















































IN SEARCH OF NEW EXCITED STATES OF $^{57}\text{Cu}^*$

A. MALINOWSKI ^{a,b}, P. SEKRECKA ^b, M. PALACZ ^b
 A. FIJAŁKOWSKA ^a, G. JAWORSKI ^b, I. KUTI ^c
 E. AHLGREN CEDERLÖF ^{d,e}, P. BEDNARCZYK ^f, M. CIEMAŁA ^f
 E. CLÉMENT ^g, G. COLUCCI ^b, J.M. DELTORO ^{h,i}
 G. DE FRANCE ^g, A. GOASDUFF ^j, V. GONZÁLEZ ⁱ, M. GÓRSKA ^k
 J. GRĘBOSZ ^f, V. GUADILLA ^a, K. HADYŃSKA-KŁEK ^b
 C. HIVER ^l, Y. HRABAR ^m, M. KISIELIŃSKI ^b, M. KOMOROWSKA ^b
 A. KORGUL ^a, M. KOWALCZYK ^b, J. KOWALSKA ^b, A. KRAKÓC ⁿ
 B. KRUSZCIC ^{c,n}, M. MATEJSKA-MINDA ^f, C. MAZZOCCHI ^a
 K. MIERNIK ^a, J. MOLNAR ^c, A. NAŁĘCZ-JAWECKI ^o, W. OKLIŃSKI ^b
 S. PANASENKO ^b, I.Z. PIĘTKA ^b, M. REGULSKA ^a
 J. SAMORAJCZYK-PYŚK ^b, E. SANCHIS ⁱ, A. ŠPAČEK ^b
 O. STEZOWSKI ^p, A. STOLARZ ^b, G. SZYMANEK ^a, N. TONIOLO ^j
 A. TUCHOLSKI ^b, K. WRZOSEK-LIPSKA ^b

^aFaculty of Physics, University of Warsaw, Warsaw, Poland

^bHeavy Ion Laboratory, University of Warsaw, Warsaw, Poland

^cHUN-REN Institute for Nuclear Research (ATOMKI), Debrecen, Hungary

^dDepartment of Physics and Astronomy, Uppsala University, Uppsala, Sweden

^eKTH Royal Institute of Technology, Stockholm, Sweden

^fInstitute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland

^gGANIL, Caen, France

^hInstituto de Física Corpuscular, Valencia, Spain

ⁱDepartment of Electronic Engineering, University of Valencia, Burjassot, Spain

^jINFN, Laboratori Nazionali di Legnaro, Legnaro, Italy

^kGSI Helmholtz Centre for Heavy Ion Research, Darmstadt, Germany

^lLaboratoire de Physique des 2 infinis Irène Joliot-Curie — IJCLab, Orsay, France

^mLund University, Lund, Sweden

ⁿUniversity of Debrecen, Doctoral School of Physics, Debrecen, Hungary

^oNational Centre for Nuclear Research, Otwock, Poland

^pIPN Lyon, IN2P3/CNRS, Université Lyon-1, France

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An experiment to search for new excited states in the proton-rich nucleus ^{57}Cu was performed at the Heavy Ion Laboratory of the University of Warsaw. This nucleus, with one valence proton outside the doubly magic

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^{56}Ni core, offers a sensitive test of Shell Model predictions in interplay with collective effects, and its structure is essential for the production of heavier elements in the astrophysical rp-process. A fusion–evaporation reaction was employed using an 85 MeV beam of ^{32}S ions incident on a ^{28}Si target. The emitted γ -rays, neutrons, and light charged particles were detected with the EAGLE, NEDA, and DIAMANT arrays, respectively. No γ -ray lines corresponding to ^{57}Cu could be identified. An upper limit for the ^{57}Cu production cross section was estimated as $\sigma = 3 \mu\text{b}$.

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1. Introduction

The ^{57}Cu nucleus has only one valence proton outside the doubly magic self-conjugate $N = Z = 28$, ^{56}Ni core. Assuming a rigid core, its ground state and low-lying excited states should thus be well described by very pure Shell Model configurations, with the valence proton placed in $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, and $g_{9/2}$ orbitals, corresponding to states with spin and parity $J^\pi = 3/2^-, 5/2^-, 1/2^-, 9/2^+$, respectively. However, evidence is available that the $N = Z = 28$ core is relatively soft and its excitations are highly collective, see Ref. [1]. Thus, an interplay of single-particle and collective effects should be manifested in the excited states of ^{57}Cu .

