Enhanced Core Polarization in $^{70}$Ni and $^{74}$Zn


The reduced transition probabilities $B(E2; 0^+ \rightarrow 2^+)$ of the neutron-rich $^{74}$Zn and $^{70}$Ni nuclei have been measured by Coulomb excitation in a $^{208}$Pb target at intermediate energy. These nuclei have been produced at Grand Accélérateur National d’Ions Lourds via interactions of a 60A MeV $^{76}$Ge beam with a Be target. The $B(E2)$ value for $^{70}$Ni is unexpectedly large, which indicates that neutrons added above $N = 40$ strongly polarize the $Z = 28$ proton core. In the Zn isotopic chain, the steep rise of $B(E2)$ values beyond $N = 40$ continues up to $^{74}$Zn. The enhanced proton core polarization in $^{70}$Ni is attributed to the monopole interaction between the neutron in the g9/2 and protons in the f5/2 and f3/2 spin-orbit partner orbitals. This interaction could result in a weakening of magicity in $^{70}$Ni.

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rates of 4200 and 800 per second were obtained for the
$^{74}\text{Zn}$ and $^{70}\text{Ni}$ isotopes, respectively. Another spectrometer
setting was set to transmit the $q = 28^+$ charge state of the
primary beam at a rate of $10^5$ s$^{-1}$ in the same optical
conditions. This aimed to confirm the known $B(E2)$ value
of $^{76}\text{Ge}$ [20], which has subsequently been used as a
reference to determine the $B(E2)$ values of $^{74}\text{Zn}$ and $^{70}\text{Ni}$. Nuclei were identified by means of their energy
loss and time of flight measured in a "removable" Si
detector placed downstream from the spectrometer at the
entrance of the target chamber. This detector was inserted
several times during each spectrometer setting to
determine the ratio of nuclei of interest over the total number of
transmitted nuclei.

Coulomb excitation at $\nu/c \sim 0.28$ for $^{74}\text{Zn}$ and $^{70}\text{Ni}$ and
0.29 for $^{76}\text{Ge}$ was induced in a $^{208}\text{Pb}$ target of 120 mg/cm$^2$
thickness located at the focal plane of LISE3. The target
was surrounded by four segmented clover Ge detectors of
the EXOGAM gamma array placed at 90° at a distance of
5.5 cm from the target, yielding a total photopeak effi-
ciency of $\epsilon_\gamma = 5.0\%$ at 1.3 MeV.

Two $x$-$y$ drift chambers were mounted at 27 and 47 cm
downstream from the $^{208}\text{Pb}$ target in order to reconstruct
the trajectories of the emergent nuclei after their interac-
tion. This allows one to determine the diameter of the beam
spot at the target location. Within the error bars, a FWHM
of 11.4(6) mm was found for all nuclei, which ensures that
all Coulomb excitations were measured under the same
geometrical conditions.

Two annular Si detectors, with internal (external) diam-
eters of 3 cm (9 cm), were mounted 56 cm behind the target
in order to identify the deflected nuclei by their energy
losses and residual energies. In the case of $^{76}\text{Ge}$, the
angular coverage ranged from 1.5° to 6.1° in the center
of mass frame, the grazing angle being 6.2°. By using the
calculated angular distribution of the nuclei after Coulomb
deflection from Ref. [21] distorted by the angular strag-
gling of the nuclei into the target, a Monte Carlo simulation
shows that about 25% of the nuclei that underwent
Coulomb excitation either flew through the central hole
of the annular Si detector or were deflected at larger
angular values. The ratios $\epsilon_{\text{geom}}$ of Coulomb excited nuclei
that were detected in the annular Si detector to the total
number of deflected nuclei are listed in Table I for the three
nuclei $^{76}\text{Ge}$, $^{74}\text{Zn}$, and $^{70}\text{Ni}$. Nuclei emerging with smaller
angles were detected in a plastic scintillator 2 m down-
stream which served to determine the total number of implanted nuclei. The number $N_n$ of nuclei of interest
impinging on the target are given in Table I. It was derived
from the yields obtained in the removable Si detector and
in the plastic scintillator, the latter triggering the acquisi-
tion system at a reduced calibrated rate of 2%. The ratio of
$^{74}\text{Zn}$ over the total number of transmitted nuclei was
$68(2)\%$ over the 18 hours of accumulated beam time.
That for $^{70}\text{Ni}$ was 10.2(9)\% along the 3 days of beam
time accumulated for this nucleus. In this latter spectrome-
ter setting, 7.7(7)\% of $^{74}\text{Zn}$ were also transmitted. The proportion of the $8^+$ isomer in the $^{70}\text{Ni}$ beam was measured to be 1.4(2)\%.
Any contribution of the isomer decay to the
yield of $2^+ \to 0^+$ $\gamma$ rays attributed to the Coulomb exci-
tation process is negligible.

