"Safe" Coulomb Excitation of ^{30}Mg

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We report on the first radioactive beam experiment performed at the recently commissioned REX-ISOLDE facility at CERN in conjunction with the highly efficient γ spectrometer MINIBALL. Using ^{30}Mg ions accelerated to an energy of 2.25 MeV/u together with a thin $^{\rm nat}$Ni target, Coulomb excitation of the first excited 2^+ states of the projectile and target nuclei well below the Coulomb barrier was observed. From the measured relative deexcitation γ-ray yields the $B(E2; 0^+_{\rm gs} \rightarrow 2^+_1)$ value of ^{30}Mg was determined to be $241(31)e^2$ fm^4. Our result is lower than values obtained at projectile fragmentation facilities using the intermediate-energy Coulomb excitation method, and confirms the theoretical conjecture that the neutron-rich magnesium isotope ^{30}Mg resides outside the "island of inversion."

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The surprising finding by Thibault *et al.* that the neutron-rich sodium isotopes ^{31}Na and ^{32}Na are more tightly bound than expected by *sd* shell model calculations [1], and its subsequent interpretation by Campi *et al.* [2], has stirred much interest in this region of the nuclear chart. These nuclei are now considered, together with the neutron-rich Ne and Mg isotopes, to belong to the so-called "island of inversion" [3], where strongly deformed intruder configurations involving neutron excitations across a melted $N = 20$ shell gap are dominating the ground state wave functions. However, despite considerable theoretical and experimental efforts, the question as to where in the $Z - N$ plane and how rapid the transition from normal to intruder-dominated configurations takes place is still uncertain; even the origin of the large collectivity of the $0^+_{\rm gs}$ to 2^+_1 transition in ^{32}Mg is still under debate [4].

A characteristic feature of isotopes that belong to the "island of inversion" is the presence of highly collective $E2$ transitions between the low lying states. The availability of beams of these exotic nuclei at projectile fragmentation facilities in the 1990s therefore prompted several of these laboratories to start programs to measure $B(E2; 0^+_{\rm gs} \rightarrow 2^+_1)$ values of even-even nuclei in this mass region using the method of intermediate-energy Coulomb excitation [5]. For the neutron-rich ^{30,32,34}Mg isotopes, for example, $B(E2)\uparrow$ values have been obtained by three groups working at RIKEN [5,6], MSU [7], and GANIL [8] (see also Fig. 2 below); however, their results are neither conclusive nor consistent. Differences between the data points for a given isotope are as large as a factor of 2 and do not allow the various theoretical model predictions [9–11] to be distinguished, nor can any firm conclusion be drawn from these data alone regarding the boundary of the "island of inversion."

In an attempt to clarify the experimental situation, with the long term goal to map the collectivity of nuclei in and around the "island of inversion," an experimental program was started to measure the $B(E2) \uparrow$ values with a standard model-independent technique, namely, "safe" Coulomb excitation in reversed kinematics, employing ISOL beams accelerated to energies well below the Coulomb barrier in conjunction with a high-resolution detector system. We report here on the first experiment performed with the isotope ^{30}Mg using the newly commissioned REX-ISOLDE accelerator [12], located at the ISOLDE facility [13] at CERN, together with the high-resolution γ detector array MINIBALL [14] and ancillary Si detectors [15].

The radioactive ^{30}Mg atoms [$t_{1/2} = 335(17)$ ms] were produced by sending 1.4 GeV protons, provided by the CERN PS Booster with a maximum intensity of 3.2×10^{13} p/pulse and a repetition time of typically 1.2 or 2.4 s, onto a uranium carbide or graphite target. The Mg atoms diffusing out of the target were selectively ionized in the Resonance Ionization Laser Ion Source [16], and the extracted 1^+ ions were mass separated by the ISOLDE General Purpose Separator [13].

The REX-ISOLDE accelerator [12], which employs novel techniques to accumulate, bunch, charge breed, and accelerate radioactive ions, was used to boost the energy of the ^{30}Mg ions to 2.25MeV/u. The 1^+ ions delivered by ISOLDE were first accumulated, cooled, and bunched in a Penning trap for up to 20 ms before they were transferred to an electron beam ion source (EBIS), where they were ionized within 12 ms to a charge state of 7^+. The highly charged ions were then extracted in ~50–100 μs long pulses, mass separated with a q/A resolution of 100, and finally injected into a linear accelerator consisting of a radio frequency quadrupole, an interdigital-H-type structure, and three seven-gap resonators. The cycle frequency for this process was 49 Hz. The average intensity of the ^{30}Mg^{7+} beam on the secondary target was about 2×10^4 s^{-1} with an efficiency of the REX accelerator (including trap and EBIS) of about 5%.

