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E0 transition strength in stable Ni isotopes

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Excited states in $^{58,60,62}$Ni were populated via inelastic proton scattering at the Australian National University as well as via inelastic neutron scattering at the University of Kentucky Accelerator Laboratory. The Super-e electron spectrometer and the CAESAR Compton-suppressed HPGe array were used in complementary experiments to measure conversion coefficients and $\Delta(E2/M1)$ mixing ratios, respectively, for a number of $2^+ \rightarrow 2^+$ transitions. The data obtained were combined with lifetimes and branching ratios to determine E0, M1, and E2 transition strengths between $2^+$ states. The E0 transition strengths between $0^+$ states were measured using internal conversion electron spectroscopy and compare well to previous results from internal pair formation spectroscopy. The E0 transition strengths between the lowest-lying $2^+$ states were found to be consistently large for the isotopes studied.

I. INTRODUCTION

The strength of an electric monopole (E0) transition, $\rho^2(E0)$, can be directly related to the difference in deformation between the initial and final states, as well as the degree of mixing between them. Evidence of significant E0 strength has been associated with shape coexistence [1]. The presence of an E0 transition can also be used as a test of various nuclear models, such as the axially symmetric metric quadrupole rotor or the spherical vibrator model, in which selection rules are placed on E0 transitions [2].

Single γ-ray emission is forbidden for an E0 transition as a photon must carry away at least 1ℏ of angular momentum. While E2 transition matrix elements can be extracted in Coulomb excitation studies, the E0 component is not directly accessible in this approach. Therefore, there is a need to employ electron spectroscopy for the determination of E0 transition strengths.

The number of E0 transition strengths known experimentally is quite low in comparison to measurements of E2 transitions, as a result of a number of experimental challenges. Comparing the experimental data available from the three most recent compilations, one finds that there are 447, 87 and 14 evaluated values reported for $B(E2 : 2^+_1 \rightarrow 0^+_1)$ [3], $\rho^2(E0 : 0^+_2 \rightarrow 0^+_1)$ [4] and $\rho^2(E0 : 2^+_2 \rightarrow 2^+_1)$ [2] transition strengths, respectively. These statistics are expected to change as there have been a number of advances and a rejuvenation of the detection systems being employed for electron and positron spectroscopy worldwide in recent years [5–10]. One area where data are still particularly lacking is a characterization of E0 transition strengths between states of $J > 0$ in spherical nuclei. This deficiency is the motivation for the present study of the nickel isotopes [11–13]. Detailed muonic X-ray measurements [14] and optical spectroscopy [15] indicate that the ground states of these isotopes are spherical with little variation.

Previous experimental work has yielded the $\rho^2(E0)$ values between $0^+$ states in $^{58,60,62}$Ni [16, 17]. Two previous experiments were performed with the $(p, p')$ reaction and E0 transition strengths were determined by observing the electron-positron pairs emitted in internal pair formation (π) decay. There has been no previous work in determining $\rho^2(E0)$ values between $J^+ = 0^+$ states in these nuclides through the measurement of conversion electrons.

There is a notable deficiency of $\rho^2(E0)$ values measured...
between $J_i^m = J_j^m \neq 0^+$ states across the entire chart of nuclides and especially in light- and medium-mass nuclei; none have been previously measured in the Ni isotopes. As the $E0$ strength is closely related to the change in shape of a nucleus, there is a need for values to be measured in a wide range of nuclei. Determining the $E0$ strength between $J_i^m = J_j^m \neq 0^+$ states requires the experimental determination of a number of quantities, often necessitating different experimental setups. The experimental quantities include the $E2/M1$ mixing ratio, the parent state half-life, the internal conversion coefficient, and the transition branching ratio.

In this article, we report details and results from measurements of $E0$ transition strengths between $2^+$ states in $^{58,60,62}$Ni. Initial results from this experimental study, focusing on only the $2^+_2 \rightarrow 2^+_1$ transitions, were published in Ref. [18]. The measurements were performed at the Australian National University (ANU) and the University of Kentucky Accelerator Laboratory (UKAL).

II. EXPERIMENTS AND ANALYSIS FOLLOWING (P, P') REACTIONS

Two experiments were carried out at the Heavy Ion Accelerator Facility at the ANU. Proton beams between 4.7 and 9.2 MeV were provided by the 14UD pelletron. Self-supporting targets with a thickness of 1.4 mg/cm$^2$ for $^{58}$Ni and 1.3 mg/cm$^2$ thickness for $^{60,62}$Ni were used. The isotopic enrichments for the $^{58,60,62}$Ni foils were 99.1%, 99.8% and 98.8%, respectively. The same set of targets was used in all measurements.