Photons emitted in flight in coincidence with the scattered
nuclei were detected in the four segmented EXOGAM Ge
clover detectors. The segmentation of the clover detectors allowed us to reduce the Doppler broad-
kening by 40%, leading to an energy resolution (FWHM)
of 75 keV at 1 MeV. The Doppler-corrected spectra for the
$^{76}\text{Ge}$, $^{74}\text{Zn}$, and $^{70}\text{Ni}$ nuclei are shown in Fig. 1. They
exhibit photopeaks associated with the Coulomb excitation
of the $2^+$ energy level. The structure of the $\gamma$ background is
very similar for all nuclei, as shown in the right part of
Fig. 1. The number of $\gamma$ rays in the peaks $N_\gamma$ is given in
Table I.

During the Coulomb excitation process, a certain
amount of angular momentum alignment is present while
ejectiles are emitted at very forward angles. As compared to
an isotropic $\gamma$-ray distribution, the $\Delta \ell = 2 \gamma$ rays emi-
ted in flight exhibit two lobes focused at the forward
direction according to the Lorentz energy boost. However, the rate of $\gamma$ rays, within the laboratory angular
coverage of $78° - 120°$, was close to that of an isotropic
source as the loss of photons at backward angles was
compensated by the gain of photons at forward angles.
The angular efficiency relative to that of a calibration
source located at the $^{208}\text{Pb}$ target position $\epsilon_{\text{ang}}$ is listed in
Table I.

Applying the correction factors $\epsilon_{\text{geom}}$ and $\epsilon_{\text{ang}}$ to the
experimental cross section, we find a Coulomb excitation
cross section up to the grazing angle of $\sigma(0^+ \to 2^+) =
1070(100)$ mb for $^{76}\text{Ge}$. The EXCAMP code [22] deter-
imines, for a given $B(E2)$ value, the integrated semiclassical
Coulomb excitation cross section [21]. The present
$\sigma(0^+ \to 2^+)$ for $^{76}\text{Ge}$ corresponds to $B(E2) =
2990(270) e^2$ fm$^4$, in agreement with the value of the
$2680(80) e^2$ fm$^4$ [20] derived from low-energy Coulomb
excitation studies. To minimize systematical effects in the
determination of the absolute $B(E2)$ values, the $B(E2)$

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$N_n$ (10$^5$)</th>
<th>$N_\gamma$</th>
<th>$\epsilon_{\text{geom}}$</th>
<th>$\epsilon_{\text{ang}}$</th>
<th>$B(E2)_{\text{rel}}$ (e$^2$ fm$^4$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>2.19(2)</td>
<td>6450(150)</td>
<td>0.78</td>
<td>1.06</td>
<td>2680(80)$^a$</td>
</tr>
<tr>
<td>$^{74}\text{Zn}$</td>
<td>2.78(8)</td>
<td>5630(140)</td>
<td>0.74</td>
<td>1.06</td>
<td>2040(150)</td>
</tr>
<tr>
<td>$^{70}\text{Ni}$</td>
<td>1.58(14)</td>
<td>675(90)</td>
<td>0.75</td>
<td>0.98</td>
<td>860(140)</td>
</tr>
</tbody>
</table>

