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Single-particle shell strengths near the doubly magic nucleus $^{56}\text{Ni}$ and the $^{56}\text{Ni}(p,\gamma)^{57}\text{Cu}$ reaction rate in explosive astrophysical burning


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Abstract

Angle-integrated cross-section measurements of the $^{56}\text{Ni}(d,n)$ and $(d,p)$ stripping reactions have been performed to determine the single-particle strengths of low-lying excited states in the mirror nuclei pair $^{57}\text{Cu}$–$^{56}\text{Ni}$ situated adjacent to the doubly magic nucleus $^{56}\text{Ni}$. The reactions were studied in inverse kinematics utilizing a beam of radioactive $^{56}\text{Ni}$ ions in conjunction with the GREITINA $\gamma$-array. Spectroscopic factors are compared with new shell-model calculations using a full $p$/$f$ model space with the GPFX1A Hamiltonian for the isospin-conserving strong interaction plus Coulomb and charge-dependent Hamiltonians. These results were used to set new constraints on the $^{56}\text{Ni}(p,\gamma)^{57}\text{Cu}$ reaction rate for explosive burning conditions in $\gamma$-ray bursts, where $^{56}\text{Ni}$ represents a key waiting point in the astrophysical $rp$-process.

Keywords: X-ray bursts, shell model, transfer reactions, radioactive beams

Doubly magic nuclei represent special cornerstones in our understanding and exploration of nuclear structure (see, e.g., \cite{1,2}). These nuclei, and the nuclei in their immediate vicinity, should be well described by very pure shell-model configurations. In the case of the doubly magic, self-conjugate nucleus $^{56}\text{Ni}$, the major shell closure at $N = Z = 28$ arises from the spin-orbit splitting of the $0f_{5/2}$ and $0f_{7/2}$ orbitals. There is evidence that $^{56}\text{Ni}$ has a relatively soft core with significant configuration mixing in the shell structure \cite{3,4,5}. It exists on the cusp between stability, having a (terrestrial) half-life of $6.08\text{ d}$, and particle instability; the neighboring nucleus, $^{57}\text{Ni}$, has a ground-state spin-parity of $3/2^-$, corresponding to a $1p_{3/2}$ neutron shell-model configuration, and $5/2^-$ and $1/2^-$ excited states corresponding to the occupation $0f_{5/2}$ and $1p_{3/2}$ neutron shells, respectively \cite{3}. A pioneering study of the $^{56}\text{Ni}(d,p)^{57}\text{Ni}$ transfer reaction, measuring the differential cross section in inverse kinematics, found these three lowest-lying states were described with relatively pure single-neutron configurations with spectroscopic factors $C^2S \sim 0.9$, with an approximate factor of two uncertainties \cite{3}. This information was then used to estimate the resonance contributions of the two low-lying analog excited states in $^{57}\text{Cu}$ \cite{6,7} for the $^{56}\text{Ni}(p,\gamma)^{57}\text{Cu}$ reaction rate, assuming isospin symmetry. Subsequently, an attempt was made to measure the single-particle strengths of these states directly in $^{57}\text{Cu}$ using the $^{56}\text{Ni}(^3\text{He},d)^{57}\text{Cu}$ proton transfer reaction; however, due to the limited resolution of $\sim 700\text{ keV}$ in excitation energy and low statistics, definite conclusions could not be drawn \cite{11}. Two higher-lying $5/2^-$ and $7/2^-$ states in $^{57}\text{Cu}$ are expected to dominate the $^{56}\text{Ni}(p,\gamma)^{57}\text{Cu}$ reaction rate for burning temperatures $T > 1\text{ GK}$ (see, e.g., ref. \cite{12}) but only limits were set for the experimental $C^2S$ values in $^{57}\text{Ni}$ \cite{9}. Calculations predict the combined resonant capture reaction rate on the four lowest-lying excited states in $^{57}\text{Cu}$ is expected to dominate (by 3 orders

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of magnitude) over the direct-capture contribution in explosive astrophysical burning conditions \[13,17]\.