A. Apparatus

The CAESAR array, composed of nine Compton-suppressed HPGe detectors, was used for measurements of angular distributions of $\gamma$ rays. Data were collected for approximately 2 hours with each target at a beam intensity of 5-10 nA.

The second experimental setup was the superconducting electron spectrometer, Super-e [19], which is composed of a solenoid magnet and thick lithium-drifted silicon [Si(Li)] detector. The configuration of the Super-e is shown in Fig. 1. A Compton-suppressed HPGe detector was placed close to the target to allow for simultaneous measurements of $\gamma$ rays. The proton beam was incident on the self-supporting target tilted at 45° to the beam. Unreacted beam continues on to a Faraday cup in the beam dump for the purpose of monitoring the beam current. The proton beam was provided at up to 800 nA for approximately 6-12 hours on each target.

Electrons emitted from the target are transported by the magnetic field of the superconducting solenoid magnet to be incident on a set of six 9 mm thick Si(Li) detectors located 35 cm from the target. The geometry is such that each electron of a given energy ($E$) must complete 2.5 helical orbits in the magnetic field before reaching the detector. During an experiment, the magnetic field was swept over a range between the minimum and maximum set values. The period of time spent at each step of the magnetic field setting in the cycle was variable so that the integrated charge of the proton beam recorded in the Faraday cup was the same for each field value. The peak-to-total ratio in the electron energy spectrum was improved by gating on the magnetic field value that is recorded in the data stream. As the energy of the transported electron is related to the momentum window defined by the magnetic field, the selection of only events in

FIG. 1. Schematic diagram (not to scale) of the superconducting electron (Super-e) spectrometer at the ANU. The spectrometer was developed for electron-positron pair spectroscopy, but here it was used to collect electron singles events.

FIG. 2. Gamma-ray (a) and electron (b) energy spectra collected for the $^{58}$Ni targets.
FIG. 3. Gamma-ray (a) and electron (b) energy spectra collected for the $^{60}\text{Ni}$ targets.

FIG. 4. Gamma-ray (a) and electron (b) energy spectra collected for the $^{62}\text{Ni}$ targets.

FIG. 5. Peak fitting of the $2^+_2 \rightarrow 2^+_1$ transitions in the electron spectra collected with Super-e for the (a) $^{58}\text{Ni}$, (b) $^{60}\text{Ni}$ and (c) $^{62}\text{Ni}$ target. The background fit is shown by a black dashed line, each individual peak is shown by a grey dotted line and the total fit is shown by a full red line. For each transition, there are two peaks corresponding to the K and L electrons. Each fit has a reduced $\chi^2$ value of (a) 1.1, (b) 1.0 and (c) 1.2.

this window can reduce the contribution of background\textsuperscript{123} and of events in which the full electron energy has not been recorded in the Si(Li) detector. Gamma-ray and electron energy spectra collected from the Super-e detector\textsuperscript{124} are shown in Figs. 2, 3 and 4 for each of the $^{58,60,62}\text{Ni}$ isotopes.

The $\gamma$ rays emitted from the target were detected by a single Compton-suppressed HPGe detector located outside the chamber, approximately 50 cm from the target.\textsuperscript{125} The $\gamma$-ray energy spectrum was used for normalization\textsuperscript{126} of the electron data and in the measurement of internal conversion coefficients.

### B. Calibration source preparation

The radionuclide $^{170}\text{Lu}$ decays by electron capture with a half-life of 2 days to excited states in $^{170}\text{Yb}$ and subsequently emits a large number of $\gamma$ rays and conversion electrons between 20 keV and 3.4 MeV. This large number of discrete transitions in this decay make $^{170}\text{Lu}$ an...
excellent calibration source for the determination of the relative efficiency of both γ-ray and electron detectors.

In order to produce a $^{170}$Lu source, a $^{171}$Yb foil of 95.1% isotopic enrichment and a thickness of 2 mg/cm$^2$ was irradiated in a shielded location at the ANU. Over a period of 16 hours, an 18 MeV proton beam with a current of 25 nA impinged upon the target. The beam current was limited by the levels of radiation permitted in the experimental hall.

The internal conversion coefficients of the majority of transitions emitted following the decay of $^{170}$Lu have been measured with good accuracy [20, 21]. The use of this calibration source is also discussed in Ref. [22]. This $^{170}$Lu source is particularly useful in the case of electron detectors as there are few long-lived radionuclides suitable as discrete-energy electron calibration sources, especially at higher electron energies.

