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Proton single particle energies next to ^{78}Ni: Spectroscopy of ^{77}Cu via single proton knock-out reaction

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ABSTRACT

Excited states of ^{77}Cu have been investigated by use of single proton knock-out reaction at the Radioactive Isotope Beam Factory in RIKEN in order to reveal the main components of the proton single-particle states. Three excited states were observed at 271, 902 and 2068 keV in ^{77}Cu. The lowest-energy excited state follows the trend predicted for the crossing of the $3/2^-_1$ and $5/2^-_1$ states. Comparing the excitation energies of the $3/2^-$, $5/2^-$ and $7/2^-$ levels from ^{69}Cu to ^{77}Cu one can see that the $Z = 28$ shell gap between the $p_{3/2}$ and $f_{7/2}$ states is rather stable, while the $f_{5/2} - f_{7/2}$ spin–orbit splitting decreases by ∼1.5 MeV in agreement with shell model calculations using the tensor force.

Since the observation of disappearance of the magic numbers in nuclei (see e.g. Ref. [1] and references therein) search for the stability of the shell closures became the forefront of the nuclear structure research. The strength of the shell closures can be characterized by the shell gaps, determined by the energy differences between single-particle states. It has been shown that the monopole component of the spin–flip $\Delta\ell = 1$ proton–neutron interaction plays an important role in shifting of the single-particle energies. Such an interaction can be assigned to the tensor component of the *pn* interaction [2], which on the other hand can be traced back to a one-meson-exchange interaction [3].

Having observed the disappearance of the magic behaviour of $N = 8$, $N = 20$ and $N = 28$ at large enough neutron excess, in the last decades the efforts are focused on the study of stability of the next major neutron shell closure, $N = 50$ at ^{78}Ni. The doubly magic nature of ^{78}Ni depends on the strength of both the $N = 50$ and $Z = 28$ shell closures. The latter one can be deduced from the experimental energies of the excited states in heavy Cu nu-

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clei in the vicinity of ^{78}Ni. Since both ^{68}Ni and ^{78}Ni are considered to have closed proton shells, comparison of the energies of the excited states in ^{69}Cu and ^{77}Cu may reveal the evolution of the single-proton energies while filling the neutron $g_{9/2}$ orbit. In this way the heavy Cu nuclei present an excellent ground for testing the predictions on the isospin dependence of the spin–orbit splitting caused by the tensor force [3]. Theory predicts a significant weakening of the spin–orbit splitting for the $f_{7/2} - f_{5/2}$ spin–orbit partner orbitals going from $N = 40$ to 50, and a slight decrease of the $Z = 28$ shell gap between the $\pi p_{3/2}$ and $\pi f_{7/2}$ orbitals [3]. As a byproduct, crossing of the proton $f_{5/2}$ and $p_{3/2}$ orbits is predicted, which is confirmed by all the other shell model calculations [4–9]. Experimentally, a quick lowering of the $5/2^-_1$ state has been observed in the ^{69,71,73}Cu isotopic chain [10] and the inversion of the $p_{3/2}$ and $f_{5/2}$ orbits has been found in ^{75}Cu [11,12]. In this connection it has to be mentioned that although the crossing of the $f_{5/2}$ and $p_{3/2}$ states was predicted in a model with tensor force [2], it may also be at least partly assigned to the short range character of the effective interaction, since the radial overlap of the $\pi f_{5/2}$ orbit with the $\nu g_{9/2}$ one is much larger than that of the $\pi p_{3/2}$ orbit. As a consequence, the $\pi f_{5/2}$ orbit is expected to be more bound than the $\pi p_{3/2}$ one while filling up the $\nu g_{9/2}$ orbit. Thus, to estimate the effect of the tensor force information on the splitting of the $f_{7/2} - f_{5/2}$ spin–orbit partner orbitals has to be obtained.