Here, we present a first study of the $^{56}\text{Ni}(d,n)^{57}\text{Cu}$ proton transfer reaction aimed at the first direct experimental determinations of the proton single-particle strengths of the key low-lying excited states in $^{57}\text{Cu}$ by angle-integrated cross-section measurements. The method exploits the high resolution and efficiency of the GRETINA (Gamma-Ray Energy Tracking In-beam Nuclear Array) device \[13\] and an intense $^{56}\text{Ni}$ radioactive beam produced in flight by the National Superconducting Cyclotron Laboratory (NSCL). This new approach has been shown to work successfully in determining spectroscopic factors, including key astrophysical resonances \[14,15\], and is described for the present application in detail below. In addition, we have performed a measurement of the $^{56}\text{Ni}(d,p)^{57}\text{Ni}$ transfer reaction to study analog states in the mirror nucleus $^{57}\text{Ni}$, and explore evidence for isospin symmetry breaking effects. Furthermore, the $^{56}\text{Ni}(d,p)$ data were also used to measure for the first time the single-particle strength of a high-lying excited state in $^{57}\text{Ni}$ whose analog likely determines the explosive astrophysical burning rate above $T \sim 1\text{ Gk}$ in the $^{56}\text{Ni}(p,\gamma)^{57}\text{Cu}$ reaction.

The $^{56}\text{Ni}(d,n)^{57}\text{Cu}$ and $^{56}\text{Ni}(d,p)^{57}\text{Ni}$ reaction studies were performed in inverse kinematics. A 33.6 MeV/u $^{56}\text{Ni}^{28+}$ beam was produced by in-flight fragmentation of a 28-pnA 160-MeV/u primary beam of $^{56}\text{Ni}^{27+}$ ions which impinged upon a 1316-mg/cm$^2$ thick $^6\text{Be}$ production target. The A1900 fragment separator \[16\] selected the ions based on their mass-to-charge ratio and used a 150-mg/cm$^2$ thick Al achromatic wedge to provide isotopic separation at its focal plane. The resulting $^{56}\text{Ni}^{28+}$ beam had a purity of 47\% (contaminated mainly by $^{55}\text{Co}$ with traces of $^{52}\text{Mn}$ and $^{51}\text{Cr}$ ions) and an average intensity of $3 \times 10^5$ $^{56}\text{Ni}$ particles per second. The $^{56}\text{Ni}$ beam impinged on a 10.7(8)-mg/cm$^2$ thick deuterated polyethylene target, $(\text{CD}_2)_n$, which was surrounded by the GRETINA detectors \[13\] positioned in two rings at laboratory angles of 58$^\circ$ and 90$^\circ$ with respect to the beam direction. Beam-like residues were collected and analyzed with the S800 spectrograph \[17\] positioned at 0$^\circ$ scattering angle. The analysis line to the S800 was operated in achromatic mode to obtain a total acceptance of nearly 100\% for $^{57}\text{Cu}^{29+}$, and 50(10)\% for $^{57}\text{Ni}^{28+}$ run settings (the lower value for $^{57}\text{Ni}$ reflects the need to block out scattered $^{56}\text{Ni}^{28+}$ ions from part of the focal plane). Using the S800, we measured the intensity of $^{56}\text{Ni}^{28+,27+,26+}$ species after the CD$_2$ target relative to the number of incident $^{56}\text{Ni}^{28+}$ beam ions, where we observed that 80\% of the incident ions emerged in the fully-stripped charge state. Given the similar properties of energy, mass, and nuclear charge of the $^{56}\text{Ni}$ beam and heavy residues $^{57}\text{Cu}$ and $^{57}\text{Ni}$, we estimated an 80(5)\% and 40(11)\% collection and detection efficiency for $^{57}\text{Cu}^{29+}$ and $^{57}\text{Ni}^{28+}$ ions, respectively. To account for reactions on carbon producing the residues of interest, measurements were also performed for approximately half the duration of the CD$_2$ runs with an 8.8(15)-mg/cm$^2$ thick (CH$_2$)$_n$ target.