C. Efficiency calibrations

The relative efficiencies of the HPGe detectors in the CAESAR array were calibrated over the energy region of interest using $^{56}$Co and $^{170}$Lu sources.

The theoretical transport efficiency of the Super-e spectrometer is calculated as,
\[
y(E) = \frac{A}{m_e c^2} \cdot \sqrt{E^2 + 2m_e c^2E},
\]
where $A$ is a normalizing factor, $m_e$ is the electron rest mass, $c$ is the speed of light and $E$ is the kinetic energy of an electron in keV. The normalizing factor can take three values corresponding to the lower and upper limits and optimum transmission for a given energy.

At higher energies, consideration of the detector response to the transport efficiency. A GEANT4 [23] simulation was used to determine the ratio of events that deposit their full energy in the detector to the total number of electrons that are incident on the detector. The inputs to this simulation were the electron momentum vectors resulting from a simulation of the trajectories through the spectrometer in order to correctly consider the variation in incident angle of the electrons reaching the detector surface. The detector response determined from the simulation is combined with the transport efficiency of Eq. (1) to obtain the total efficiency. The total efficiency was normalized to the data from the $^{170}$Lu source. The energy dependence of the detector efficiency is only significant above 2 MeV, thus for all transitions studied in this work, the total efficiency is equal to the transport efficiency.

D. Angular distributions

The angular distributions of γ rays can be used to determine the $E2/M1$ mixing ratio, $\delta$, for transitions of mixed multipolarity by fitting the function
\[
W(\theta) = N \cdot [1 + \alpha_2 Q_2 A_2 P_2(\cos \theta) + \alpha_4 Q_4 A_4 P_4(\cos \theta)],
\]
where $N$ is a normalization parameter, $Q_k$ are finite solid angle correction factors, $P_k(x)$ are the Legendre polynomials of the $k$th order, $\alpha_k$ are the attenuation coefficients, which depend on the degree of alignment of the parent state, and $A_k$ are the angular distribution coefficients, which depend on the parent spin and the mixing ratio of the transition [24].

There can be variations in the physical position of the beam incident on each of the targets as well as with the positioning of the radioactivity in the calibration source. Such differences modify the apparent angle of each detector and the emitted radiation. Following the efficiency calibration, the apparent angle of each detector was determined separately for each target by a chi-squared minimization using the angular distribution of known pure $E2$ transitions emitted from the target nuclei. Deviations were at most a few degrees from the nominal angles determined from physical measurements of detectors with respect to the beam axis.

The parameter $Q_k$ is a solid-angle correction factor for the finite size of the HPGe detectors that depends on the size, orientation and opening angle of the crystal exposed by the collimator [25]. The geometrical solid angle attenuation coefficients for CAESAR have been previously evaluated to be $Q_2=0.98$ and $Q_4=0.94$ [26]. The uncertainty in the $Q_k$ coefficients does not exceed 1%, which more than covers their dependence on γ-ray energy.

The alignment of the parent state for each transition of interest was determined by fitting the angular distribution of the competing γ ray from the parent state to the $0^+$ ground state with the function of Eq. (2). As this is a pure $E2$ transition, the alignment coefficients, $\alpha_k$, are determined by fixing the other angular distribution coefficients, $A_k$, to the theoretical values. The alignment coefficients were then adopted in determining the mixing ratio of the mixed transitions. The values of $\delta$ are taken from the minima in a plot of $\chi^2$ versus $\delta$ and the 1σ limits are defined by the range of $\chi^2 + 1$ [27, 28].

E. Internal conversion coefficients and $\rho^2(E0)$ values

Accurate peak fitting is essential in the determination of yields for transitions that lie close in energy and are, therefore, overlapping in the electron spectrum. The shape parameters of the electron peaks, which in this case depend primarily on the energy of the electron and detector effects, were fixed by fitting transitions of sim-
ilar energy in an $^{54}$Fe dataset that was collected during the same beam time. The contribution to peak shape from energy straggling in the target or energy broadening from in-flight emission is minimal in this study and was not specifically considered in the fitting of electron peaks. In the case of pure $E2$ transitions, it was possible to also fix the expected ratio of conversion from the K and L atomic subshells. The change in efficiency between the K and L energies (~8 keV) is negligible.

