

SINGLE-PARTICLE STRENGTH  
IN NEUTRON-RICH  $^{69}\text{Cu}^*$ 

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The nuclear structure of  $^{69}\text{Cu}$  has been investigated by means of the ( $d, ^3\text{He}$ ) transfer reaction at the Orsay tandem in direct kinematics using a deuteron beam at  $E_d = 27$  MeV and a target of  $^{70}\text{Zn}$  isotopically enriched to 95.4%. The  $^3\text{He}$  of interest from the transfer reaction were detected with the split-pole spectrometer at different angles in the laboratory frame in order to perform angular distributions and assign the angular momentum for each populated state in  $^{69}\text{Cu}$ . In this paper, the transferred angular momenta of the populated states will be presented.

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## 1. Introduction

Today, the evolution of single-particle states in an isotopic chain is of great interest to nuclear structure. It is very important to understand this evolution in order to constrain the nuclear models. It is already known that magic numbers can change with the exoticity of the nuclei [1]. An interesting case are the Ni isotopes ( $Z = 28$ ). Moving from  $^{68}\text{Ni}$  to  $^{78}\text{Ni}$  the neutron  $g_{9/2}$  orbital is filled. For example, the residual tensor interaction is supposed to be attractive for the  $\nu g_{9/2} - \pi f_{5/2}$  and repulsive for the  $\nu g_{9/2} - \pi f_{7/2}$  configurations. With such an interaction we can see that the single-particle levels could evolve with the exoticity of the Ni isotopes. The three-body strength could also have a role in this mass region [2]. One key question today concerns the double magicity of  $^{78}\text{Ni}$ . Here, we focus on the  $Z = 28$  part: how does the  $Z = 28$  gap evolve towards  $^{78}\text{Ni}$ ?

The Cu isotopes ( $Z = 29$ ) with one proton outside the  $Z = 28$  shell gap are a good candidate to probe the single-particle character in this mass region.

The neutron-rich Cu isotopes have been studied extensively. From the  $\beta$ -decay [3, 4], we know that a sudden drop in energy of the first  $5/2^-$  level appears beyond  $N = 40$ . This level is believed to carry most of the  $\pi f_{5/2}$  strength. There is even a spin inversion in  $^{75}\text{Cu}$  where the ground state is  $J^\pi = 5/2^-$  [5]. These results show a strong interaction between  $\nu g_{9/2}$  and  $\pi f_{5/2}$  suggesting a possible weakening of the  $Z = 28$  gap towards  $^{78}\text{Ni}$ . Therefore, it is important to understand the evolution of the  $\pi f_{7/2}$  spin-orbit partner to see the gap evolution. It is the position of the  $\pi f_{7/2}$  strength which will tell us whether there is any weakening of the gap. In order to access this information, it is most interesting to perform a ( $d, ^3\text{He}$ ) transfer reaction from a Zn isotope, which gives precisely access to the  $f_{7/2}$  proton hole state. Moreover, to follow the evolution in a systematic way, we need to perform this reaction in every odd neutron-rich Cu isotope and the starting point for this is  $^{69}\text{Cu}$  ( $N = 40$ ) with no neutron in the  $g_{9/2}$  neutron orbital.

An earlier study of  $^{69}\text{Cu}$  by transfer reaction has been done by Zeidman *et al.* [6] at the ANL cyclotron in direct kinematics with a deuteron beam of  $E_d = 23.3$  MeV. Because a target containing all stable zinc isotopes was used, they were able to perform a systematic study of  $^{63,65,67,69}\text{Cu}$ . In Table I, we show the results obtained by Zeidman *et al.* for  $^{69}\text{Cu}$ . One can see that 60% of the  $\pi f_{7/2}$  strength is missing and only low-lying states have been assigned. The article mentions the presence of three other peaks at higher excitation energy but no assignment was possible. Two  $7/2^-$  states are assigned in this experiment, today with the work of Franchoo [4] and Stefanescu [7], the interpretation of the first one with the largest spectroscopic

TABLE I

Energy states and angular momentum of the different populated states.

