Structure of unstable nuclei from nuclear moments and $\beta$ decays

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Abstract. The structure of neutron-rich nuclei around the $N=20$ magic number is studied through the measurements of static electromagnetic moments. Recent data on the magnetic dipole moments and electric quadrupole moments for neutron-rich Al isotopes are discussed to clarify whether the emergence of a strong deformation reported for $Z=10$–12 nuclei in this region might happen also in these $Z=13$ nuclei. Possibility to study the nuclear structure via the $\beta$ transition matrix elements is also discussed.

1. Introduction

In what form a quantum system of nucleons with an unusual proton/neutron composition ratio exists, is one of the fundamental questions in contemporary nuclear physics. Recently, there have been a number of interesting phenomena found experimentally or predicted theoretically to occur. Formation of a halo structure in nuclei along the neutron/proton driplines, quantum correlation implemented in the dynamics of weakly bound nucleons, erosion of traditionally known magic numbers, and possible decoupling between the neutron and proton collectivities would be examples of them [1, 2, 3]. Experimentally, such studies have been largely facilitated by the powerful production method based on the radioactive ion (RI) beams technique. Taking advantage of the extended region of accessible nuclei, one could pursue systematic measurements e.g., for nuclei in a range of $N$ with a fixed $Z$. In such a case $N$, or the ratio $N/Z$, may serve as a control parameter over which one looks for a change in some observable, or a “phase transition”. In this report we present data recently obtained for the electromagnetic moments in the ground state of neutron-rich Al isotopes, and discuss their implication in the study of structure in neutron-rich nuclei. The possibility of using $\beta$ decay observables for the nuclear structure study is also discussed.

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2. Electromagnetic moments

Suppose that a new region of nuclides in the nuclear chart has become accessible to experimenters. The first experimental information that we obtain for a nucleus of the region would be the existence/nonexistence (or, positiveness/negativeness of the binding energy) of the nucleus. If it exists, one would proceed to the measurement of the nuclear mass to know more quantitatively about the binding energy, or the interaction cross section to discuss the radius of the matter distribution. These data already offer quite important information that might reveal, e.g., change in the shell structure or formation of a halo, and provide tests for models of nuclear structure. If the production yield for the objective nucleus is sufficiently high and the appropriate experimental techniques applicable, the next step would be the spectroscopic studies such as spin-parity determination and the measurement of the first $2^+$ level energy, $B(E2)$ and static electromagnetic moments. The magnetic dipole moment $\mu$ provides information on the single-particle orbits that the valence nucleons occupy, while the electric quadrupole moment $Q$ is sensitive to the collective aspects of nuclear structure. Recent analysis for neutron-rich Na isotopes [4] has demonstrated that the nuclear moments are sensitive indicators for a fundamental change in nuclear structure. The observed $\mu$ starts to exhibit a significant discrepancy from the USD model prediction at $N = 19$. Moreover, the experimental $Q$ starts to deviate from the USD model even earlier, at $N = 18$. In order to clarify whether the island of inversion extends to $Z = 13$ in the $N = 19$ isotones, we have carried out the measurement of $Q$ for $^{32}\text{Al}$, as well as the $\mu$ measurement which we reported previously [5].

2.1. Experimental method

A beam of $^{32}\text{Al}$ produced from the fragmentation of 95 MeV/u $^{40}\text{Ar}$ projectiles on a Nb target was used. To obtain spin-polarized $^{32}\text{Al}$ nuclei [6], the emission angles $\theta = 1.3^\circ - 5.7^\circ$ and momenta within $\delta p/p_c = \pm 3\%$ from the peak momentum $p_c = 12.6$ GeV/c were selected. The beam was implanted in a single crystal $\alpha$-$\text{Al}_2\text{O}_3$ stopper to which a static magnetic field $B_0$.

![Figure 1. Schematic layout of the $\beta$-NMR experiment using a spin-polarized radioactive beam at the fragment separator RIPS.](image-url)
was applied. The stopper was kept around 80 K to avoid the spin-lattice relaxation in the stopper. The experimental setup used is shown in Fig. 1. An Al atom implanted in α-Al2O3 is expected to stop at the substitutional site of Al where an electric field gradient eq is exerted, and thus the quadrupole moment Q of 32Al is deduced from the the quadrupole coupling constant νQ = e2qQ/h measured in the β-NMR experiment. Here h and e denote the Planck’s constant and the electric charge, respectively.

The angular distribution of β-rays emitted from the polarized nuclei is given as W(θ) = 1 + 2AβP cos θ where P and Aβ denote the degree of polarization and the β-ray asymmetry parameter, respectively. θ is the angle of the β-ray emission. v and c are the β-ray velocity and the speed of light, respectively, and we approximate as v/c ≈ 1. In the β-NMR technique, the resonance is detected as a change in the asymmetry in W(θ). In Fig. 2, the up/down ratio R = W(0°)/W(180°) of the β-ray counts are plotted as a function of νQ. From thus obtained β-NMR spectrum the quadrupole moment Q of 32Al is determined as |Q(32Al)| = 24 ± 3 mb.

Figure 2. The β-NMR spectrum obtained for determination of the electric quadrupole moment Q of 32Al.