The electric monopole transition strength, $\rho^2(E0)$, can be determined from [4]

$$\rho^2(E0) = \frac{1}{\Omega_K(E0) \cdot \tau_K(E0)}, \quad (3)$$

where $\Omega_K(E0)$ is the electric factor obtained from atomic theory [29] and $\tau_K(E0)$ is the partial mean lifetime of the $E0$ component converted in the K shell. The $\tau_K(E0)$ is calculated using the relative branching ratio of the $E0$ transition, $\lambda_{E0}$, to the sum of all available decay modes, $\sum_i \lambda_i$, from the parent state, i.e.,

$$\tau_K(E0) = \sum_i \lambda_i \frac{T_{1/2}}{\ln(2)}, \quad (4)$$

where $T_{1/2}$ is the half-life of the parent state. Each contribution, such as the mixing ratio, if not measured in the present experiment, can be calculated from experimental data available in the literature. A number of the input values, particularly the parent half-life and mixing ratios, have asymmetric uncertainties. These asymmetric values lead to an overestimated uncertainty in the final value when calculated through standard error propagation. As such, the final value and uncertainties in this work were determined through a Monte Carlo method from which the median value and the 1 sigma (68%) confidence interval are presented.

### III. EXPERIMENTS AND ANALYSIS AT THE UKAL

Inelastic neutron scattering (INS) measurements were performed at the University of Kentucky Accelerator Laboratory (UKAL), which houses a 7 MV Van de Graaff accelerator capable of producing high-quality pulsed and bunched beams. Nearly monoenergetic neutrons were produced using the $^3$H(p,n)$^4$He reaction using a gas cell containing approximately an atmosphere of tritium gas. A single $\approx50\%$ efficient HPGe detector surrounded by an annular bismuth germanate (BGO) shield for Compton suppression was used for $\gamma$-ray detection. Time-of-flight gating was also employed to reduce the background from the prompt spectra. For the measurements, a cylindrical scattering sample of Ni metal of natural abundance, 45.94 g mass, 1.84 cm height, and 1.88 cm diameter was used.

Angular distribution measurements were performed for incident neutron energies of 2.42 and 2.90 MeV. The detector was rotated between 40 and 150° with respect to the incident beam direction. A $^{207}$Bi radioactive source was placed near the HPGe detector during the measurements. A $^{207}$Bi source was placed near the HPGe detector during the measurements to provide an “online” energy calibration.

![FIG. 6. Gamma-ray energy spectrum of inelastic neutron scattering on a natural Ni target. A $^{207}$Bi source was placed near the HPGe detector during the measurements to provide an “online” energy calibration.](image)

![FIG. 7. Doppler-shift data for the 1321 keV $\gamma$ ray from the 2775 keV $2^+_2$ level in $^{58}$Ni. The line is a linear fit to the data.](image)
IV. RESULTS AND DISCUSSION

A. $E2/M1$ mixing ratios from angular distributions of $\gamma$ rays

The results for $\delta(E2/M1)$ mixing ratios from this work are presented in Table I. The values presented for the $2^+ \rightarrow 2^+$ transitions in the three isotopes have been discussed in our previous publication [18]. The $\gamma$-ray angular distribution for the $2^+_2 \rightarrow 2^+_1$ transition in $^{58}$Ni from the ANU data is shown in Fig. 9. The $\delta(E2/M1)$ mixing ratio of the 1321.2 keV transition of $^{58}$Ni is from the UKAL data (Fig. 8), for the 826.06 keV $2^+_2 \rightarrow 2^+_1$ transition in $^{60}$Ni the weighted mean of the values obtained in the ANU and UKAL measurements are used, and for the 1128.82 keV $2^+_2 \rightarrow 2^+_1$ transition in $^{62}$Ni the weighted mean of our value from the ANU data and that reported in Ref. [33] is used. The measurements for $\delta(E2/M1)$ mixing ratios of all other transitions reported here are from the ANU data. The $\chi^2$ distributions for angular distribution data collected with CAESAR are shown in Fig. 10 with the corresponding results summarized in Table I. Two values are reported for some transitions as there are two minima in the $\chi^2$ plot, both of which are used in determining the $\rho^2(E0), B(M1)$, and $B(E2)$ values of the $2^+ \rightarrow 2^+$ transitions. The majority of the new measurements, for which literature values are available, agree within 1$\sigma$ of the adopted values listed in the evaluated Nuclear Data Sheets [34–36]. There are also a number of new values from the present work, particularly in $^{60}$Ni.

The $\delta$ value of the 1791 keV transition in $^{60}$Ni could not be measured due to intense background in the spectrum from the 1779 keV $2^+ \rightarrow 0^+$ $\gamma$ ray of $^{28}$Si, which was observed in the CAESAR data only as a result of scattered protons striking the glass target chamber. The

FIG. 8. Gamma-ray angular distribution of the 1321 keV $\gamma$ ray from the 2775 keV $2^+_4$ level in $^{58}$Ni. The line is a Legendre polynomial fit to the data.

