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Coulomb excitation of ^{107}In

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The radioactive isotope ^{107}In was studied using sub-barrier Coulomb excitation at the REX-ISOLDE facility at CERN. Two γ rays were observed during the experiment, corresponding to the low-lying $11/2^+$ and $3/2^-$ states. The reduced transition probability of the $11/2^+$ state was determined with the semiclassical Coulomb excitation code GOSIA2. The result is discussed in comparison to large-scale shell-model calculations, previous unified-model calculations, and earlier Coulomb excitation measurements in the odd-mass In isotopes.

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The odd-mass In isotopes are one proton hole away from the closed $Z = 50$ shell. These isotopes provide important information on the neutron-proton interaction near ^{100}Sn, particularly in light of the recently observed enhancement of the reduced transition strengths in the even-even Sn isotopes ^{106,108,110}Sn [1–4], compared to shell-model predictions. It has been suggested that this increase may be related to the lack of proton excitations across the $Z = 50$ shell gap in the calculations, brought about by computational limits encountered when applying the nuclear shell model. For this reason, it is interesting to explore the collectivity of excited states in other nuclei in the nearby region, especially in systems where proton excitations can be included in the calculations. In several previous studies in the ^{100,102,104}Cd isotopes [5–7], it was found that large-scale shell-model calculations yielded good agreement with the reduced transition probabilities of the first excited 2^+ states in these nuclei. These calculations employed a model space, also relevant for the light-In nuclei, with protons in the $p_{1/2}$ and $g_{9/2}$ orbits and neutrons in the $d_{5/2}$, $s_{1/2}$, $d_{3/2}$, $g_{7/2}$, and $h_{11/2}$ orbits. To compliment the above investigations, we report here on the first Coulomb excitation measurement of the radioactive isotope ^{107}In.

It has been previously shown that unified-model calculations [8], considering both one-hole and two-hole one-particle (seniority $\nu = 1$ and $\nu = 3$) proton configurations coupled to the collective 2^+ and 3^- excitations in the even-even Sn nuclei [9–12] form a most interesting truncated approach to study the interplay of collective and single-particle excitations in the In nuclei. All these nuclei exhibit a $9/2^+$ ground state and a $1/2^-$ isomeric state [13], corresponding to the proton hole moving mainly in the $1g_{9/2}$ and $2p_{1/2}$ orbitals. The unified-model calculations yield (i) a set of low-lying core coupled states, ranging from $5/2^+$ to $13/2^+$, that result mainly from the $|1g_{9/2}^{-1},\mathrm{Sn}(2^+); JM\rangle$ configuration, and (ii) a strongly coupled band built on top of the low-lying $1/2^+$ state, originating mainly from $|2d_{5/2},\mathrm{Cd}(2^+,4^+,\ldots); JM\rangle$ and $|1g_{7/2},\mathrm{Cd}(2^+,4^+,\ldots); JM\rangle$ configurations. The latter result is a most interesting feature of the odd-mass In nuclei, showing the presence of both spherical core (Sn) coupled states

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and a deformed band, originally interpreted as being based on the $1/2^+[431]$ Nilsson orbital [9,11,12,14–16], which arise in a natural way from the unified-model approach.

The Coulomb excitation experiment of ^{107}In was carried out at REX-ISOLDE at CERN together with two other Coulomb excitation experiments on the nuclei ^{107,109}Sn. The results of those measurements have been published elsewhere [17,18] and provide additional details of the experimental conditions for the measurement presented here. The ^{107}In nuclei were produced in parallel with the ^{107}Sn nuclei during the bombardment of a 27 g/cm^2 LaC$_x$ primary target with a 1.4 GeV proton beam from the PS booster. Both the ^{107}Sn and ^{107}In atoms diffused out of the target into a transfer cavity. During this stage, the In atoms were singly ionized by the surface walls of the cavity and were extracted for electromagnetic separation, according to $A = 107$, in the general purpose separator at the facility. The extraction of the ^{107}Sn isotopes was controlled by using a resonant laser ionization scheme [19], which could be switched on and off at different times over the course of the experiment. After cooling and bunching in REX-TRAP [20] and charge breeding in the electron beam ion source (EBIS) [21], the isobaric beam was accelerated to an energy of 2.87 MeV/nucleon and incident on a 1.95 mg/cm^2 ^{58}Ni target, isotopically enriched to 99.93%. Following Coulomb excitation of the target and projectile nuclei, the de-excitation γ rays were detected with the MINIBALL Ge detector array [22]. The raw γ-ray spectra were Doppler corrected using the angles of the emitted γ rays and the detected particles, based on the data collected in a double-sided-silicon-strip detector (DSSSD) placed behind the secondary target location.

