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Coulomb excitation of re-accelerated ^{208}Rn and ^{206}Po beams

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Abstract. In the present study, $B(E2; 2^+ \to 0^+)$ values have been measured in the ^{208}Rn and ^{206}Po nuclei through Coulomb excitation of re-accelerated radioactive beams in inverse kinematics at CERN-ISOLDE. The resulting $B(E2; 2^+ \to 0^+)$ in ^{208}Rn is $\sim 0.08\ e^2$b^2. These nuclei lie in, or at the boundary of the region where seniority scheme should persist. However, contributions from collective excitations may be present when moving away from the $N = 126$ shell closure. To date, surprisingly little is known of the transition probabilities between the low-spin states in this region.

1 Introduction

Reduced transition probabilities, $B(E2)$ values, give particularly precise information of the collectivity and its development in atomic nuclei as a function of N and Z. Furthermore, with sophisticated nuclear models, information of the underlying microscopic single particle and collective structures can be gained through the knowledge of the $B(E2)$ values.

In Ref. [1] evolution of the $B(E2)$ values in the context of seniority and collectivity has been discussed. When nuclear structure is dominated by a relative high-j single-particle orbital (with $j \geq 7/2$), seniority ν can be regarded as a good quantum number. In such cases the usual increasing trend of the $B(E2)$ values within a band can be reversed. This is due to the fact that the $2^+ \to 0^+$ transition is a seniority changing transition ($\Delta\nu \neq 0$), whereas the transitions with $2 < I_i < 2j-1$ conserve the seniority ($\Delta\nu = 0$). When a high-j orbital is only fractionally filled, transitions with $\Delta\nu \neq 0$ can have larger $B(E2)$ values than those for $\Delta\nu = 0$ transitions. Such behaviour is illustrated later in Fig. 6, where the predictions of the seniority scheme are plotted . The seniority changing $\Delta\nu = 2$ $2^+ \to 0^+$ transition shows parabolic upward behaviour across the sub-shell, similar to that from collective models. The $B(E2; 2^+ \to 0^+)$ value is maximised at mid-j shell. Seniority-conserving $\Delta\nu = 0$ transitions such as the $8^+ \to 6^+$ transition, however, show contrasting parabolic downward behaviour crossing zero at the mid-j shell.

In Fig. 1 the level energy systematics for the $N = 122$ isotones are illustrated. The level pattern develops from a well pronounced seniority $\nu = 2$ level structure of the 2^+ and 4^+ states in ^{204}Pb into a more evenly spaced levels when approaching ^{210}Rn. The isomeric nature of the $I^\pi = 8^+$ states is characterised by the low energy of the $8^+ \to 6^+$ transition. As discussed in Ref. [3], the low-spin states in the $N = 122$ isotones may arise from the coupling of the two protons in the $h_{9/2}$ orbital. On the other hand in Ref. [4], shell-model calculations with empirical one- and two-body interactions have been carried for ^{208}Rn. The calculations predict that the 8^+ state would be a pure $\nu = 2$ proton $h_{9/2}$ state, which is consistent with the

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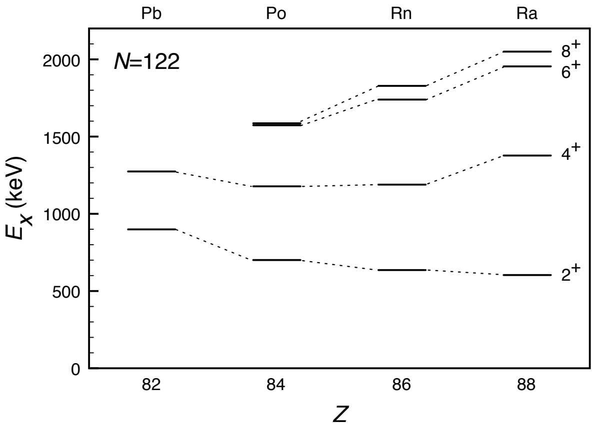

Figure 1. Partial level-energy systematics of the trans-Pb $N = 122$ isotones. The data are extracted from Refs. [2, 3]