The data acquisition system was triggered either by a residue-$\gamma$ coincidence or downscaled (by a factor of 5) residue singles events. The GRETINA absolute singles efficiency was calibrated with $^{56}\text{Co}$ and $^{152}\text{Eu}$ sources as described in ref. \[18\]. An efficiency of 5.5\% for $E_\gamma = 1332$ keV was achieved for the nine-module setup employed here. The in-beam GRETINA efficiency was boosted by a factor 1.06(5) compared to a stationary source. Doppler-adjusted $\gamma$-ray energy spectra gated on $^{57}\text{Cu}$ and $^{57}\text{Ni}$ ions are shown in Figs. (1a) and (b), respectively. Events induced by reactions on carbon atoms have already been subtracted, following the procedure in refs. \[14,15\]. In the $^{57}\text{Cu}$ spectrum, two strong peaks are observed at energies of 1028(1) and 1109(2) keV, which are assigned to the $\gamma$ decays to the ground state of the first and second excited states at 1028(4) and 1106(4) keV observed by Zhou et al. in a study of the $^1\text{H}^{(58}\text{Ni},^{57}\text{Cu})n$ reaction \[10\]. There is no evidence for the $\gamma$ decay at 2398(10) keV reported in the same study, or for previously unobserved $\gamma$ decays from the excited state at 2525(17) keV \[19,20\]. In Fig. (1b), three peaks are observed at energies of 768(1), 1122(5), and 2579(4) keV. The first two are assigned to the known decays of the $5/2^-$ and $1/2^-$ levels at 769 and 1113 keV in $^{57}\text{Ni}$ \[8,9\], respectively. The third peak is assigned to the known decay of the $7/2^-$ state at 2578 keV \[8\]. Angle-integrated cross sections for the four lowest excited states in $^{57}\text{Cu}$ and $^{57}\text{Ni}$ are shown in Table II assuming 100\% $\gamma$ branches to the ground states (consistent with nuclear compilation data for $^{57}\text{Ni}$ \[8\]), and insignificant $\gamma$-decay feeding from higher-lying excited states (there are no other $\gamma$-ray lines observed). The overall errors for the cross sections in Table II were obtained from a combination of statistical uncertainties for individual transitions, and an uncertainty of 20\% (28\%) for $^{57}\text{Cu}$ ($^{57}\text{Ni}$) estimated by combining contributions to the uncertainty.
from target thicknesses, Doppler-corrected γ-ray detection efficiency, residual charge-state distributions, and the momentum acceptance, in quadrature.

The theoretical angle-integrated single-particle (C²S = 1) cross sections for the ⁵⁶Ni(d,p)⁵⁷Cu and ⁵⁶Ni(d,p)⁵⁷Cu reactions shown in Table 1 were calculated using the finite-range adiabatic approximation [21], which incorporates deuteron breakup. A laboratory beam energy of 32 MeV/u was used corresponding to the approximate center-of-target energy. Nucleon-target interactions used the CH89 [22] optical potential and the nucleon-nucleon interaction from ref. [23]. The n(p) and ⁴⁰Ni final states were described by a real Woods-Saxon potential with central and spin-orbit terms. The radius and diffuseness of these potentials were set to 1.23 fm and 0.67 fm, respectively. The spin-orbit term was given the standard depth of Vos = 6 MeV. For the (d,p) calculations, the central potential depth was adjusted to reproduce the final bound-state binding energies. For the (d,n) calculations, the final states are resonances. Here, we applied a bound-state approximation in which we adjusted the depth of the central potential to produce a final state bound by just E = 0.001 MeV, as was done in [14]. For low-lying resonances, this approximation introduces less than 1% error, but for the two higher-lying resonances, this approximation can introduce an error of ~6%. Repeating the calculation with the Becchetti-Greenlees potential [24] changed the total cross section by about 15%, dominating the error introduced by the bound-state approximation. Based on this and other studies [25], we estimate an error of up to 30% in the total cross section calculations. The effective adiabatic potentials for (d,p) and (d,n) were computed with tworfs [26] and the transfer calculations were performed with the reaction code, FRESCO [22]. Shell-model wavefunctions for ⁵⁶,⁵⁷Ni and ⁵⁷Cu were obtained in the full pf model space with the GPFX1A Hamiltonian [28] for the isospin-conserving strong interaction plus the Coulomb and charge-dependent Hamiltonians from ref. [29]. The spectroscopic factors (shown in Table 1) were derived from the overlap of these wavefunctions.

Table 1: Angle-integrated experimental (σexp) and theoretical (σth) reaction cross sections and derived spectroscopic factors (C²S(d,p), C²S(d,n)). Comparisons are made with shell-model (SM) calculations.

Table 2: Resonance parameters used in the ⁵⁶Ni(p,γ)⁵⁷Cu reaction rate calculation. See the text for details.