Recently several theoretical and experimental studies have been performed to understand the shell evolution in the vicinity of ^{78}Ni. Coupled-cluster calculations with three-particle–three-hole corrections confirm that ^{78}Ni is doubly magic [13]. Large-scale shell-model calculations using a valence space including the full *pf* shell for the protons and the full *sdg* shell for the neutrons preserve the doubly magic nature of the ground state of ^{78}Ni, while predict the appearance of shape coexistence and emerging of a new island of inversion at $N = 50$ [14]. From experimental side the development of the next generation radioactive beam facilities opened the possibility to perform investigations much closer to ^{78}Ni. For ^{77}Cu preliminary results have been reported from a beta-decay study assigning γ-rays to it [15]. The detailed analysis of this experiment has been published very recently [16]. After the submission of the present work several experimental results have been reported for neutron-rich copper isotopes. Nuclear spins and precise values of the magnetic dipole and electric quadrupole moments of the ground states of $^{73-78}$Cu have been determined in the first high-resolution laser spectroscopy measurements of the studied nuclei [17]. Very recently in-beam γ-ray spectroscopy of ^{79}Cu has been performed through proton knock-out reaction from a ^{80}Zn beam and the level scheme up to 4.6 MeV has been established [18]. Furthermore, the masses of $^{75-79}$Cu have been measured with a combination of Penning-trap and time-of-flight mass spectrometry offering a first accurate view of the mass surface adjacent to ^{78}Ni [19]. All the obtained experimental results support a doubly magic character for ^{78}Ni. In the present paper we report on study of the heavy odd ^{77}Cu isotope by use of proton knock-out reaction which is expected to selectively populate the single-particle states.

The experiment was performed at Radioactive Isotope Beam Factory operated by RIKEN Nishina Center and CNS, University of Tokyo [20,21]. To produce the ^{78}Zn beam ^{238}U primary beam impinged on a 925 mg/cm^2 beryllium target with an energy of 345 MeV/u. The average primary beam intensity was 1.8 pnA. The secondary beams were selected in the BigRIPS separator [22,23]. The momentum acceptance of BigRIPS was set to be 6% and was optimized for ^{80}Zn. To purify the fission products, an achromatic wedge-shaped aluminum degrader of 1.6 g/cm^2 thickness was placed at the F1 dispersive focus. Ions passing through the BigRIPS were identified event-by-event by measuring the $B\rho$, energy loss

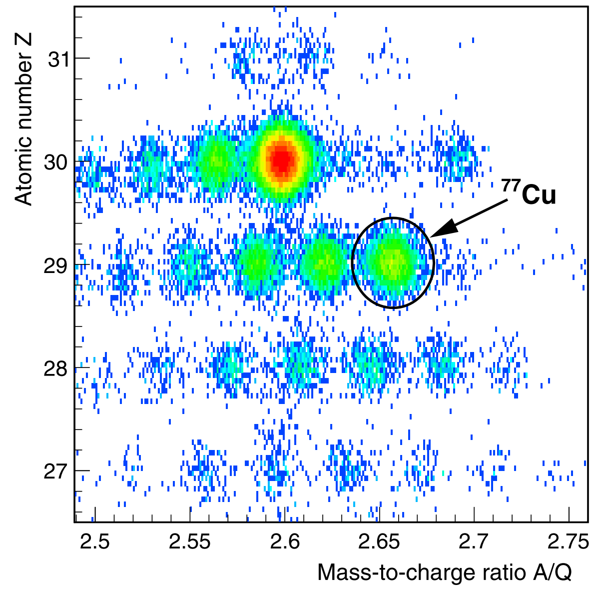

Fig. 1. Reaction products from interaction of the ^{78}Zn beam with the ^{9}Be secondary target identified by measuring $B\rho$, ΔE, and TOF at the ZeroDegree spectrometer.

Table 1
Energies and relative intensities of transitions assigned to ^{77}Cu in the present work.

E_γ (keV)	I_γ (rel.)
271(16)	20(4)
902(28)	21(3)
2068(64)	100(15)

(ΔE), and time-of-flight (TOF) values. The $B\rho$ value was deduced using the positions and angles measured at F3 and F5 by Parallel Plate Avalanche Counters (PPACs) [24]. The ΔE value was measured by an ionization chamber located at the F7 focus. The TOF was measured between two plastic scintillators located at F3 and F7. In the secondary cocktail beam ^{82}Ge and ^{83}Ge were the main components. The intensity of the ^{78}Zn beam was ~16 particles per second.

The secondary beams impinged on a 1.89 g/cm^2 thick ^{9}Be secondary target placed at the F8 focus. The average energy of the Zn isotopes was about 240 MeV/u. The reaction residues were analyzed by the ZeroDegree spectrometer [23]. The particle identification at the ZeroDegree spectrometer consisted of measuring $B\rho$, ΔE, and TOF event-by-event. $B\rho$ values were set to maximize the yield of ^{78}Ni with a full momentum acceptance of 8%. TOF was obtained from F8 to F11 by two plastic scintillators. Particle identification was obtained from ΔE-TOF and $B\rho$-TOF correlations, respectively. Identification of the reaction products from the ^{78}Zn beam is presented in Fig. 1. It is seen that the different isotopes can be clearly separated.