	Zeidman		This work	
	$E$ [MeV]	$J^\pi$	$E$ [MeV]	$L$
A	0	$3/2^-$	0	1
B	1.11	$1/2^-$	1.11	—
C	1.23	$5/2^-$	1.23	3
D	1.74	$7/2^-$	1.71	3
E	1.87	$7/2^-$	1.87	3
F	3.30	—	3.35	3
G	3.70	—	3.70	4
H	3.94	—	3.94	0

factor is supposed to be of  $\pi f_{7/2}^{-1}$  single-particle character and the second one is believed to be a  $2^+ \otimes \pi p_{3/2}^1$  particle-core coupling. One should also notice the surprisingly high spectroscopic factor for the  $5/2^-$  level ( $C^2S = 1.5$ ), while one would not expect any proton in the  $f_{5/2}$  orbital from a naive shell-model point of view. On top of that the measured spectroscopic factor for the first  $5/2^-$  state in the other Cu isotopes is about  $C^2S \approx 0.3-0.5$ . Since the 1.23 MeV peak in  $^{69}\text{Cu}$  is slightly broader, one explanation given by Zeidman *et al.* is that there is a  $5/2^-$ ,  $7/2^-$  doublet in this peak. The study of  $^{69}\text{Cu}$  was also done by Ajzenberg *et al.* [8] using the transfer reaction  $^{70}\text{Zn}(\vec{t}, \alpha)$  with a polarized triton beam. Because of the polarized triton beam, it is possible to differentiate a  $J = 5/2^-$  from a  $J = 7/2^-$  by looking at the analyzing power angular distributions  $A_y$ . Nevertheless, in this experiment it was not possible to reproduce correctly the analyzing power for the peak at 1.23 MeV assuming a  $5/2^-$  state or a  $7/2^-$  state. The angular distribution shows an  $L = 3$  state but neither the  $5/2^-$  analyzing power or  $7/2^-$  analyzing power reproduce the data, also suggesting that there are two unresolved states in this peak.

As mentioned above,  $^{69}\text{Cu}$  corresponds to  $N = 40$  and will serve as a reference nucleus for the more exotic copper isotopes. With our purpose in mind to measure as much of the  $\pi f_{7/2}$  strength as possible, we have performed the  $(d, ^3\text{He})$  transfer reaction and measured the excitation energy spectrum of  $^{69}\text{Cu}$  up to 7 MeV.

## 2. The $^{70}\text{Zn}(d, ^3\text{He})^{69}\text{Cu}$ transfer reaction

### 2.1. Experimental setup

The  $^{70}\text{Zn}(d, ^3\text{He})^{69}\text{Cu}$  transfer reaction has been performed at the Orsay tandem in direct kinematics. The deuteron beam was delivered by the tandem with an energy of  $E_d = 27$  MeV and we used a target of  $^{70}\text{Zn}$  isotopically enriched to 95.4% on a backing of carbon. Because the oxidation is very rapid for zinc, one of the contaminants on top of carbon was oxygen. Also a silicon contamination was observed. We can see the different kinematical lines for the elastic scattering in figure 1, the correspondence of which with the measurements clearly shows the presence of the listed contaminants. To detect the  $^3\text{He}$  of interest from the reaction, we have used the split-pole spectrometer. The measurements were done at  $\theta_{\text{lab}} = 4, 6, 9, 12, 15, 18, 21$  and  $24$  degrees for the transfer reaction plus  $30$  and  $40$  degrees for the elastic scattering. Once the focal plane was tuned for our reaction the resolution was about  $\sigma = 18$  keV or  $\text{FWHM} = 42$  keV.