The γ-ray spectra, after applying the Doppler correction for either Ni or In particles, are shown in Fig. 1. The spectra represent the total statistics over all laser on and off runs from the experiment. The ^{107}Sn peak disappears when limiting the data to only laser off runs, as shown in Ref. [23]. The peak at 1001 keV corresponds to a previously observed $11/2^+$ level in ^{107}In [24]. The γ ray at 429 keV depopulates the $3/2^-$ state at 1107 keV [24] and feeds the isomeric $1/2^-$ state, which has a half-life of 50.4(6) s [25]. The yield of the ^{58}Ni peak was used for normalization in the analysis presented below, with $B(E2; 0^+ \rightarrow 2^+) = 0.0704(15)\ e^2\mathrm{b}^2$ [26]. The peak areas and intensities from the experiment are given in Table I.

The peak area presented in Table I for ^{58}Ni has been corrected using the determined ^{107}Sn to ^{107}In ratio. The ^{107}Sn component was calculated based on the number of particles detected in the DSSSD in combination with the number of counts in the ^{107}In peak at 1001 keV. The ^{107}In component

TABLE I. The peak areas and relative intensities from the experiment. The energies of the γ rays are given in Refs. [24,26]. The area of the ^{58}Ni peak was corrected for the ^{107}Sn and ^{107}In^m components.

Transition	E_γ(keV)	Area	Rel. int.
In $11/2^+ \rightarrow 9/2^+$	1001	658(31)	2.68(17)
In $3/2^- \rightarrow 1/2^-$	429	<315	<0.77
Ni $2^+ \rightarrow 0^+$	1454	196(28)	1.00(15)

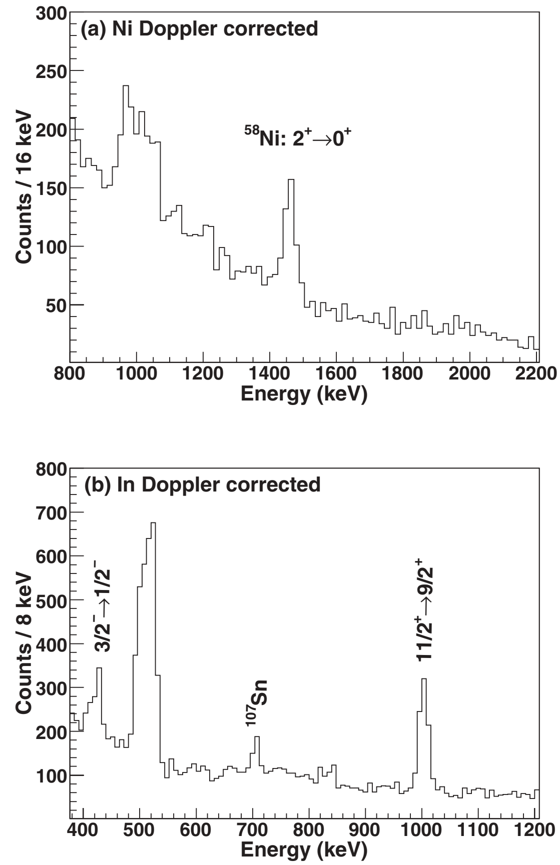

FIG. 1. The γ-ray spectra from the experiment, using either (a) Ni or (b) In particles for Doppler correction. The structure around 500 keV results from the 511 keV line, which collapses during the Doppler correction.

contains both ^{107}In in the ground state and also in the isomeric state, indicated as ^{107}In^m. Consequently, the 429 keV γ ray could be emitted following the Coulomb excitation of ^{107}In^m or potentially by direct $E3$ excitation of the ground state; see for example previous odd-mass In Coulomb excitation experiments [27,28]. The ^{107}In^m fraction was estimated based on previous electron capture decay data [24]. The relevant data for the analysis are indicated in Fig. 2. The $1/2^-$ state has only one de-excitation path leading directly to the $9/2^+$ ground state, resulting in the emission of a 679 keV γ ray. Thus, the ^{107}In^m fraction was estimated by comparing the measured intensity of the 1129 keV decay line with the intensity of the 679 keV decay line and by using the previously known intensities indicated in Fig. 2. This resulted in a fraction of 0.04(5), of the total data set, for the ^{107}In^m component and 0.77(8), of the total data set, for the ^{107}In ground-state component. As the decay lines arise from activity distributed on the beam pipes, scattering chamber, and beam dump, it was also necessary to have the relative efficiency of the MINIBALL detectors for detecting γ rays originating from these locations. Efficiency curves for this purpose have been presented in a previous publication [29] and were used in the above analysis.