FIG. 9. Example $\gamma$-ray angular distribution for the $2^+_2 \rightarrow 2^+_1$ transition in $^{60}$Ni from the $(p,p'\gamma)$ measurement. The inset shows the associated $\chi^2$ minimization curve.

FIG. 10. The $\chi^2$ plots for the sensitivity to the mixing ratio in the $\gamma$-ray angular distribution for $2^+ \rightarrow 2^+$ transitions observed in $^{58}$Ni (left) and $^{60}$Ni (right).
1.4 and to be determined for the first time. Sheets [34–36], where available. The new measurements and compared to the adopted values in the Nuclear Data taken from theory [37]. The results are shown in Table II internal conversion and internal pair formation, typically  

\[ \delta (E2/M1) \]

<table>
<thead>
<tr>
<th>Transition</th>
<th>( E_\gamma ) [keV]</th>
<th>( E_i ) [keV]</th>
<th>This work</th>
<th>NDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>( {^{58}\text{Ni}} 2^+ \rightarrow 1^+ )</td>
<td>1321.2</td>
<td>2775.42</td>
<td>-1.04±0.07</td>
<td>-1.1(1)</td>
</tr>
<tr>
<td>( 2^+ \rightarrow 1^+ )</td>
<td>1583.8</td>
<td>3037.86</td>
<td>+0.20(4)</td>
<td>+0.21(3)</td>
</tr>
<tr>
<td>( 2^+ \rightarrow 1^+ )</td>
<td>262.6</td>
<td>3037.86</td>
<td>+0.07±0.14</td>
<td>+0.10(5)</td>
</tr>
<tr>
<td>( 2^+ \rightarrow 1^+ )</td>
<td>1809.5</td>
<td>3263.66</td>
<td>+0.24(4)</td>
<td>+0.7(4)</td>
</tr>
<tr>
<td>( 2^+ \rightarrow 1^+ )</td>
<td>2444.7</td>
<td>3898.8</td>
<td>+1.42(10)</td>
<td></td>
</tr>
<tr>
<td>( {^{60}\text{Ni}} 2^+ \rightarrow 1^+ )</td>
<td>826.06</td>
<td>2158.63</td>
<td>+0.43(8)</td>
<td>+0.9(3)</td>
</tr>
<tr>
<td>( 2^+ \rightarrow 1^+ )</td>
<td>1791.6</td>
<td>3123.69</td>
<td>-0.21(4)</td>
<td></td>
</tr>
<tr>
<td>( 2^+ \rightarrow 1^+ )</td>
<td>1936.9</td>
<td>3269.19</td>
<td>+0.66(8)</td>
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<tr>
<td>( 2^+ \rightarrow 1^+ )</td>
<td>2060.58</td>
<td>3393.14</td>
<td>-0.01(2)</td>
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<tr>
<td>( 2^+ \rightarrow 1^+ )</td>
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<td>3393.14</td>
<td>+0.04(5)</td>
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<td>( 2^+ \rightarrow 1^+ )</td>
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<td>2301.84</td>
<td>+3.1(4)</td>
<td>+3.19(11)</td>
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<tr>
<td>( 2^+ \rightarrow 1^+ )</td>
<td>2444.7</td>
<td>3898.8</td>
<td>-1.1(4)</td>
<td></td>
</tr>
</tbody>
</table>

The experimental \( \delta (E2/M1) \) multipole mixing ratios determined in the present work. The columns \( E_\gamma \) and \( E_i \) are the transition and initial level energy, respectively. The \( \delta \) values listed under NDS are taken from the evaluated Nuclear Data Sheets [34–36].

