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Hindered Proton Collectivity in the Proton-rich Nucleus ^{28}S: Possible Magic Number $Z = 16$

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Abstract. The reduced transition probability $B(E2;0^+_{gs} \to 2^+_1)$ for the proton-rich nucleus ^{28}S was determined experimentally using intermediate-energy Coulomb excitation. The resultant $B(E2)$ value 181(31) e^2fm^4 is smaller than those of neighboring $N = 12$ isotones and $Z = 16$ isotopes. The double ratio $|M_n/M_p|/(N/Z)$ of the $0^+_{gs} \to 2^+_1$ transition in ^{28}S was obtained to be 1.9(2) by evaluating the M_n value from the known $B(E2)$ value of the mirror nucleus ^{28}Mg, showing the hindrance of proton collectivity relative to that of neutrons. These results indicate the emergence of the magic number $Z = 16$ in ^{28}S.

Keywords: Multipole matrix elements, Reaction induced by unstable nuclei, Coulomb excitation
PACS: 23.20.Js, 25.60.-t, 25.70.De

INTRODUCTION

Nuclear magic numbers characterize the shell structure of nuclei. Recent studies report change of the magic numbers at the very neutron-rich region [1, 2, 3]. These phenomena are associated with nuclear collectivity, for instance, the enhanced collectivity in ^{32}Mg caused by the disappearance of magicity at $N = 20$ [4].

The new neutron magic number $N = 16$ has been shown experimentally at around the neutron drip-line nucleus ^{24}O [3]. In analogy to the magic number $N = 16$, the proton magic number $Z = 16$ must also exist in proton-rich nuclei. However, it has not been

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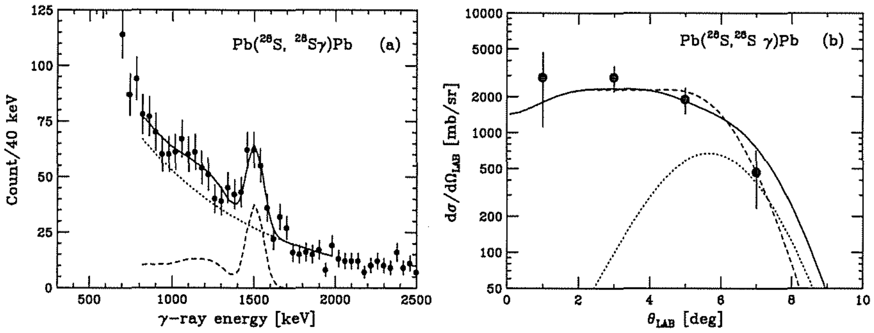

FIGURE 1. (a) Doppler-shift corrected γ-ray energy-spectrum in the Pb(^{28}S,^{28}S γ)Pb reaction. (b) Angular distribution for the scattered ^{28}S particles which were coincident with the 1.5 MeV γ-line.

identified experimentally in the proton-rich sulfur isotopes.

The relative contribution of the proton- and neutron-collectivities can be evaluated using the ratio of the neutron transition matrix element to the proton one (the M_n/M_p ratio) [5, 6]. M_p is related to $B(E2)$ by $e^2M_p^2 = B(\mathrm{E2}; 0^+_{gs} \to 2^+_1)$. The M_n value can be deduced from the M_p value in the mirror nucleus by assuming the isospin symmetry. Deviation from $|M_n/M_p|/(N/Z) = 1$ corresponds to hindrance of proton/neutron collectivity. Such a difference appears typically for the singly-magic nuclei [5, 7]. For proton singly-magic nuclei, the proton collectivity is hindered by the magicity, leading to $|M_n/M_p|/(N/Z) > 1$.

The present article reports on a study of the magic number $Z = 16$ at the ^{28}S through a measurement of the reduced transition probability $B(E2; 0^+_{gs} \to 2^+_1)$ by using intermediate-energy Coulomb excitation.

EXPERIMENT

The experiment was performed using RIBF at RIKEN Nishina Center. A ^{28}S beam was produced via projectile fragmentation of a 115-MeV/nucleon ^{36}Ar beam incident on a Be target. The secondary beam was obtained by the RIKEN Projectile-fragment separator (RIPS) and a RF deflector system. Particle identification for the secondary beam was performed event-by-event by measuring time of flight, energy loss, and the magnetic rigidity of each nucleus. The secondary target was a 348 mg/cm^2-thick lead sheet which was set at the third focal plane. The average beam energy at the center of the lead target was 53 MeV/nucleon. Three sets of PPACs were place at upstream of the secondary target to obtain the beam trajectory on the secondary target. An array of 160 NaI(Tl) scintillator crystals, DALI2, was placed around the target to measure de-excitation γ rays from ejectiles. The scattering angle, energy loss, and total energy of the ejectiles from the lead target were obtained by a detector telescope located 62 cm downstream of the target. Detail of the experimental setup can be found in ref. [8].