The semiclassical Coulomb excitation code GOSIA2 [30] was used in combination with the measured yields, given in Table I, to extract the reduced transition probability for the

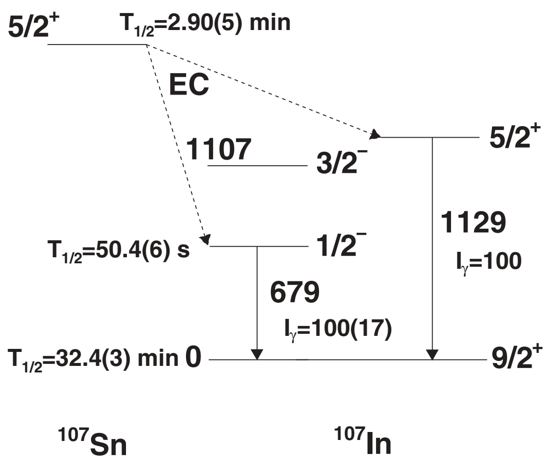

FIG. 2. Partial level scheme of ^{107}In, indicating the electron capture (EC) decay of ^{107}Sn. The energies are given in keV. The two indicated γ-ray transitions were used to estimate the ^{107}In^m contamination. The data were taken from Ref. [24].

$11/2^+$ state. The code searches for a best set of reduced matrix elements, which reproduces the experimentally determined γ-ray yields and uses a standard χ^2 minimization procedure. In the analysis, two additional levels were included above the $11/2^+$ state. All the possible $E2$ and $M1$ reduced matrix elements for these levels were defined in the input, with the starting values taken from shell-model calculations. During the minimization process, only the $9/2^+ \rightarrow 11/2^+$ $E2$ reduced matrix element was allowed to vary while all other reduced matrix elements were fixed to their starting values. The resulting $B(E2)$ value is given in Table II. The statistical errors were determined by taking into account the correlations between the ^{107}In and ^{58}Ni reduced matrix elements. The $9/2^+ \rightarrow 11/2^+$ reduced matrix element was fixed at points around the determined χ^2 minimum, while the ^{58}Ni reduced matrix elements were allowed to vary within their previously reported 1σ deviations. The minimization was again carried out and the procedure was repeated until the $\chi^2 + 1$ limits were determined. These limits represent the statistical error bars given in Table II. The effect of the correlations between the $9/2^+ \rightarrow 11/2^+$ reduced matrix element and the fixed ^{107}In reduced matrix elements was investigated by repeating the minimization with fixed reduced matrix elements set to $\pm 50\%$ of their original values. This procedure had no significant impact on the determined reduced transition probability. In addition, we investigated the influence of the isomeric content on the $B(E2)$ value. In the maximum and minimum scenarios, corresponding to an isomeric content at the 1σ limit of the fraction presented above and no isomeric content, the influence was calculated to be on the order of ± 0.01 e^2b^2. Lastly, the effect of possible $E3$ excitation to the $3/2^-$ level was investigated by including this state in the analysis. The reduced matrix element was taken from ^{115}In [28] and the minimization was repeated. An additional test was carried out by increasing the $E3$ reduced matrix element by a factor of 100. Neither case resulted in deviations from the reduced transition probability reported here.

TABLE II. Experimental and shell-model calculated $B(E2; 9/2^+ \rightarrow 11/2^+)$ values for ^{107}In and the results of previous Coulomb excitation measurements in ^{113,115}In [28]. The shell-model (SM) calculations used the effective charges $e_\nu = 1.1e$ and $e_\pi = 1.7e$ (SM A) and $e_\nu = 1.3e$ and $e_\pi = 1.7e$ (SM B).