C. Internal conversion coefficients

The experimental K internal conversion coefficients (ICC) for \( ^{58,60,62}\text{Ni} \) are listed in Table II. The uncertainties are dominated by the limited statistics of the electron spectra. The ratio of the experimental to theoretical ICC values for pure \( E2 \) and mixed \( (E0+M1+E2) \) multipolarity are shown in Fig. 11 as a function of transition energy. In the case of mixed \( (E0+M1+E2) \) transitions, the theoretical \( \alpha_{BrICC} \) value used to construct the \( \alpha_{Exp}/\alpha_{BrICC} \) ratio is calculated using the experimental \( \delta (E2/M1) \) mixing ratio. The experimental uncertainty in the mixing ratio is accounted for in the error bar. There is generally good agreement for the pure \( E2 \) transitions. Two transitions require further comment. The electron peak of the 952 keV \( 0^+ \rightarrow 2^+ \) transition in \( ^{60}\text{Ni} \) overlaps with that of a 947 keV transition reported in \( ^{60}\text{Cu} \), generated by the (p,n) reaction. Fitting of the \( \gamma \)-ray peak of the 1172 keV, \( 2^+ \rightarrow 0^+ \) transition in \( ^{62}\text{Ni} \) is complicated by overlap with the 1164 keV transition reported in the same nucleus. In these two cases, these contaminations in the experimental spectra prevent good agreement with the theoretical coefficients. In a number of the mixed transitions, particularly the \( 2^+ \rightarrow 2^+ \) transitions, there is significant \( E0 \) strength indicated by an \( \alpha_{Exp}/\alpha_{BrICC} \) ratio greater than 1.

![FIG. 11. Ratio of experimental to theoretical K-shell internal conversion coefficients.](image-url)
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dents to the $E2$ conversion coefficient of the competing decay branch to the $2^+$ state, $q_{E2}^2 = I_{01}^E / I_{02}^E$, derived from the previous work can be compared to the new data. In $^{60}$Ni, the $q_{E2}^2$ value was measured in the current work to be $0.079(8)$, which agrees well with the previously measured value of $0.074(16)$ [16]. For $^{62}$Ni, the $q_{E2}^2$ value was measured as $0.119(14)$, which only agrees with the previous value of $0.084(11)$ [16] within $2\sigma$.

Comparison of measured $q_{E2}^2$ values must consider the models used to evaluate the pair formation and $e^+ e^-$ angular distributions, which can affect the calculated efficiency of a pair spectrometer through a dependence on the emission angles of the emitted particles. In the 1990s, models suitable for all elements were developed employing the distorted-wave Born approximation (DWBA) method, which includes relativistic effects, and the finite size of the nucleus [38]. Earlier models had used the Born approximation with plane waves [39–43]. The theoretical $\alpha_\pi$ values and angular distributions of emitted particles differ considerably between the Born and DWBA approximations, particularly for magnetic transitions [38]. The previous measurements for Ni isotopes [16, 17] followed the formalism detailed in Refs. [39–41] for calculations of detection efficiency which could provide an explanation for agreement at only the $2\sigma$ with the present $^{62}$Ni result.

D. $E0$ transition strengths

Using the $\delta(E2/M1)$ mixing ratios (Section IV A, Table I) and internal conversion coefficients measured in this work, along with previously reported values from the literature [34–36], the $E0$ transition strengths were determined and are shown in Table II. Branching ratios were determined from the relative photon intensities reported in [34–36] in combination with the new values for mixing ratios and conversion coefficients. For transitions where there are two solutions for the measured $\delta(E2/M1)$ mixing ratio, both values were used individually to obtain separate $\rho^2(E0)$ values. The results, along with the previously reported results, are summarized in Fig. 12. In $^{58}$Ni, many of the newly determined $E0$ transition strengths have upper limits. In $^{60}$Ni, there is an upper limit on the 2285 keV $0^+_2 \rightarrow 0^+_1$ transition strength because the half-life of the parent state has only a lower limit of 1.5 ps [35].

The $2^+ \rightarrow 2^+$ $E0$ transition strengths found here are consistently large in all three of the Ni isotopes studied, particularly for the $2^+_2 \rightarrow 2^+_1$ transitions. In almost all transitions, the dominant source of error is the number of events observed in the $e^+$ spectra, particularly those from higher-lying states where only an upper limit could be obtained.

As has been previously discussed [1, 2], large $E0$ strength is typically associated with differences in de-excitation and mixing between configurations. This con-
FIG. 12. Experimental $\rho^2(E0) \times 10^3$ values measured in this work, combined with previous literature values in $^{58,60}$Ni [16, 17]. Unfilled transitions indicate that an upper limit has been determined. Level energies are shown in keV. The levels are grouped by their value of $J^o$ so that $E0$ transitions where $\Delta J = 0$ appear vertically.

FIG. 13. The known $\rho^2(E0)$ values for (a) $0^+_1 \rightarrow 0^+_1$ and (b) $2^+_2 \rightarrow 2^+_1$ transitions as a function of atomic mass. Upper/lower limits are shown as triangles with the error bar indicating the relevant limit. The data are from the most recent compilations by Kibédi [4] and Wood [2].