<table>
<thead>
<tr>
<th>Eγ (keV)</th>
<th>E0 (keV)</th>
<th>Jπ</th>
<th>Γp (eV)</th>
<th>Γγ (eV)</th>
<th>αγ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1028(1)</td>
<td>338</td>
<td>5/2</td>
<td>5.7 × 10⁻¹⁵</td>
<td>1.9 × 10⁻⁴</td>
<td>1.7 × 10⁻¹⁴</td>
</tr>
<tr>
<td>1108(2)</td>
<td>418</td>
<td>1/2</td>
<td>1.9 × 10⁻⁷</td>
<td>8.6 × 10⁻⁴</td>
<td>1.9 × 10⁻⁷</td>
</tr>
<tr>
<td>2398(10)</td>
<td>1708</td>
<td>5/2</td>
<td>5.5 × 10⁻³</td>
<td>9.0 × 10⁻³</td>
<td>1.0 × 10⁻²</td>
</tr>
<tr>
<td>2525(17)</td>
<td>1835</td>
<td>7/2</td>
<td>5.3 × 10⁻¹</td>
<td>6.8 × 10⁻³</td>
<td>2.7 × 10⁻²</td>
</tr>
</tbody>
</table>
for these states were calculated for the first time using the experimentally constrained \(C^2\)S values obtained for \(^{57}\)Cu in the present work. For the 7/2\(^-\) state we derive the proton width value using the \(C^2\)S(\(\ell = 3\)) value reported here for the first time for the analog state in \(^{57}\)Ni. For the proton width of the 2398-keV 5/2\(^-\) level, we take the \(C^2\)S value from the shell-model calculation which is compatible with the experimental observational limit in the present \(^{57}\)Ni data (see Table I).

The present \(^{58}\)Ni\((p,\gamma)^{57}\)Cu reaction rate and uncertainty bounds incorporating our new experimental results and shell-model calculations is shown in Fig. 2. Our rate for \(T < 1\) GK is dominated by the \(\ell = 1\) capture resonance at 417.7(1.8) keV for which we derive a resonance strength, \(\omega_T = 1.98(8) \times 10^{-7}\) eV. For the region with \(T > 1\) GK, both the \(\ell = 3\) captures on the higher-lying 5/2\(^-\) and 7/2\(^-\) states are found to contribute to, and collectively dominate, the reaction rate. The 5/2\(^-\) state is the only lower-lying resonance for which we have only an experimental upper limit on the spectroscopic factor. If this value is significantly lower than the shell-model calculation this would reduce its strength/significance relative to the 7/2\(^-\) state. A much higher value for \(C^2\)S, and therefore the proton partial width, is deemed unlikely as \(\gamma\) decay has been observed from this 5/2\(^-\) state in \(^{57}\)Cu [11]. Figure 2 also shows some previous reaction rate calculations for comparison [7, 8, 9]. At lower temperatures, the van Wormer theoretical calculation is orders of magnitude lower and reflects the then unknown resonance temperatures, the van W ormer theoretical calculation is orders \(\gamma\) and the uncertainty bounds were presented in ref. [10], these are also depicted. See text for details.

In summary, we report angle-integrated cross-section measurements for the \(^{56}\)Ni\((d,n)^{57}\)Cu and \(^{56}\)Ni\((d,p)^{57}\)Ni transfer reactions. Comparisons with reaction theory calculations allow definitive assignments of the first two excited states in \(^{57}\)Cu to their analogs in the mirror partner, \(^{57}\)Ni. First measurements of the spectroscopic factors for these two states in \(^{57}\)Cu show they have a strong single-particle character with values agreeing well with the new shell-model calculations obtained using a full \(pf\) model space with the GPFX1A interaction plus Coulomb and charge-dependent Hamiltonians. From a comparison with their analog states in \(^{57}\)Ni we find no evidence for significant isospin symmetry breaking effects. The spectroscopic factor of a high-lying 7/2\(^-\) state is determined for the first time in \(^{57}\)Ni and is found to have a much weaker single particle character in reasonable agreement with the new shell-model calculations. We use these new results to re-evaluate and significantly constrain the \(^{56}\)Ni\((p,\gamma)^{57}\)Cu astrophysical reaction rate required for modeling of explosive burning in x-ray bursts where the astrophysical \(rp\)-process is thought to occur.

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References