The γ-rays produced in the secondary reactions were measured by the DALI2 spectrometer [25]. It consisted of 186 large-volume NaI(Tl) scintillation detectors surrounding the target. The detectors were placed at angles from 14 to 148 degrees with respect to the beam direction. The target chamber was covered by a 1 mm thick Pb shield to absorb low energy bremsstrahlung. The efficiency of the array was estimated from a GEANT4 simulation. 22% efficiency was obtained for the 662 keV γ-ray emitted from a standard ^{137}Cs γ-ray source. The γ-ray spectra were Doppler shift corrected using the individual detector angles. Velocities of the fragments were taken from their TOF values.

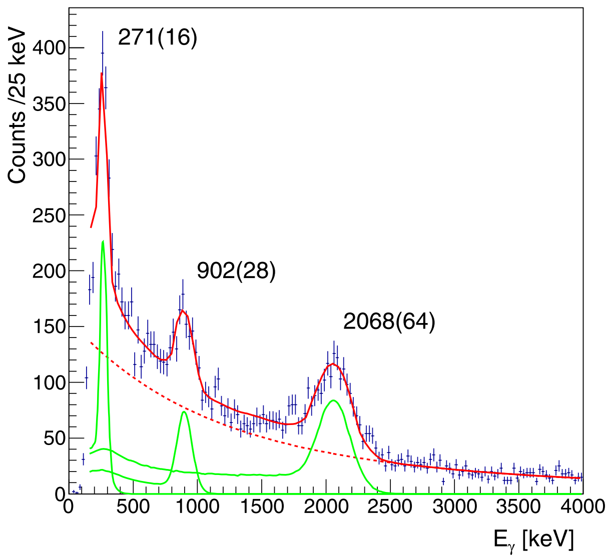

Fig. 2. Doppler-corrected γ-ray energy spectrum of ^{77}Cu for $M_\gamma = 1$ events. In the interpretation of the spectrum a double exponential background (plotted as dashed red line) is assumed. The solid red curve shows the final fit which includes the detector response functions (green solid lines) from a GEANT4 simulation and the background. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

The energy calibration of the spectrometer was performed using standard ^{60}Co, ^{88}Y and ^{137}Cs sources. Energies of known transitions in ^{72,74,76}Ni, ^{78,80}Zn and ^{82}Ge were well reproduced. All energy errors obtained in the present work include statistical and systematic contributions. The systematic error originates from uncertainties in the energy calibration, fitting the spectra with backgrounds with different shapes, and uncertainties in the Doppler-shift correction was estimated to be 3% of the γ-ray energy. For γ-lines below 300 keV 5% systematic error was applied due to the bigger uncertainties in the background determination. Furthermore, 5-keV error was included as contribution due to the binning effect.

The Doppler corrected gamma-ray energy spectrum of ^{77}Cu for gamma-ray detection multiplicity $M_\gamma = 1$ events is shown in Fig. 2. In the spectrum one can clearly see three lines at 271, 902 and 2068 keV energy. No other peak was visible above the 2068-keV line up to 6 MeV. The energies and relative intensities of the γ-rays assigned to ^{77}Cu are listed in Table 1. Performing $\gamma\gamma$-coincidence analysis no coincidence relation was found between the γ-rays observed. Consequently, all of the transitions assigned to ^{77}Cu are placed parallel to feed the ground state directly and three excited states are established at energies of 271, 902 and 2068 keV as it can be seen in Fig. 3. In the beta-decay study among others strong γ-rays with energies of 293, 946 and 2068 keV have been found and placed to decay to the ground state [16] which might correspond to the transitions detected in the present work. It has to be noted that the energy values of the gamma rays assigned to ^{77}Cu in the beta-decay study and in the present work do not overlap completely within the error bars. The energies of the two transitions below 1 MeV differ $\sim 1.5\sigma$ in the measurements.

In Fig. 3 the observed level scheme is compared to large-scale shell-model calculations performed in the fp proton and $fpgd$ neutron valence space. The same Hamiltonian has been used as in the recent studies of spectroscopic factors in ^{69,71}Cu [26] and of electromagnetic transitions in $^{69-73}$Cu [27], showing an overall good agreement between theory and experimental data. The calculations have been performed using the Strasbourg shell-model

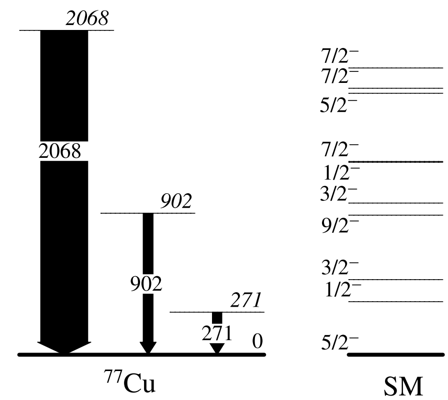

Fig. 3. Proposed level scheme of ^{77}Cu in comparison with shell model calculations.