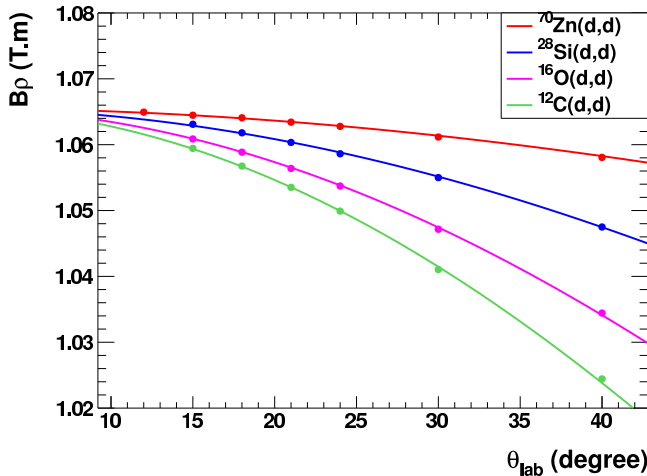


Fig. 1. Kinematical lines for the elastic scattering of the different contaminants in the target. The points correspond to measured  $B\rho$  and the line to the kinematical calculation.

### 2.2. Experimental results

The position of the detected particle in the focal plane is proportional to the magnetic rigidity  $B\rho$ . Once we know this  $B\rho$  and the angle of detection in the laboratory frame, one can reconstruct the excitation energy spectrum of  $^{69}\text{Cu}$ . In figure 2, we can see a typical energy spectrum at  $\theta_{\text{lab}} = 21$  degrees. The observed states are labelled by different letters. We

also see broader peaks that correspond to transfer reactions on the contaminants with especially the broadest ones corresponding to the  $(d, t)$  transfer reaction on carbon. The width is due to the kinematical factor, which is very different between the  $^{12}\text{C}(d, t)^{11}\text{C}$  reaction and the  $^{70}\text{Zn}(d, ^3\text{He})^{69}\text{Cu}$  reaction of interest.

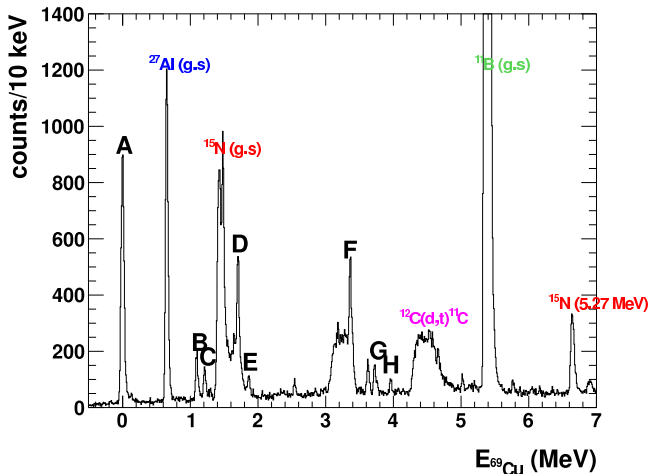


Fig. 2. Excitation energy spectrum of  $^{69}\text{Cu}$  at  $\theta_{\text{lab}} = 21^\circ$ .

For our case of  $^{69}\text{Cu}$ , we have populated eight states. We confirm the assignments of Zeidman *et al.* for the lowest lying states and we observe new angular distributions for three states at higher excitation energy. The transferred angular momenta  $L$  obtained from the angular distributions are listed in Table I. In this work, because of the contamination in the target, it was not possible to perform any angular distribution for the state at 1.11 MeV. At this point, the normalization is still under progress because of the contamination. A Rutherford-backscattering analysis of the target is ongoing in order to quantify the quantity of  $^{70}\text{Zn}$  in the target and extract the spectroscopic factors for the different populated states.

### 3. Conclusion

The  $^{70}\text{Zn}(d, ^3\text{He})^{69}\text{Cu}$  transfer reaction was performed at the Orsay tandem using the split-pole spectrometer. The excitation energy spectrum of  $^{69}\text{Cu}$  was obtained up to 7 MeV and angular distributions of the populated states were obtained, from which the transferred angular momenta were extracted. The analysis confirms the assigned  $L$  values for the low-lying states populated in previous work and new  $L$  values are assigned for three states at higher excitation energy. Among these an  $L = 3$  state was measured,

suggesting that part of the  $\pi f_{7/2}$  strength is located at 3.3 MeV. Finally, a Rutherford-backscattering analysis is ongoing to normalize correctly the data with the aim of extracting the spectroscopic factor for each state and especially the  $7/2^-$  state, for which the strength will thus be determined.

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