$^a$Ref. [20].
values of $^{70}$Ni and $^{74}$Zn in Table I have been determined relative to that of $^{76}$Ge [20]. For $^{74}$Zn, we have additionally found a consistent $B(E2)$ value of 1970(240)$e^2$ fm$^4$ from the $1.25(12) \times 10^8$ $^{74}$Zn which were transmitted in the spectrometer setting dedicated to the study of $^{70}$Ni. The agreement between the $B(E2)$ value of $^{76}$Ge determined by low- and high-energy Coulomb excitation adds evidence that contributions to the measured $2^+ \rightarrow 0^+$ $\gamma$ transition from a nuclear process or/and from the side feeding by higher lying excited states are minor. This is confirmed for the three studied nuclei by the fact that one does not observe any other $\gamma$ line in their spectra which would arise from the deexcitation of high-lying states, as, in particular, from the known $2^+_1$ states in $^{76}$Ge [20], $^{74}$Zn [23], and $^{70}$Ni [12].

The behavior of the $B(E2; 0^+ \rightarrow 2^+)$ values (Fig. 2) is used in the following to gauge the role of the $N = 40$ subshell closure and the evolution of collectivity in the Ni and Zn isotopic chains. In the Ni isotopic chain, the $\pi f_{7/2}$ orbital is separated from the remaining proton orbitals of the $fp$ shell by the $Z = 28$ gap. In the Zn isotopic chain, valence protons in the $\pi p_{3/2}$ and $\pi f_{5/2}$ orbitals (above the $Z = 28$ gap) also add to polarization by proton-neutron interaction besides their direct contribution to the $E2$ strength. Below $N = 40$, the $B(E2)$ curve reaches a maximum in the Ni and Zn chains at or near midoccupation by neutrons of the $fp$ shell ($N = 34$) and subsequently decreases until $N = 38$. The parabolic curve in the proton-magic Ni chain follows the trend of a generalized seniority scheme for a $\Delta n = 2$ transition [4–6,24]. As the neutron $fp$ orbitals are progressively filled, the core polarization occurs through quadrupole excitations via $\pi f_{7/2}^{-1} p_{3/2}$ configurations [7,11]. The offset of the parabola below $N = 40$ in the Zn isotopic chain is caused by the two added valence protons. The large scale shell model reproduces the Ni and Zn $B(E2)$ curves below midshell $N = 34$ within a $fp$ model space [25,26], while for $N \geq 34$ the $g_{9/2}$ neutron orbit is essential for a correct description as shown in Refs. [11,26].