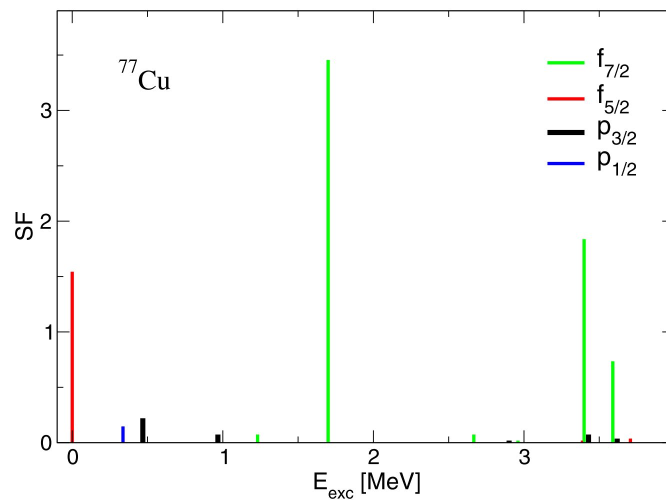

Fig. 4. Calculated spectroscopic factors in ^{77}Cu.

code ANTOINE [28], allowing up to $8p - 8h$ excitations across the proton $Z = 28$ and neutron $N = 40$ gaps.

As it can be seen in Fig. 3 the experimental and calculated level densities are rather different. The $-1p$ knock-out reaction seems to be very selective, only 3 experimental states are observed. Since, in ^{78}Zn the valence protons fill up the $\pi f_{7/2}$ orbit and a pair of them reside mainly in the $f_{5/2}$ and $p_{3/2}$ orbits, experimental states with $7/2^-$ are expected to be populated primarily, while $5/2^-$ and $3/2^-$ states might be excited with much less intensity. $5/2^-$ spin and parity has been assigned to the ground state [29] which is in accordance with the $\pi f_{5/2}$ shell model configuration. The theoretical lowest lying $3/2^-$ state, which may correspond to the first observed state at 271 keV excitation energy, has a large $\pi p_{3/2}$ component and it is accompanied by a $1/2^-$ level at similar energy in the calculations. The spin-parity assignment of the 271-keV state is based on the high selectivity of the applied reaction and the primary population of the $7/2^-$ state. Through the simplest, two-step decay of the $7/2^-$ state to the $5/2^-$ ground state levels with spin values 3/2–9/2 can be fed. Since, a low-lying $1/2^-$ level is neither expected to be excited directly in the present experiment nor through direct gamma decay of the $7/2^-$ state, we assign $3/2^-$ spin-parity to the state at 271 keV. A $1/2^-$ state at low energy has been observed in less neutron-rich coppers, $^{71-75}$Cu, however it was interpreted to have a collective nature mainly with a $\pi f_{5/2} \otimes 2^+$ configuration in agreement with the present calculations. The experimental state at 902 keV might correspond to the $3/2^-_2$ or the $9/2^-_1$ theoretical state both belonging predomi-