The core ^{56}Ni nucleus has a half-life of 6.08 days and forms a key waiting point in the astrophysical rp-process. The $^{56}\text{Ni}(p, \gamma)^{57}\text{Cu}$ reaction is particularly crucial for the flow of material up the proton drip-line, so is the competition of the proton-capture $^{57}\text{Cu}(p, \gamma)^{58}\text{Zn}$ reaction with the β^+ decay of ^{57}Cu [2]. Moreover, the proton capture in stars happens in very high temperature environments (above 10^9 K), so that protons have sufficient energy to overcome the Coulomb barrier. The product nuclei are thus created in excited states. In this context, knowledge of the shell structure and properties of excited states in ^{57}Cu are essential for the production of heavier elements in the universe, see, for example, Ref. [3] and references therein.

Currently, the ground state and the first two known excited states (1028 and 1106 keV) of ^{57}Cu are interpreted as Shell Model configurations $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, respectively [3–5]. A few high-energy states were also observed as resonances in transfer reactions [6] or via spectroscopy of protons emitted after the ^{57}Zn β^+ decay [4]. In the present work, we aim to identify the $9/2^+$ single-particle state and a possible collective negative-parity cascade above $7/2^-$, seen in the mirror ^{57}Ni nucleus [7]. The proton-separation energy in ^{57}Cu is $S_p = 690$ keV, but observation of higher excited states should still be possible due to the Coulomb and centrifugal barriers. The results presented in this paper are of a preliminary character.

2. Experimental details and data analysis

The experiment was performed at the Heavy Ion Laboratory in Warsaw. A pulsed beam of 85 MeV ^{32}S ions, with an average intensity of about 3 pA, was provided by the Warsaw Cyclotron and used to bombard a ^{28}Si target of thickness 3.5 mg/cm^2 on a 700 mg/cm^2 -thick gold backing. The backing was thick enough to stop the produced recoil nuclei. A significant in-beam build up of oxygen and carbon contamination on the target was observed. Thus, targets were exchanged to new ones in regular intervals. Altogether 10 targets were employed during about 330 hours of data taking.

In this reaction, one proton and two neutrons ($p2n$) have to be emitted from the compound nucleus ^{60}Zn to reach ^{57}Cu . The reaction is dominated by the $3p$ and $2pn$ channels. The cross section for the $p2n$ reaction channel leading to ^{57}Cu is very low, thus a method to select events of interest is needed. To this end, the high-purity germanium detector array EAGLE [8] was employed alongside the neutron detection array NEDA [9] and the light charged particle detector DIAMANT [10]. The signals were processed by a digital data acquisition system with a single γ -ray trigger condition. For more details on the detector setup, see Refs. [10, 11]. The functioning of the DIAMANT detector was highly unstable, and thus its data could not be used at the stage of the analysis presented in this paper.

In the ideal case, the conditions to identify 2 neutrons of the $p2n$ reaction channel (^{57}Cu) should be optimized by using events in which 2 neutrons were emitted and other, higher cross-section final nuclei were produced. In the studied reaction, no such channel exists. An additional 12-hours run was thus performed with the same beam but a thick ^{27}Al target. The cross section for the production of isotopes with two-neutron emission on the ^{27}Al target is significantly higher than that in the primary reaction.

In the off-line analysis, the entire data set was scanned in intervals corresponding on average to about 1 hour of beam time each, and all the experimental parameters were semi-automatically checked and corrected by using the Align [12] program for instrumental drifts and instabilities. The instabilities detected in the γ -ray spectra were corrected by applying linear corrections, while the time parameters were eventually modified using simple shifts (without changing the gain). No instabilities could be observed in the structureless light spectra from the NEDA detectors. The energy calibration and relative efficiency of the Ge detectors were determined using the standard radioactive sources ^{133}Ba and ^{152}Eu . The photopeak efficiency of 1.4(1)% for 1 MeV γ -rays was obtained. Signals from the HPGe detectors were prompt time-gated, where the first γ -ray or neutron detected in NEDA detectors provided the time reference.