The ^{30}Mg ions were incident on a natural nickel foil of 1.0 mg/cm^2 located in the center of a small scattering chamber. Scattered projectiles and recoiling target nuclei were detected by a 500 μm thick, compact-disk-shaped double sided silicon strip detector (CD) [15], which is subdivided into four independent quadrants with 24 sector strips and 16 annular strips each. The detector covered forward angles between 16.4° and 53.3°. Scattered projectiles and recoiling target nuclei could be well separated via their different energies at a given laboratory angle.

The deexcitation γ rays following the Coulomb excitation of the projectile and target nuclei were detected with the MINIBALL array [14], consisting of eight triple cluster detectors, each combining three sixfold segmented HPGe detectors. By choosing a target-detector distance of only 9 cm, the cluster detectors covered laboratory angles from 30° to 85° and 95° to 150°, and an overall full-energy peak efficiency of about 7% at $E_\gamma = 1.3$ MeV (with cluster addback) could be achieved. The interaction point of each γ ray was determined by an online-onboard pulse shape analysis [17], resulting in an about 100-fold increase in granularity in comparison to an array of nonsegmented HPGe detectors. Together with the direction of the projectile or target nucleus measured in coincidence, it was therefore possible to correct for the large Doppler shifts of the γ rays, which are caused by the high velocities of the γ-emitting nuclei ($v/c \sim 5\%$).

The γ-ray energy spectra observed after 76 h of data taking in coincidence with projectiles in the CD detector are shown in Fig. 1, with the upper and lower panels displaying part of the Doppler-corrected spectrum assuming the γ emitting nucleus to be the projectile or the recoil, respectively. The prominent peak in the upper panel observed at an energy of 1482 keV corresponds to the transition from the first 2^+ state to the ground state of ^{30}Mg, while the two lines observed at 1454 and 1333 keV in the bottom spectrum result from the decay of the first excited 2^+ state in ^{58}Ni and ^{60}Ni, respectively. Note that Doppler-smeared contributions of the Ni lines in the upper spectrum were avoided by suppressing events contributing to the Ni lines in the lower spectrum, and vice versa. The influence of this procedure on the line intensities was carefully investigated and resulted only in small corrections to the deduced intensity values.

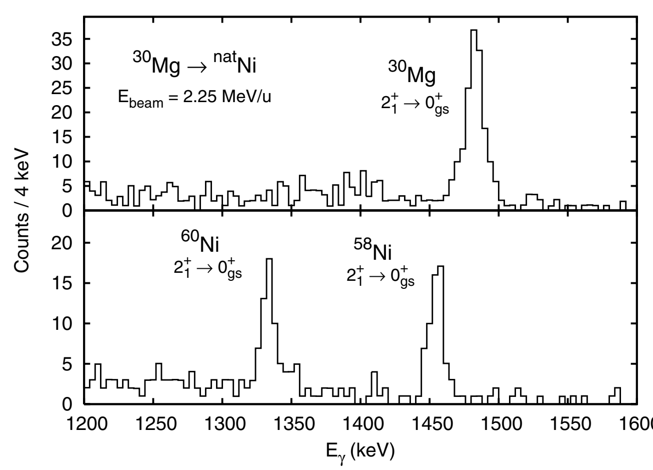

FIG. 1. Doppler-corrected γ-ray spectra observed in coincidence with projectiles in the CD detector. The upper panel shows the spectrum performing a Doppler correction relevant for γ emission from the detected projectile (without Ni-line contributions; see text), while the Doppler-corrected spectrum assuming γ emission from the corresponding recoiling target nucleus is displayed in the lower panel (without the Mg-line contributions; see text).

In order to fulfill the safe Coulomb excitation condition [18], i.e., to ensure that only the electromagnetic interaction is causing the excitation of the projectile and target nuclei, the analysis of the observed γ intensities in terms of $B(E2)\uparrow$ values was restricted to events observed in coincidence with forward scattered ^{30}Mg, for which the closest distance D_s between the surfaces of the projectile and target nucleus does not drop below 6 fm [18]. Because of the occurrence of both projectile and target excitation the Coulomb excitation cross section σ_{CE} to the first excited 2^+ state in ^{30}Mg can be deduced relative to that of ^{58,60}Ni from the measured γ-ray yields N_γ by

$$\frac{\sigma_{CE}(^{30}\mathrm{Mg})}{\sigma_{CE}(^{58,60}\mathrm{Ni})} = \frac{\epsilon_\gamma(^{58,60}\mathrm{Ni})}{\epsilon_\gamma(^{30}\mathrm{Mg})}\frac{W_\gamma(^{58,60}\mathrm{Ni})}{W_\gamma(^{30}\mathrm{Mg})}\frac{N_\gamma(^{30}\mathrm{Mg})}{N_\gamma(^{58,60}\mathrm{Ni})},$$