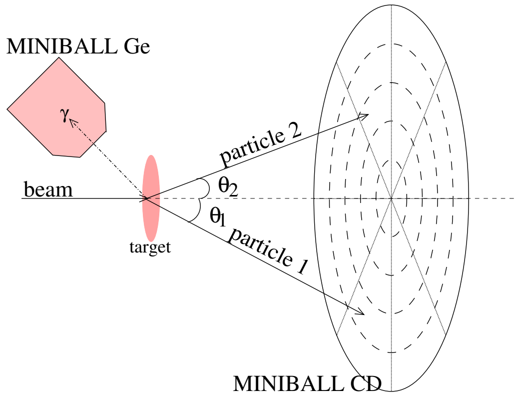

Figure 2. Principle of the Coulomb excitation measurements at MINIBALL. The re-accelerated beam impinges onto a target, in which both beam and target nuclei are Coulomb excited and recoil out of the target. The CD detector records the position (angular) and energy information. Coincident γ rays are recorded with the MINIBALL Ge detectors.

outcome of Ref. [3]. The calculations also predict rather low-lying non-yrast $\nu = 2$ proton multiplet (see Fig. 10 of Ref. [4]). For the 2^+ state the predictions of the two frameworks are controversial. While according to the seniority scheme the 2^+ state should be the similar $\nu = 2$ proton $h_{9/2}$ state as the 8^+ state, the shell-model calculations predict it to be a neutron-hole state. The proton-neutron interaction in this region should not be strong due to the large Δn and $\Delta \ell$ between the available proton and neutron orbitals [5]. Therefore, a possible increase in the $B(E2)$ values is likely to be manifested by the increasing valence proton space and indicate the $\nu = 2$ proton structure.

In the $N = 122$ isotones with $Z \geq 82$, just four neutrons removed from the $N = 126$ shell closure, behaviour of the $B(E2)$ values resembling the seniority scheme predictions has been observed [3]. These nuclei lie at the boundary of the region where seniority scheme should persist [1]. Therefore, the knowledge of the $B(E2; 2^+ \to 0^+)$ values for the ^{206}Po and ^{208}Rn nuclei, respectively, provide important benchmarks for the validity of the models and for the interplay of the seniority regime and collective motion around the $N = 126$ and $Z = 82$ shell closures. In order to address this issue we have carried out measurements of the $B(E2; 0^+ \to 2^+)$ values in ^{206}Po and ^{208}Rn nuclei at the REX-ISOLDE facility [6] at CERN.

2 Experiments

The ^{206}Po and ^{208}Rn nuclei of interest were produced by bombarding uranium carbide ISOLDE primary targets with 1.4 GeV protons delivered by CERN PS-Booster. Polonium atoms were ionised using the RILIS laser ion source [7] and mass selected with the ISOLDE High Resolution Separator (HRS). Radon as a noble gas was ionised with the VADIS ion source [8] with cooled Ta transfer line and subsequently mass selected with the ISOLDE General Purpose Separator (GPS). Both ^{206}Po and ^{208}Rn nuclei were injected into the REX-ISOLDE re-accelerator complex consisting of the REX-TRAP penning trap, the REX-EBIS charge breeder and the REX linear accelerator. REX-TRAP was used to cool, bunch and purify the beam while REX-EBIS matched the mass to charge ratio suitable to be for re-acceleration. REX delivered 2.85 MeV/u and 2.82 MeV/u ^{206}Po and ^{208}Rn beams, respectively to the target position of the MINIBALL γ-ray spectrometer [9]. The ^{206}Po beam was in fact extracted without the proton irradiation as the half-life of ^{206}Po is 8.8 days. Therefore sufficient yield for the present experiment was extracted from the ^{206}Po activity accumulated during the previous irradiations of the primary target.

The radioactive beams of ^{206}Po and ^{208}Rn were delivered to the MINIBALL target position and Coulomb excited using the secondary 2 mg/cm^2 thick ^{104}Pd and ^{116}Cd targets, respectively. The target was chosen so that the excitation energy of the first 2^+ state is lower than the corresponding energies in the nuclei of interest in order to minimise the γ-ray background arising from Compton scattering. The MINIBALL Ge-detector array, with a photopeak efficiency of 7 % for 1.3 MeV γ rays, detected γ rays de-exciting the levels under investigation. Both scattered projectiles and target recoils were detected using a double-sided silicon strip detector (CD) with 16 annular strips positioned downstream of the secondary target. The principle of the Coulomb excitation measurement is illustrated in Fig. 2. Both beams were found to be $\approx 100\%$ pure by measuring the γ-ray spectra with the RILIS laser set off (^{206}Po), and by measuring the beam composition using the ionisation chamber located upstream of the secondary target (^{208}Rn).