A large effort was devoted to optimizing the conditions to identify two neutrons detected in NEDA. First, the discrimination of neutrons and γ -rays was done by setting 3-dimensional gates on the time-of-flight between the target and the detector, the charge comparison parameter (see Ref. [9]), and the amount of light produced. Secondly, events with two neutrons detected had to be distinguished from events in which a single neutron scattered in more than one detector ($1n/2n$ discrimination). This was done by setting gates on the time difference between two interactions and the distance between the involved detectors. Figure 1 shows γ -ray spectra from the run with the ^{27}Al target, gated on the number of detected neutrons. One and two neutron detection efficiencies were obtained $\epsilon_n = 28.0(4)\%$, and $\epsilon_{2n} = 5.7(10)\%$, respectively. An upper limit for the probability to

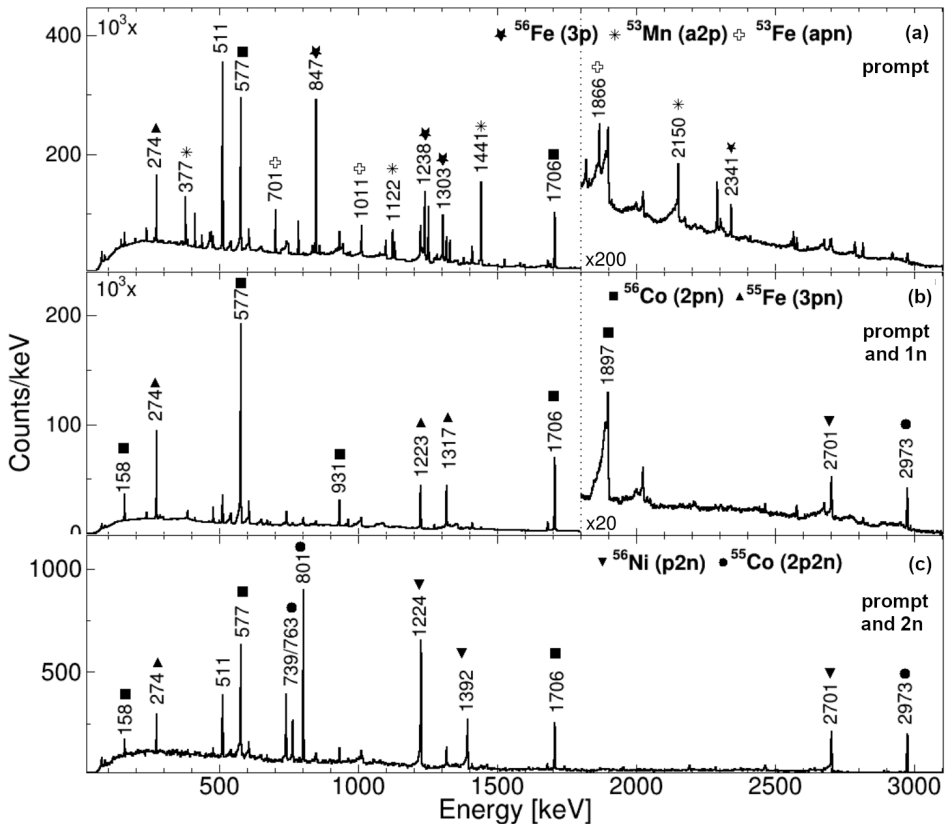


Fig. 1. Gamma-ray spectra from the reaction of the ^{32}S beam on the ^{27}Al target with conditions on the number of detected neutrons. A prompt time condition was applied to all the spectra, thus spectrum (a) is effectively gated by the requirement of detecting a γ -ray or a neutron in NEDA.

misidentify a γ -ray as a neutron was estimated as $P_{\gamma \rightarrow n} < 0.27\%$, while the probability of misinterpreting a single neutron interaction in multiple detectors as two neutrons was $P_{1n \rightarrow 2n} = 0.08(2)\%$. See Ref. [13] for the details of the method used for the $1n/2n$ discrimination and the determination of the efficiency and misinterpretation values.