$E0$ strength, which should provide values that are independent of mass [2, 47]. When this is done, the observed Ni values remain amongst the largest, along with the $2^+_2 \rightarrow 2^+_1$ transition in $^{238}$Pu. In the case of $0^+ \rightarrow 0^+$ transitions this scaling was suggested to perhaps be insufficient [4] as a downward trend in $E0$ transition strength was still present as a function of mass number. The low number of experimental values available for $2^+ \rightarrow 2^+$ $E0$ transitions prevents global conclusions on systematic behavior from being drawn at this time.

On the experimental side, it would be of value to measure $E0$ transition strengths for other $2^+ \rightarrow 2^+$ transitions in order to build a comprehensive picture of the behavior of $E0$ transition strengths in atomic nuclei. This enterprise will require precise measurements of lifetimes, branching ratios, and mixing ratios along with conversion coefficients: such measurements are challenging, but feasible, and will illuminate an important aspect of nuclear structure that is poorly characterized at present.

V. CONCLUSION

In this work, the $E0$ transition strengths between $J^o = 2^+$ states were measured for three of the stable Ni isotopes, $^{58,60,62}$Ni. These new values were obtained through measurements of the $\delta(E2/M1)$ mixing ratio and internal conversion coefficients combined with level lifetimes. The new data also allow a number of $B(M1)$ and $B(E2)$ values to be determined for the first time. The $E0$ transition strengths between $0^+$ states were measured using internal conversion electron spectroscopy for the first time and compare well to previous results from internal pair formation spectroscopy [16, 17].

As was discussed in our previous publication [18], this work contains the first reported $E0$ transition strength...
mixing ratios (see Table I), K internal conversion coefficients \( q_K \), electric monopole transition strengths \( \rho_0 \), and \( E0 \) matrix elements \( M(E0) \) obtained in this work. \( q_K^2 \) is the ratio of the \( E0 \) conversion coefficient to the \( E2 \) conversion coefficient of the competing decay branch. Transition strengths of \( B(M1) \) and \( B(E2) \) are also given as determined from the present work. Comparisons are made to the adopted values in the Nuclear Data Sheets where available [34–36]. The columns \( E_{trans} \) and \( E_1 \) are the transition and parent level energy respectively, and \( T_{1/2} \) is the half-life of the parent state.

