $7/2^-$ levels that make part of these bands are those at 1190 and 981 keV, respectively. If we assume a dominant $M1$ character for the second band, Coulomb excitation to the $7/2^-$ level at 981 keV would involve a structurally different configuration, which would not be as favourable as the excitation to the $7/2^-$ level at 1190 keV. Taking together the preceding arguments, we conclude that there is insufficient evidence for a $\pi f_{7/2}^{-1}$ interpretation of the level at 981 keV, as it was first proposed by the PCM calculations and later inferred from its non-observation in Coulomb excitation.

5. Conclusion

Notwithstanding the low cross section of the order of 10 mb and the low energy of the outgoing light particles that did not exceed 7 MeV/u for the angles of interest, it has been possible to measure the spectroscopic factors for the (d,^{3}He) proton pick-up reaction with a ^{72}Zn radioactive beam in the neutron-rich copper region beyond $N = 40$. Three levels carrying $\pi f_{7/2}$ strength were found in ^{71}Cu. Their spectroscopic factors were determined from the comparison of the experimental angular distributions with finite-range DWBA calculations. We found 86% of the $f_{7/2}$ proton strength and a centroid of the $\pi f_{7/2}$ force that remains situated at several MeV of excitation energy, precluding an early closure of the $Z = 28$ shell gap in the neutron-rich copper isotopes.

References

 [1] Sorlin O and Porquet M-G 2008 *Prog. in Part. and Nucl. Phys.* **61** 602
 [2] Engelmann C *et al* 1995 *Z. Phys.* A **352** 351
 [3] Hosmer P *et al* 2005 *Phys. Rev. Lett.* **112501** 94
 [4] Bernas M, Dessagne P, Langevin M, Payet J, Pougheon F and Roussel P 1982 *Phys. Lett.* B **113** 279
 [5] Mueller W *et al* 2000 *Phys. Rev.* C **61** 054308
 [6] Recchia F *et al* 2013 *Phys. Rev.* C **88** 041302
 [7] Tsunoda Y *et al* 2014 *Phys. Rev.* C **89** 031301
 [8] Franchoo S *et al* 1998 *Phys. Rev. Lett.* **81** 3100
 [9] Zeidman B and Nolan J A 1978 *Phys. Rev.* C **18** 2122
[10] Grzywacz R *et al* 1998 *Phys. Rev. Lett.* **81** 766
[11] Ishii T, Asai M, Hossain I, Kleinheinz P, Ogawa M, Makishima A, Ichikawa S, Itoh M, Ishii M and Blomqvist
     J 1998 *Phys. Rev. Lett.* **81** 4100
[12] Oros-Peusquens A and Mantica P 2000 *Nucl. Phys.* **A669** 81
[13] Stefanescu I *et al* 2008 *Phys. Rev. Lett.* **100** 112502
[14] Ottini S *et al* 1999 *Nucl. Instr. and Meth. in Phys. Res.* A **431** 476
[15] Pollacco E *et al* 2005 *Eur. Phys. J.* A **25** 287
[16] Daehnick W, Childs J and Vrcelj Z 1980 *Phys. Rev.* C **21** 2253
[17] Perey C and Perey F 1976 *At. Data and Nucl. Data Tabl.* **17** 1
[18] De Angelis G 2012 *Phys. Scr.* T 150 014010