Coulomb excitation event for both the beam and target nuclei can be identified based on the reaction kinematics. Fig. 3 shows the spectrum of particle annular position and deposited energy recorded with the CD detector. The γ rays were recorded in coincidence with one-particle events observed in CD. As the reactions kinematics can be reconstructed from the angular and energy information of the events recorded with CD, event-by-event Doppler

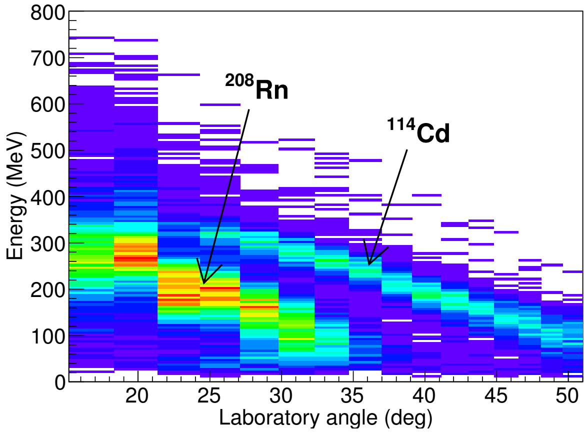

Figure 3. Kinematics of the Coulomb excitation of the ^{208}Rn beam impinging onto the ^{114}Cd target recorded with the CD detector.

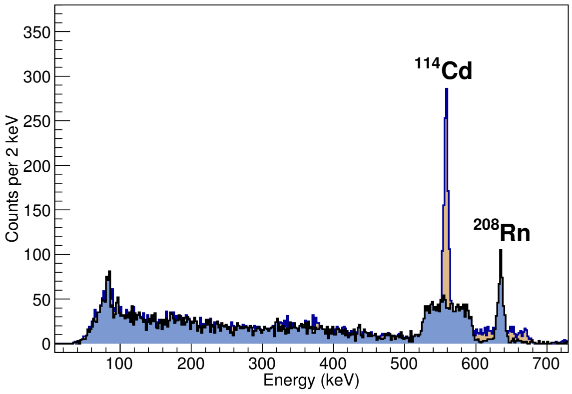

Figure 4. Doppler-corrected, background subtracted γ-ray spectrum recorded in coincidence with a target-nucleus event in the CD detector. Doppler correction is applied for projectile (^{208}Rn, blue and target (^{114}Cd, brown) excitations.

correction for the γ rays can be applied. A sample γ-ray spectrum is shown in Fig. 4.

The Coulomb excitation analysis was carried out with the Gosia2 code, in which the simultaneous χ^2 minimisation of the measured and calculated projectile and target γ-ray yields of the $2^+ \rightarrow 0^+$ transition was carried out. With such a minimisation procedure one can extract matrix element of the $2^+ \rightarrow 0^+$ transitions in ^{206}Po and ^{208}Rn. In certain cases Coulomb excitation measurement is sensitive to the quadrupole moment, which is a second-order effect emanating from the interactions between the magnetic sub-states of a given state. However, in the present study that is not the case as no other second order effect, such as the $4^+ \rightarrow 2^+$ transition was seen. Therefore, in the present analysis the diagonal matrix element of the 2^+ state, $\langle 2^+ || \hat{E}2 || 2^+ \rangle$, which is proportional to the spectroscopic quadrupole moment Q_s, was set to zero. In order to cross check that assumption, the Gosia2 analysis was carried out is cases with $\langle 2^+ || \hat{E}2 || 2^+ \rangle$ set to constant values of ± 1, ± 0.5 and 0 eb. The results are shown in Fig. 5, which demonstrates that $\langle 2^+ || \hat{E}2 || 0^+ \rangle$ is only marginally sensitive to the diagonal matrix element in the present study. The variation of the χ^2 minima falls within the statistical uncertainties of the $B(E2)$ value.