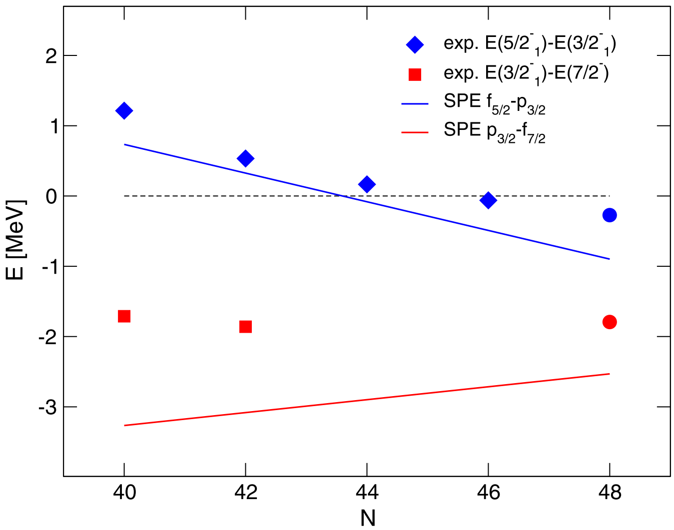

Fig. 5. Systematics of $E(5/2^-_1) - E(3/2^-_1)$ and $E(3/2^-_1) - E(7/2^-)$ in heavy odd Cu isotopes, where the $7/2^-$ states are observed in transfer reactions. Data for the $3/2^-_1$ and $5/2^-_1$ states in $^{69-75}$Cu shown with diamonds are taken from Refs. [10–12], while the $7/2^-$ states of ^{69}Cu and ^{71}Cu shown with rectangles are from transfer reactions [30,26]. Data on ^{77}Cu shown with circles are from the present work. The straight lines show the corresponding proton effective single-particle energy differences in Ni isotopes taken from Ref. [3].

nately to the $\pi f_{5/2} \otimes 2^+$ multiplet. Due to the reaction mechanism the levels with large spectroscopic factors are populated with high probabilities. Calculated spectroscopic factor distributions are shown in Fig. 4. As it can be seen in the figure a considerable spectroscopic strength is carried by the calculated $7/2^-_2$ state at 1.7 MeV with a significant $(f_{7/2})^{-1}(f_{5/2})^2$ proton–hole component. This theoretical state may correspond to the experimental level at 2068 keV, which is populated 5 times more than the ones at 271 and 902 keV, respectively, and can be considered as the $\pi f_{7/2}$ hole state. Although, the shell model predicts some $\pi f_{7/2}$ strength around 3.5 MeV, experimentally no more strength is visible up to 6 MeV. It can also be seen from the spectroscopic factor calculations that a direct population of the states at 271 and 902 keV is not expected, these states may include feeding from unresolved higher-lying states. In the recent beta-decay study similar configurations have been assigned to the states observed at 293, 946 and 2068 keV excitation energies [16].

Using the above tentative assignments one can compare the $E(5/2^-_1) - E(3/2^-_1)$ and $E(3/2^-_1) - E(7/2^-)$ energy differences in heavy odd Cu isotopes, where the $7/2^-$ states are observed in transfer reactions. It can be seen in Fig. 5 that the $(7/2^-)$ states of ^{69,71}Cu and ^{77}Cu are sitting on a constant line at about 1800 keV relative to the $(3/2^-)$ ones. This observation shows that the $Z = 28$ shell gap between the $p_{3/2}$ and the $f_{7/2}$ states has only a small isospin dependence if any. In Fig. 5 one can see a steady decrease of the energy of the $(5/2^-)$ state relative to the $(3/2^-)$ state as well as to the $(7/2^-)$ one. In $^{71-75}$Cu there is some deviation from a simple linear decrease suggesting that the $(3/2^-, 5/2^-)$ states are more complex in these nuclei. Experimentally, there is a 1.5 MeV energy change in the position of the first $(5/2^-)$ state relative to the $(7/2^-)$ one from transfer reactions carrying the most of the $\pi f_{7/2}$ strength going from ^{69}Cu to ^{77}Cu. Assuming $\pi f_{5/2}$ and $\pi f_{7/2}$ configurations to these states, one can conclude that adding neutrons to the $\nu g_{9/2}$ orbit makes the $\pi f_{5/2}$ state more bound than the $\pi f_{7/2}$ one. This extra binding can be assigned to the tensor force. Both observations are in a qualitative agreement with the predictions of the schematic calculations using a $\pi + \rho$ meson exchange force [3]. It has to be noted that despite the inversion of the proton $p_{3/2} - f_{5/2}$ orbits and the extra binding of the $\pi f_{5/2}$ state, the $Z = 28$ shell gap remains ~4 MeV large in ^{77}Cu, which indicates a doubly magic character for ^{78}Ni.

In summary, three excited states were observed at 271, 902 and 2068 keV in ^{77}Cu via $-1p$ knock-out reaction at the RIKEN Radioactive Isotope Beam Factory. The first excited state continues the trend of the crossing of the $3/2^-_1$ and $5/2^-_1$ states. Comparing the excitation energies of the $3/2^-$ and $7/2^-$ levels from ^{69}Cu to ^{77}Cu the $Z = 28$ shell gap shows only a small isospin dependence. At the same time, a steady decrease was found in the splitting of the $f_{7/2} - f_{5/2}$ spin–orbit partner orbitals in agreement with the predicted effect of the tensor force.

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