where ϵ_γ is the full-energy peak efficiency at the corresponding γ energy and W_γ the angular correlation factor for the respective transitions. The Coulomb excitation cross sections σ_{CE}, which are in first approximation proportional to the corresponding $B(E2)\uparrow$ value, as well as the angular correlation factors W_γ were calculated using a standard multiple Coulomb excitation code [19], taking into account the energy loss of the beam in the target and the angles subtended by the CD detector and the MINIBALL array. For the Ni isotopes known values for the $B(E2)\uparrow$ and quadrupole moments were used [20,21], while for Mg the $B(E2)\uparrow$ value was varied [assuming a $Q(2^+)$ moment as expected within the rotational model for a prolate deformed nucleus—the assumption of an oblate deformation would reduce the extracted $B(E2)\uparrow$ by 12%] until the experimental value was reproduced. The analysis was performed separately for the two nickel isotopes and the weighted average of the results was taken as the final value.

Even though the applied procedure is straightforward, a measurement with a stable ^{22}Ne beam of 2.25 MeV/u was performed for test purposes [22]; the deduced $B(E2)\uparrow$ of $243(27)e^2$ fm^4 was not only found to be in excellent agreement with the literature value [23] of $230(10)e^2$ fm^4, but it also confirmed our choice to neglect the recently published [24] $B(E2)\uparrow$ values for ^{58,60}Ni, which are in contradiction to all previous measurements [20,21].

In contrast to relative Coulomb excitation experiments with stable isotopes, however, in measurements with radioactive ions possible beam contaminations have to be carefully investigated. While contaminations with $A \neq 30$ can be excluded in the present study due to the q/A selection of the REX separator and the measurement of the total projectile energy in the CD detector, there are, in principle, three sources for isobaric contaminations: β decay products of ^{30}Mg collected during trapping and charge breeding, isobaric contaminants directly released from and ionized at the primary ISOLDE target, and residual gas contaminations produced in the EBIS source. The first contribution, which is inherent to our technique, can be estimated from the trapping and breeding time, which ranged from 12 to 32 ms depending on the time the ^{30}Mg ion entered the trap; based on the known lifetime of ^{30}Mg of 483(25) ms a ^{30}Al contamination of the beam of 4.5(0.5)% is calculated. Possible isobaric beam contributions from the second source, which are expected to mainly consist of ^{30}Al as other isobars have negligible yields, and from the EBIS residual gas were investigated by the following means: (i) A LASER-on/off measurement was performed. (ii) The time dependence of the incident beam intensity with respect to the proton pulse impact on the ISOLDE target (T1) was analyzed; the ^{30}Mg ions show a high intensity only for short times after the proton impact due to their fast release and short lifetime. (iii) The time dependence of the γ yields for ^{30}Mg and ^{58,60}Ni with respect to T1 was studied. (iv) The Coulomb excitation of the first excited state in ^{30}Al at 244 keV was searched for. (v) The γ intensities due to the β decay of ^{30}Mg and ^{30}Al collected in the target chamber were analyzed. The various investigations resulted in a consistent picture for the purity of the beam, in that the only noticeable contamination is ^{30}Al. The combined analysis yielded a total ^{30}Al contribution of 6.5(1.0)% to the ^{30}Mg beam within the window of $t - t_{T1} \leq 1.2$ s, which was applied when extracting the γ intensities. This contribution leads to corrections of the measured γ intensities of the Ni transitions of $-5.0(1.0)$%.

Including the correction due to the ^{30}Al beam impurity, a $B(E2; 0^+_{gs} \rightarrow 2^+_1)$ value of $241(31)e^2$ fm^4 was determined for ^{30}Mg. The quoted one σ error is dominated by the statistical error, but also includes those caused by the $E2$ matrix elements adopted for ^{58,60}Ni, by the assumed $Q(2^+)$ value for ^{30}Mg and possible excitations to higher lying states, and takes care of uncertainties in the correlation functions W_γ caused by possible deorientation effects [22].

The present $B(E2)\uparrow$ value for ^{30}Mg of $241(31)e^2$ fm^4 has to be compared to the results obtained at MSU and at GANIL using the method of intermediate-energy Coulomb excitation, which resulted in values of $295(26)e^2$ fm^4 [7] and $435(58)e^2$ fm^4 [8], respectively (see also Fig. 2). While the MSU value is about 20% larger but still consistent within errors with the present value, the GANIL result exceeds our value by 80%. The origin of the discrepancy is unclear.