2.2. Results

The emergence of deformation at around N = 20 in neutron-rich Na isotopes was first suggested from the mass and magnetic moment measurements [7]. Experimental studies since then for the first excited-state energies [8], B(E2) values [9], electric quadrupole moments [10] and magnetic moments [11] have provided evidences that the deformed ground states are indeed realized in 30Ne, 31,32Na and 31,32,34Mg. Theoretical works [12, 4] have been done in order to explain these remarkable phenomena, in which the deformation is considered to set in when the extent of intrusion of the f-orbit from the upper shell into the sd-shell reaches some critical level (such a region of nuclei where this happens is called the “island of inversion”). The extent of intrusion is considered to vary gradually as the ratio N/Z increases, based on the notion that the shell gap for neutron at N = 20 varies with varying number of particles in the proton orbits [13]. The N = 19 nuclei 30Na and 31Mg, although within the island of inversion, are considered to locate somewhat close to the critical point. Thus 32Al, being a nucleus after the ”inverted” nuclei 30Na and 31Mg in a N = 19 isotonic chain, should represent an important testing site for models to describe mechanism of inversion.
In Fig. 3 the present $Q$ moment result for $^{32}$Al, together with the previous $\mu$ data for $^{30,32}$Al and $Q$ and $\mu$ of the other isotopes from literature, is compared with the USD model [14] calculations using the shell-model code OXBASH [15]. (In these calculations the neutron and proton effective charges $e_n = 0.5$ and $e_p = 1.3$ are tentatively employed. The possibility of using smaller values will be discussed elsewhere.) The agreements in both the $Q$ and $\mu$ moments are quite reasonable, indicating that $^{32}$Al should be spherical and the border of the island of inversion is considered to run between $Z = 12$ and 13 for the $N = 19$ isotones.

The conclusion that the $N = 20$ shell gap persists for $^{32}$Al may be further confirmed by investigating the experimental level schemes of $^{30}$Al and $^{32}$Al: In an $sd$ space model the two nuclei $^{30}$Al and $^{32}$Al are described by a hole in the proton $d_{5/2}$ orbit and a particle or a hole in the neutron $d_{3/2}$ orbit, and moreover, the two are connected to each other by the particle-hole replacement. In such a case there is a relation [16] between the level spacings in the two nuclei, as expressed by

$$\Delta E(j_p^{-1} j_n^{-1}; JM) = - \sum_{J'} (2J' + 1) \begin{pmatrix} J_p & j_p & j_n \\ J & j & J' \end{pmatrix} \Delta E(j_p^{-1} j_n^{-1}; J' M),$$

where $\Delta E(\alpha; JM)$ is the energy difference between states $J$ of the configuration $\alpha$. Since the energy spectrum of $^{30}$Al is known, one may deduce from this relation the energy spectrum for $^{32}$Al. As presented in Fig. 4, the transformed level energies from the $^{30}$Al experimental spectrum [17] through the above relation reproduce well the spacings of the observed $^{32}$Al spectrum [18], as well as their ordering.

### 3. $\beta$ Decays

Prospecting that nuclei in the newly accessible region might exhibit richer structures than known from the presently available observables, the $\beta$ decays would be of interest. In addition to the Fermi and Gamow-Teller transitions, the unique (or nearly unique) forbidden transitions might provide useful information in studying nuclear structure. Figure 5 represents what types of information the unique first-forbidden $0^+ \leftrightarrow 2^-$ and nearly unique second-forbidden $0^+ \leftrightarrow 2^+$
Figure 4. Level schemes for $^{32}$Al inferred (middle) from the observed level scheme for $^{30}$Al (left) via the Pandya transformation assuming that the two nuclei are well described by an $sd$ model, and the experimental level schemes for $^{32}$Al (right).

$\beta$ transition could provide. Also, it is illustrated that the $\beta$-neutrino directional correlation measurements could be used to separate one of the three $0^+ \leftrightarrow 2^+$ second-forbidden nuclear matrix element from the other two. Note that in neutron-rich nuclei with $N$ far different from $Z$ the $\beta$ transition takes place mostly between single-particle orbits with different angular momenta and parities, and consequently the forbidden transitions tend to share non-negligible part of decay branches. In order to facilitate such measurements a setup as shown schematically in Fig. 6 might be used.

4. Summary
The study of structure of neutron-rich nuclei around the traditional magic number $N=20$ was made through the measurements of static electromagnetic moments using spin-polarized

Figure 5. Nuclear matrix elements responsible for the unique first-forbidden ($0^+ \leftrightarrow 2^-$) and (neally unique) second-forbidden ($0^+ \leftrightarrow 2^+$) $\beta$-transitions, and the directional correlation between the $\beta$ and neutrino emission expected for cases of the second-forbidden transitions.
Figure 6. A proposed experimental scheme to single out one of the three $0^+ \leftrightarrow 2^+$ second-forbidden nuclear matrix element, through the $\beta$-neutrino directional correlation.

radioactive ion beams with the $\beta$-NMR technique. Newly obtained data for the electric quadrupole moments, as well as the previously reported magnetic moments for neutron-rich Al isotopes are compared with shell-model calculations. It is found that the $^{32}$Al nucleus should be spherical and hence the border of the island of inversion runs between $Z = 12$ and 13 for the $N = 19$ isotones. Finally, the possibility to study the nuclear structure via the $\beta$ decay is also discussed. It is pointed out that the forbidden $\beta$ transition measurements with $\beta$-neutrino correlation detection might be a useful tool for studying nuclear structure.

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