3. Results

Gamma-ray spectra from the reactions on the ^{28}Si target gated on 1 and 2 neutrons ($1n$ and $2n$) are shown in Fig. 2. The $2n$ gated spectrum is dominated by the 511 keV line originating from β^+ decays followed by the e^+e^- annihilation. Transitions from ^{58}Cu , ^{57}Ni , and ^{56}Co nuclei produced with the emission of 1 neutron are also clearly visible. This is observed in spite of the fact that strict conditions mentioned above were applied in the analysis of the NEDA data, and is due to a residual misinterpretation of γ -rays as neutrons or a residual $1n/2n$ misinterpretation. Visible left-hand tailing in some of the peaks is due to the Doppler shift caused by the short lifetimes of the relevant states [14].

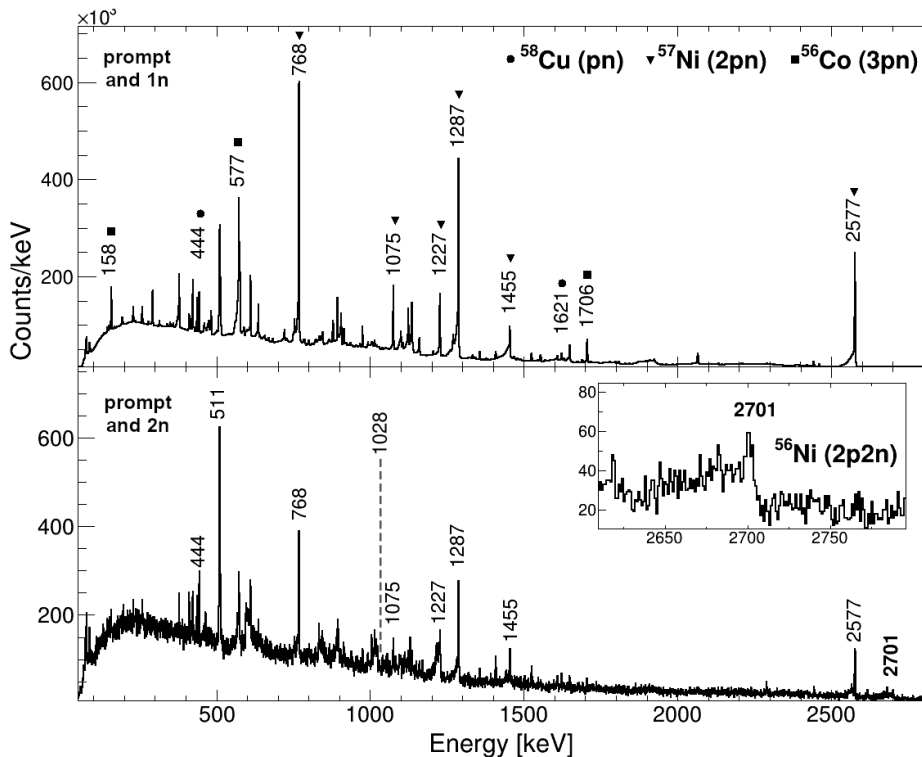


Fig. 2. Gamma-ray spectra from the reaction of the ^{32}S beam on the ^{28}Si target, gated by the condition of detecting 1 (top) and 2 (bottom) neutrons.

No γ -rays originating from ^{57}Cu could be identified. In turn, a weak 2701 keV peak of the transition to the ground state in ^{56}Ni was observed. The ^{56}Ni nucleus is produced with the emission of two neutrons and two protons. A cross-section limit of $3 \mu\text{b}$ for the production of ^{57}Cu was estimated at this stage of the data analysis. The relevant ^{56}Ni cross section was estimated at $2 \mu\text{b}$. This evaluation also lead to the conclusion that the effective beam energy should be about 10 MeV lower than assumed, which can be due to the target contamination, target thickness, or beam energy measurement errors. We note that in the proposal of the experiment a ^{57}Cu cross-section value of about 0.1 mb was predicted, based on HIVAP [15] calculations. In addition, we note that in determining cross sections from gamma spectra, there is an assumption that nuclei were produced in excited states, while there is no such requirement in the HIVAP calculations, which may matter for products with low proton separation energy. The evaluation of the data will be continued.

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