In searching for possible sources for these deviations, it should be noted that in intermediate-energy measurements at beam energies around 30–50 MeV/u several effects can influence the deduced $B(E2)\uparrow$ values such as feeding from higher lying states and Coulomb-nuclear interference, which have to be corrected for. While the adiabatic cutoff limits the single-step excitation energy to values below 1–2 MeV in sub-barrier experiments, as presented here, in measurements with intermediate-energy beams 2^+ (or even 1^-) states up to 5–10 MeV excitation energy can be populated [25], which may feed the first 2^+ state. Unless

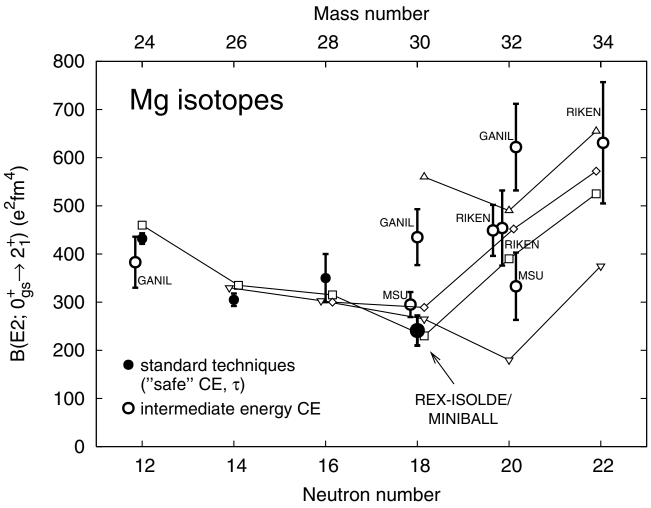

FIG. 2. Experimental (open and filled circles) and theoretical $B(E2)\uparrow$ values (connected by thin lines to guide the eye) for the even Mg isotopes. The experimental data are from Refs. [5–8,23] and the present experiment; the theoretical values are from □ [11], ◇ [9], ▽ [10,26] (normal), △ [10] (intruder).

these feedings are taken into account, they will likely result in increased $B(E2)\uparrow$ values. Based on the apparent absence of feeding transitions in their γ spectra, no feeding correction was applied to the MSU value [7], while a 15% correction deduced from model calculations including Coulomb-nuclear interferences was applied to the GANIL value [8]. However, while feeding and interference effects may account for the slightly larger MSU value as compared to the present one, it is questionable if uncertainties in their estimate can be the cause for the large $B(E2)\uparrow$ value measured at GANIL. The present result, on the other hand, which is based on the well established technique of Coulomb excitation with beam energies well below the Coulomb barrier, is safe with regard to nuclear interference effects and is barely influenced by real or virtual excitations of higher lying states; moreover, because of the relative measurement of projectile to target excitation it is rather insensitive to systematic experimental uncertainties.

Our present experimental knowledge of the $B(E2)\uparrow$ values for the even Mg isotopes with $N \geq 12$ is displayed in Fig. 2 together with theoretical predictions obtained within three different model approaches [9–11], chosen representatively from a large number of recent publications (see [4] and references therein). It is obvious that precise values are needed to judge the quality and predictive power of these calculations. In particular, the results by Caurier *et al.* [10] are interesting as they give the $B(E2)\uparrow$ values separately for the pure "intruder" and "normal" configurations, i.e., with and without excitations across the $sd-pf$-shell boundary, respectively, since their calculation did not allow the determination of the amount of mixing between these two configurations. Our result provides clear evidence that the lowest 0^+ and 2^+ states of the $N = 18$ isotope ^{30}Mg can still be well described within the sd shell, in agreement with most theoretical predictions.

In summary, we have presented the result of the first Coulomb excitation experiment performed with the newly commissioned REX accelerator and the MINIBALL array, which shows the strength of this novel facility for the study of nuclei far from stability by well established, yet adapted, nuclear physics techniques. The $B(E2; 0^+_{gs} \rightarrow 2^+_1)$ of ^{30}Mg was measured to be $241(31)e^2$ fm^4 (8.7 W.u. for the corresponding $2^+_1 \rightarrow 0^+_{gs}$ transition), which is lower than those extracted in previous measurements performed at intermediate energies. It supports the theoretical conjecture that ^{30}Mg is still located outside the "island of inversion." In the near future it is planned to extend these studies to other even-even isotopes in this mass region, in particular, to ^{32}Mg, where only conflicting results from intermediate-energy Coulomb excitation experiments are available so far, which do not allow one to distinguish between the various theoretical predictions.

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