<table>
<thead>
<tr>
<th>Transition</th>
<th>( E_{trans} ) (keV)</th>
<th>( E_1 ) (keV)</th>
<th>( T_{1/2} ) (ps)</th>
<th>( \delta(E2/M1) )</th>
<th>( \alpha_K \times 10^4 )</th>
<th>( q_K^2 )</th>
<th>( \rho_0^2(E0) ) (W.u.)</th>
<th>( M(E0) ) (keV)</th>
<th>( B(M1) ) (W.u.)</th>
<th>( B(E2) ) (W.u.)</th>
<th>( T_{1/2} ) (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{58}\text{Ni}) 0(^+) ( \rightarrow ) 1(^+)</td>
<td>2942.6</td>
<td>2942.6</td>
<td>1460(140)</td>
<td>-</td>
<td>-</td>
<td>0.65(10)</td>
<td>0.0063(10)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0(^+) ( \rightarrow ) 0(^+)</td>
<td>3531.1</td>
<td>3531.1</td>
<td>0.19(6)</td>
<td>-</td>
<td>-</td>
<td>0.27(4)</td>
<td>80(30)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2(^+) ( \rightarrow ) 2(^+)</td>
<td>1321.2</td>
<td>2775.42</td>
<td>0.60(^{+0.19}_{-0.12})</td>
<td>1.04(^{+0.07}_{-0.08})</td>
<td>1.38(3)</td>
<td>0.46(7)</td>
<td>230(^{+0.50}_{-0.80})</td>
<td>10.3(^{+1.1}_{-2.0})</td>
<td>7.3(^{+1.6}_{-2.4}) ( \times 10^{-3})</td>
<td>9(^+)</td>
<td></td>
</tr>
<tr>
<td>( \rho_0^2 )</td>
<td>+1.48(13)</td>
<td>&lt;0.01</td>
<td>&lt;22</td>
<td>&lt;3</td>
<td>0.018(4)</td>
<td>30(5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2(^+) ( \rightarrow ) 2(^+)</td>
<td>262.6</td>
<td>3037.86</td>
<td>0.057(8)</td>
<td>+0.20(4)</td>
<td>0.72(3)</td>
<td>&lt;0.7</td>
<td>&lt;70</td>
<td>&lt;6</td>
<td>0.055(8)</td>
<td>1.7(7)</td>
<td>0.055(8)</td>
</tr>
<tr>
<td>2(^+) ( \rightarrow ) 2(^+)</td>
<td>1809.5</td>
<td>3263.66</td>
<td>0.037(5)</td>
<td>+0.24(4)</td>
<td>0.52(9)</td>
<td>&lt;1.3</td>
<td>&lt;120</td>
<td>&lt;7</td>
<td>0.037(6)</td>
<td>1.3(5)</td>
<td>0.027(11)</td>
</tr>
<tr>
<td>( \rho_0^2 )</td>
<td>+1.42(10)</td>
<td>&lt;0.05</td>
<td>&lt;80</td>
<td>&lt;5</td>
<td>0.013(2)</td>
<td>15(2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2(^+) ( \rightarrow ) 2(^+)</td>
<td>0.49(13)</td>
<td>-0.11(4)</td>
<td>-</td>
<td>-</td>
<td>0.079(8)</td>
<td>&lt;30</td>
<td>&lt;4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{60}\text{Ni}) ( \alpha^+ ) ( \rightarrow ) 0(^+)</td>
<td>2284.8</td>
<td>2284.8</td>
<td>1.5</td>
<td>-</td>
<td>-</td>
<td>0.079(8)</td>
<td>&lt;30</td>
<td>&lt;4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0(^+) ( \rightarrow ) 0(^+)</td>
<td>3317.8</td>
<td>3317.8</td>
<td>0.24(^{+0.28}_{-0.11})</td>
<td>-</td>
<td>-</td>
<td>0.29(3)</td>
<td>78(^{+6}_{-46})</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0(^+) ( \rightarrow ) 0(^+)</td>
<td>3587.7</td>
<td>3587.7</td>
<td>&lt;40</td>
<td>-</td>
<td>-</td>
<td>1.26(20)</td>
<td>&gt;0.43</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>2(^+) ( \rightarrow ) 2(^+)</td>
<td>826.06</td>
<td>2158.63</td>
<td>1.28(^{+0.74}_{-0.35})</td>
<td>+0.43(8)</td>
<td>3.0(1)</td>
<td>0.4(^{+0.2}_{-0.3})</td>
<td>150(^{+40}_{-110})</td>
<td>9(^+)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \rho_0^2 )</td>
<td>+2.62(^{+0.36}_{-0.14})</td>
<td>&lt;0.3</td>
<td>&lt;200</td>
<td>&lt;8</td>
<td>2.1(^{+0.7}_{-1.0}) ( \times 10^{-3})</td>
<td>6(^+)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>2(^+) ( \rightarrow ) 2(^+)</td>
<td>2060.58</td>
<td>3393.14</td>
<td>0.13(^{+0.06}_{-0.04})</td>
<td>-0.01(2)</td>
<td>0.48(11)</td>
<td>150</td>
<td>(^{+100}_{-150})</td>
<td>40(^{+200}_{-200})</td>
<td>4(^+)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \rho_0^2 )</td>
<td>+2.3(^{+0.4}_{-0.3})</td>
<td>1.5(^{+0.7}_{-0.4})</td>
<td>&lt;10</td>
<td>&lt;4</td>
<td>10(2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{62}\text{Ni}) ( \alpha^{+}_{1} ) ( \rightarrow ) 0(^+)</td>
<td>2048.68</td>
<td>2048.68</td>
<td>0.92(^{+0.67}_{-0.20})</td>
<td>-</td>
<td>-</td>
<td>0.084(11)</td>
<td>130(^{+60}_{-70})</td>
<td>8.1(^{+1.7}_{-2.6})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \rho_0^2 )</td>
<td>+3.1(1)</td>
<td>1.95(11)</td>
<td>0.22(7)</td>
<td>140(^{+50}_{-70})</td>
<td>8.4(^{+1.4}_{-2.5})</td>
<td>9(^+)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{62}\text{Ni}) ( \alpha^{+}_{2} ) ( \rightarrow ) 2(^+)</td>
<td>1128.82</td>
<td>2301.84</td>
<td>0.67(^{+0.20}_{-0.13})</td>
<td>+3.1(1)</td>
<td>1.95(11)</td>
<td>0.22(7)</td>
<td>140(^{+50}_{-70})</td>
<td>8.4(^{+1.4}_{-2.5})</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A weighted average is taken from Refs [36] and [33].
information for $2^+ \rightarrow 2^+$ transitions in nuclei with $A < 531$
100. These also represent the first evaluation of $2^+ \rightarrow 2^+$
$E0$ strengths in nuclei with spherical ground states, and previous research focused on the lanthanide region. The explanation of the significant $E0$ strength observed in these isotopes should be the focus of future theoretical efforts.

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