	Energy (keV)	$B(E2)$ (e^2b^2)
Exp	1001	0.12(2)
SM A	1063	0.09
SM B	1063	0.12
^{113}In	1173	0.093(6)
^{115}In	1133	0.100(5)

In the following, the experimentally determined $B(E2)$ value is compared to large-scale shell-model calculations based on a realistic nucleon-nucleon interaction and previous unified-model calculations. The shell-model calculations were carried out for the light odd-mass In isotopes using a ^{88}Sr core with the single-proton energies set to $p_{1/2} = 0.00$ MeV and $g_{9/2} = 0.90$ MeV and the single-neutron energies set to $d_{5/2} = 0.00$ MeV, $s_{1/2} = 1.26$ MeV, $d_{3/2} = 2.23$ MeV, $g_{7/2} = 2.63$ MeV, and $h_{11/2} = 3.50$ MeV, taken from Ref. [31]. In the calculations, a maximum of three particles were allowed in the $h_{11/2}$ neutron orbital. The effective interaction used is based on a G-matrix renormalized CD-Bonn potential [32]. Here, it can be mentioned that this interaction was previously employed in a Coulomb excitation study of the ^{106,108}In isotopes [33]. The effective charges used in the current analysis, $e_\nu = 1.1e$ and $e_\pi = 1.7e$, were taken from Refs. [5,6].

The shell-model calculated $B(E2)$ values for the $11/2^+$ state are shown in Table II, compared to the result presented in this paper. The calculation using the effective charges of $e_\nu = 1.1e$ and $e_\pi = 1.7e$ (SM A) underestimates the present measurement. Increasing the neutron effective charge to $e_\nu = 1.3e$ (SM B) yields better agreement.

Considering the unified-model approach, the $B(E2; 9/2^+ \rightarrow 11/2^+)$ value results from a coherent superposition of both the collective $0^+ \rightarrow 2^+$ $E2$ contribution (related to the Sn core) and the $\langle 1g_{9/2} || E2 || 1g_{9/2} \rangle$ single-particle $E2$ contribution. The effective charge for the collective part of the $E2$ operator has been taken from the ^{116}Sn $B(E2; 0^+ \rightarrow 2^+)$ value and a proton effective charge of $e_\pi = 1.5e$ has been used for the In nuclei [9,11], resulting in a value of $B(E2; 9/2^+ \rightarrow 11/2^+) = 0.08$ e^2b^2 for ^{115}In. This value is expected to be rather stable for the neutron-deficient odd-mass In nuclei, considering the nearly constant, around midshell values, of the reduced transition probabilities in the even-even neutron-deficient Sn isotopes [1–4]. The proton effective charge is slightly smaller than the value used in the large-scale shell-model calculations, which most probably comes from the fact that in the unified-model calculations, both single-hole and collective $E2$ matrix elements contribute.

The experimentally determined $B(E2)$ value for ^{107}In is also compared to previous Coulomb excitation measurements in the nuclei ^{113,115}In in Table II. The data support a constant or possibly increasing trend in the light In isotopes with decreasing neutron number, reminiscent of the $B(E2)$ values in the neutron-deficient Sn isotopes. In the light Sn isotopes, the lowest 2^+ states are thought to be based primarily on configurations including neutrons in the five orbits above the $N = 50$ shell gap. However, large-scale shell-model calculations in this model space have not been able to reproduce the observed behavior of the $B(E2)$ values, suggesting missing degrees of freedom. Interestingly, the trend is also observed in the In isotopes, which have one proton hole relative to the $Z = 50$ shell. The current result suggests that the proton degree of freedom may be important for reproducing the behavior observed in the neutron-deficient Sn isotopes.

In summary, we have reported on the first Coulomb excitation measurement of ^{107}In, which is the lightest odd-mass In nucleus studied using this method. By using the semiclassical Coulomb excitation code GOSIA2, it was possible to extract the $B(E2)$ value of the first $11/2^+$ excited state. The result was interpreted under the framework of large-scale shell-model calculations employing a realistic nucleon-nucleon interaction. It was found that renormalization of the effective charge, increased by $\sim$20%, yielded good agreement with the measurement. In addition, the result was compared with previous unified-model calculations, including one-hole and two-hole one-particle proton configurations coupled to underlying excitations of the core. These calculations make it possible to obtain interesting physics insight through the constructive interference between collective and single-hole contributions. The current study compliments a number of recent Coulomb excitation measurements near ^{100}Sn and provides additional input on the neutron-proton interaction in nuclei in this mass region. The result suggests that the proton degree of freedom may be partly responsible for explaining the trend of $B(E2)$ values in the neutron-deficient Sn isotopes.

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