At $N = 40$, the $B(E2; 0^+ \rightarrow 2^+)$ value reaches a minimum in the Ni chain. Such a minimum has been ascribed mainly to the lack of $E2$ excitation between the $fp$ and the $g_{9/2}$ orbitals of different parity value [9,11,13]. In the Zn isotopic chain, the minimum is shifted to $N = 38$, which does not necessarily document an $N = 38$ subshell closure as suggested in Ref. [24]. From the calculated occupancies of the $\nu g_{9/2}$ orbital ($n$) shown in Fig. 2, it is seen that the pairing correlations [11,13] start to empty the $fp$ orbitals in the Zn isotopic chain earlier and to a larger extent than in Ni (i.e., $n = 1.2$ for $^{68}$Ni and 2.9 for $^{70}$Zn). The enhanced filling of the $\nu g_{9/2}$ orbit at $N = 40$ in the Zn chain brings a direct contribution to the $B(E2; 0^+ \rightarrow 2^+)$ value through the $(\nu g_{9/2})^2$ configuration, in contrast to the Ni isotopic chain. This displaces the $B(E2)$ minimum from $N = 40$ in the Ni isotopes to $N = 38$ in the Zn isotopic chain.
Beyond $N = 40$, the present work indicates a steep rise for $^{70}\text{Ni}$, even within the experimental uncertainties. In the Zn isotopes, the $B(E2)$ values continue to increase with $N$ with the expected parabolic trend at least towards the $g_{9/2}$ midshell ($N = 44$). We can infer the amount of the $^{68}\text{Ni}$ core polarization of the $2^+$ state in $^{70}\text{Ni}$ through the evolution of the $B(E2; J \rightarrow J - 2)$ values along the $8^+$, $6^+$, $4^+$, $2^+$ components of the $(g_{9/2})^2$ multiplet. We expect the $8^+$ state of this multiplet to be almost only of neutron origin, as a $8^+$ spin value cannot be built with protons in the $fp$ orbitals. The $B(E2; 8^+ \rightarrow 6^+)$ would therefore correspond to a reference value for the weakest core polarization. Recently, $E2$ transition strengths were determined [27–29] for high-spin states in $^{70}\text{Ni}$, and a new empirical $T = 1$ effective interaction was derived in the pure neutron $p, f; f$ model space [30]. In this approach, the experimental $B(E2; 8^+ \rightarrow 6^+) = 19(4)$ [27], $B(E2; 6^+ \rightarrow 4^+) = 43(1)$ [28,29], and the present $B(E2; 2^+ \rightarrow 0^+) = 172(8)e^2\text{fm}^4$ are calculated as 17.3, 44.6, and 92.2$e^2\text{fm}^4$, respectively, using an effective neutron charge $e N = 1.2e$. The good agreement for the high-spin states breaks down for the $2^+ \rightarrow 0^+$ transition, which is a clear signature for an enhanced proton core polarization at low excitation energy. This conclusion is at variance with the quasi-random-phase approximation (QRPA) [13] and shell-model results [11] (see Fig. 2) which predict that the low-energy $B(E2)$ strength in $^{70}\text{Ni}$ predominantly corresponds to neutron excitations, decoupled from the proton core.

The strong polarization in the Ni and Zn isotopes beyond $N = 40$ could be due to the attractive $\pi f_{5/2}\nu g_{9/2}$ monopole interaction [31–33], ascribed to the tensor force of the in-medium nucleon-nucleon interaction [3]. This force is also predicted to act through the repulsive $\pi f_{7/2}\nu g_{9/2}$ interaction to reduce the apparent $\pi f_{7/2}\pi f_{5/2}$ spin-orbit splitting. From these mutual interactions, the effective $Z = 28$ shell gap and the $N = 40$ subshell gap are reduced as $N$ increases, favoring the development of collectivity. This hypothesis is supported by the fact that the experimental $B(E2)$ values in the Zn isotopic chain scale with the calculated occupation of the $g_{9/2}$ orbital (cf. Fig. 2).

In summary, the $B(E2; 0^+ \rightarrow 2^+)$ values of $^{70}\text{Ni}$ and $^{74}\text{Zn}$ have been determined for the first time. The $B(E2)$ value of $^{70}\text{Ni}_{40}$ increases by a factor of 3, as compared to $^{68}\text{Ni}_{40}$, indicating that the filling of the neutron $g_{9/2}$ shell induces a rapid polarization of the proton core. The $B(E2)$ value is still increasing with the neutron number at $^{74}\text{Zn}$, which corresponds to midoccupancy of the neutron $g_{9/2}$ orbital. The strong polarization effect beyond $N = 40$ has been ascribed to the $\pi f_{5/2}\nu g_{9/2}$ neutron-proton interaction which plays an essential role for rapidly bringing collectivity above $Z = 28$ as neutrons are added in the $g_{9/2}$ shell. It is foreseen that this hitherto poorly studied part of the nucleon-nucleon force would influence the behavior of shell closures far from stability as, in particular, the effectiveness of the magicity of $^{78}\text{Ni}$.

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