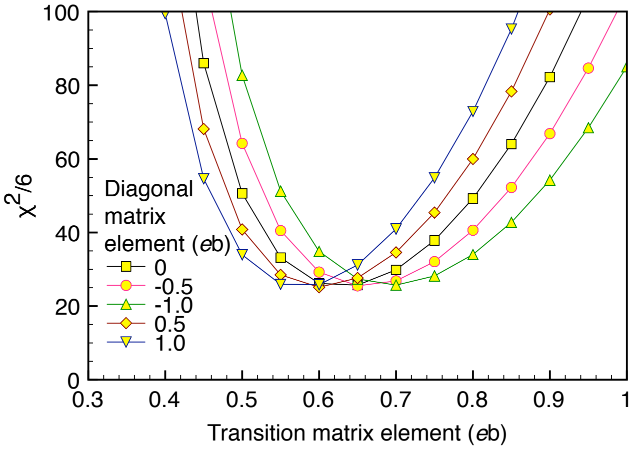

Figure 5. Locations of the χ^2 minima on the transition matrix element axis with different values of the diagonal matrix element.

The theoretical $B(E2)$ values predicted by the seniority scheme for the $N = 122$ isotones against the fractional filling $f = n/(2j+1)$, where n denotes the number of particles in the sub-shell j, are plotted in Fig. 6 as a function of fractional filling f of the $1h_{9/2}$ proton orbital. The preliminary $B(E2; 2^+ \rightarrow 0^+)$ values for ^{206}Po and ^{208}Rn together with the previously known data for the $8^+ \rightarrow 6^+$ transitions are also shown in Fig. 6. The predictions of the seniority scheme reproduce the experimental data for the $\Delta v = 0$, $8^+ \rightarrow 6^+$ transitions as the $B(E2)$ values minimise at $f \approx 0.5$. With the new data for the supposed $f = 0.2, 0.4$ nuclei the upward parabolic trend can be seen. The predictions of the simple model such as seniority scheme should be treated with caution as the structure of the 2^+ states in $N = 122$ isotones are likely to be more complex. This may be inferred from the results in Ref. [4], in which neutron structure is predicted for the yrast 2^+ state in ^{208}Rn, while the proton 2^+ state is predicted to be non-yrast. In Ref. [10] the level-energy systematics are discussed and based on that the 2^+ state is deduced to have similar neutron-hole structure as those in Pb nuclei. Furthermore, based on the interacting boson approximation the 2^+ state is discussed to be a collective state consisting of admixture of proton and neutron components.

We have measured the preliminary $B(E2; 2^+ \rightarrow 0^+)$ values in ^{206}Po and ^{208}Rn and addressed the nature of these states in nuclei which lie at the boundary of seniority regime and collective motion. The data have been collected also for ^{210}Rn, however no preliminary value is available at the moment. These data points will provide important benchmarks of the transition probabilities in this region. While the data is reproduced by the seniority scheme rather well no clear conclusions can be drawn yet, It would also be beneficial to measure $B(E2; 4^+ \rightarrow 2^+)$

values, however those are beyond the energy of the current re-accelerator REX but may become available in the advent of HIE-ISOLDE.

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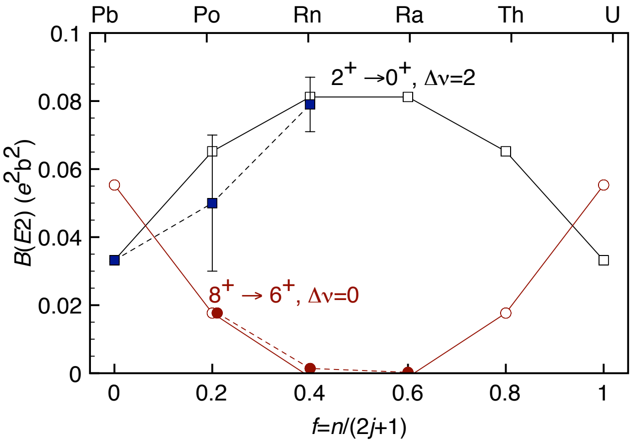

Figure 6. Calculated (open symbols) and experimental (filled symbols) $B(E2)$ values as a function of fractional filling f of the $\pi h_{9/2}$ orbital for the $\Delta\nu = 2$ $2^+ \rightarrow 0^+$ (black squares) and $\Delta\nu = 0$ $8^+ \rightarrow 6^+$ (red circles) transitions in the $N = 122$ isotones. The calculated values are obtained within the seniority scheme (for equations, see e.g. Ref. [1]) and have been normalised to the experimental values of ^{204}Pb ($\Delta\nu = 2$ transitions) and ^{206}Po ($\Delta\nu = 0$ transitions). The experimental $B(E2)$ values have been extracted from the present work and from Refs. [2, 3].