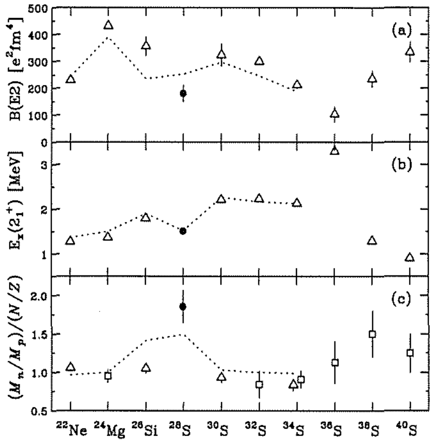

FIGURE 2. Plot of the $B(E2;0^+_{gs} \to 2^+_1)$ values (a), the excitation energies of 2^+_1 states (b), and the double ratio $|M_n/M_p|/(N/Z)$ (c) for $N = 12$ isotones and sulfur ($Z = 16$) isotopes. The present result is represented by the filled circles.

RESULTS AND DISCUSSIONS

The Doppler-shift corrected γ-ray energy-spectrum measured in coincidence with inelastically scattered ^{28}S is shown in Fig. 1(a). A peak is clearly seen at 1.5 MeV. The spectrum was fitted by a detector response obtained by the Monte-Carlo simulation (dashed curve) and an exponential background (dotted curve). The peak energy was obtained to be 1.497(11) MeV, which was consistent with 2^+ state energy in the previous measurement [9]. The angular distribution of the scattered ^{28}S excited to its 1.5 MeV state is shown in Fig. 1(b). The distribution was fitted by that for an angular momentum transfer of $\Delta L = 2$, calculated by DWBA code ECIS97 [10] taking into account the detector resolutions. As seen in the figure, the $\Delta L = 2$ distribution well reproduced the experimental one. The optical potential parameters were taken from ref. [11]. The dashed and dotted curves in Fig. 1(b) shows the Coulomb and nuclear contributions, respectively. The $B(E2;0^+_{gs} \to 2^+_1)$ value was determined to be 181(31) e^2fm^4 from this analysis. The associated error included the uncertainty of the measured cross section and the systematic error due to the choice of optical potentials.

The $B(E2)$ and $E_x(2^+_1)$ values for $N = 12$ isotones and $Z = 16$ isotopes are plotted in Fig. 2(a) and (b), respectively. The filled circles show the present results. The open triangles for $B(E2)$ and $E_x(2^+_1)$ represent known values [12]. The $B(E2)$ value of ^{28}S is smaller than those of neighboring isotones and isotopes. An explanation of these smaller $B(E2)$ and $E_x(2^+_1)$ at ^{28}S is given by the hindered proton collectivity. A similar mechanism is proposed for ^{16}C [13, 14] where small $B(E2)$ and $E_x(2^+_1)$ values in comparison with neighboring isotopes are observed.

Figure 2(c) shows the double ratios $|M_n/M_p|/(N/Z)$. The filled circle and open triangles show the present result and the known values, respectively. They are obtained by the $B(E2)$ values of the mirror pairs. The open squares represent the double ratios obtained by the combinations of $B(E2)$ and the result of (p, p') on the nuclei of interest [15]. The ratio of 1.9(2) for ^{28}S, taking the present result and adopted $B(E2)$ of 350(50) e^2fm^4 for the mirror nucleus ^{28}Mg [12], shows the hindered proton collectivity in ^{28}S. This hindrance can be understood if ^{28}S is the proton singly-magic nucleus by the $Z = 16$ magicity. The double ratios of $N = 12$ isotones and $^{30-36}$S are close to unity, as seen in the figure, indicating that the hindrance of the proton collectivity does not appear in these nuclei. The large double ratios for ^{38,40}S can be explained by the neutron skin effect caused by the $Z = 16$ sub-shell closure [15, 16].

The dotted lines in Fig. 2 (a)-(c) show shell model predictions with the USDB effective interaction using the empirically optimized effective charges [17, 18]. The calculation shows relatively good agreement with the experimental results. It indicates that the shell model with the USDB interaction accounts for the phenomena observed in the present study.

SUMMARY

The $B(E2; 0^+_{gs} \to 2^+_1)$ value for ^{28}S was determined to be 181(31) e^2fm^4 using Coulomb excitation at 53 MeV/nucleon. This $B(E2)$ value and the evaluated double ratio $|M_n/M_p|/(N/Z)$ shows the hindered proton collectivity in ^{28}S and indicates the emergence of $Z = 16$ magicity in ^{28}S.

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