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The first excited state in ^{30}Ne studied by proton inelastic scattering in reversed kinematics

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Abstract

The energy of the first 2^+ state in the very neutron-rich nucleus ^{30}Ne was determined via the proton inelastic scattering. A liquid hydrogen target was bombarded by a radioactive ^{30}Ne beam at 48 MeV/nucleon, and energies of

the de-excitation γ rays from the excited ^{30}Ne were measured. The observed 2^+ energy, 791 (26) keV, is lower than that of ^{32}Mg, indicating enhancement of deformation as the neutron number increases in the N =20 isotones. The result shows evidently that ^{30}Ne belongs to the 'island of inversion'.

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An interesting aspect of nuclei around $N = 20$ is the transition from spherical to deformed shapes in a region centered at $Z \sim 11$ and $N \sim 21$ which is referred to as 'island of inversion' [1]. The collapse of the shell closure has been derived from the systematics of nuclear deformation. Occurrence of anomalous deformation was first suggested from the large binding energies of the sodium isotopes ^{31,32}Na as measured via mass spectroscopy [2]. Direct information on deformation can be obtained from properties of low-lying excited state. The $N = 20$ nucleus ^{32}Mg has been proven to be well deformed by the very low excitation energy $E(2^+)$ of 885.5(7) keV [3,4] and the enhanced B(E2) of 454(78) e^2fm^4 measured in the $0^+ \rightarrow 2^+$ Coulomb excitation [5]. Recently, the $N = 20$ nucleus ^{31}Na was also studied by the Coulomb excitation [6] and its large deformation was suggested. A larger deformation of ^{34}Mg compared with ^{32}Mg has been revealed via the in-beam γ spectroscopy [7,8]. The possible deformation of ^{30}Ne, the next N =20 isotone to ^{32}Mg, has attracted much interest with respect to the extent of this deformation region, and has required investigation for many years. Mass measurements of $N = 20$ isotones suggested that the region of the 'island of inversion' persists in the nucleus ^{30}Ne [9].

Theoretical studies for $N = 20$ isotones in the proton deficient region have been made in the framework of the shell model [11–15], antisymmetrized molecular dynamics (AMD) [16] and mean field theory [17–25]. These calculations predict the large quadrupole collectivity in the nucleus with $N = 20$ and $Z \leq 12$, including the ^{30}Ne nucleus, as a result of $2p$ - $2h$ excitations of neutrons across the gap between the sd and fp shells.

In the present letter, we report on the first measurement of the first 2^+ excited state in ^{30}Ne, which is expected to be the last even-even $N = 20$ nucleus before the neutron drip-line is reached, since ^{28}O has been found to be particle unbound [10]. We have performed an experiment of the proton inelastic scattering using a radioactive ^{30}Ne beam and a liquid hydrogen target [26]. The location of the first 2^+ excited state in ^{30}Ne was determined by measuring de-excitation γ rays in coincidence with the scattered ^{30}Ne.

In-beam γ spectroscopy using fast radioactive beams was initiated by the study of Coulomb excitation of ^{32}Mg, and has been extensively carried out in recent years. Gamma rays associated with the the intermediate-energy Coulomb excitation [5,6,27], proton inelastic scattering [28], nucleon knockout reaction [29] and fragmentation reaction [7,30] were measured. The Coulomb excitation has been employed to determine $E(2^+)$ and B(E2; $0^+ \rightarrow 2^+$) for a large variety of neutron-rich isotopes. The projectile fragmentation has afforded a better access to higher excited states whereas the nucleon knockout reaction selectively populates single-hole states. We have employed proton inelastic-scattering measured in reversed kinematics with a liquid-hydrogen target. This method is advantageous with its a high experimental efficiency in determining the locations of low-lying excited states. Compared with a high-Z target used in Coulomb excitation experiments, the number of hydrogen nuclei in a liquid target can be much larger, typically by two orders of magnitude, and this overcomes the relatively small (p,p') cross section of a few tens mb. Note that a typical Coulomb excitation cross section is a few hundred mb. If the cross section is 10 mb and the photo-peak efficiency of γ rays measurement is 15%, a practical lower limit of the beam intensity is as low as 0.1 counts per second (cps), which is lower by an order of magnitude than for Coulomb excitation experiments. The fragmentation reaction is also an efficient tool to study excited states. However, the fraction of γ-rays of interest in the total γ-yield is much larger for the proton inelastic scattering, making the γ-ray measurement easier especially for nuclei far from stability line.

The experiment was performed at the RIKEN Accelerator Research Facility using the RIKEN projectile-fragment separator (RIPS) [32]. A primary ^{40}Ar beam of 94 MeV/nucleon with a typical intensity of 60 pnA bombarded a ^{181}Ta target with a thickness of 641 mg/cm^2. The reaction products were collected and analyzed by RIPS operated in an achromatic mode. To reduce the total beam rate for measuring charged particles, an aluminum wedged-degrader with a mean thickness of 321 mg/cm^2 was used at the momentum dispersive focal plane (F1). To maximize the beam intensity of ^{30}Ne, the experiment was performed with the full momentum acceptance of $\pm 3\%$. The $B\rho$ setting was optimized for ^{30}Ne. Particle identification was carried out event by event by a method on the basis of energy loss (ΔE), time-of-flight (TOF) and magnetic rigidity ($B\rho$) [10]. The positions of the fragments at F1 were measured in order to determine the $B\rho$ values using a parallel plate avalanche counter (PPAC). Its large sensitive area of 15 cm (H) $\times$ 10 cm (V) covered the full momentum range of the secondary beam. A plastic scintillator with a thickness of 0.5 mm was set at the first achromatic focal plane (F2) for measuring TOF together with the cyclotron RF. Two silicon detectors were located in front of the final focal plane (F3) for the ΔE measurement. The thicknesses of both silicon detectors were 0.35 mm. Figure 1 shows a two-dimensional scatter plot for the incident particle identification. The horizontal axis corresponds to A/Z deduced from $B\rho$ and TOF, and the vertical one is for Z from the TOF and ΔE information, where A and Z are respectively the mass and atomic numbers of the incident particles. As seen in the figure, the ^{30}Ne isotope was clearly separated from ^{29}Ne and other isotopes mixed in the secondary beam. Typical intensity and purity of the ^{30}Ne beam were about 0.2 cps and 6.7 %, respectively. A liquid hydrogen target [26] was placed at the final focus of RIPS to excite the projectiles. Thickness of the hydrogen target cell was 24 mm and its entrance- and exit-windows were made of 6.6 μm thick Havar foils. A cryogenic refrigerator cooled hydrogen gas down to 22 K, and liquefied it. The resultant areal density of hydrogen was 186 mg/cm^2 on average. The averaged energy of ^{30}Ne in the target was calculated to be 48 MeV/nucleon from the mean incident-beam energy of 56 MeV/nucleon and energy loss in the target. The position and the incident angle of the beam at the target were measured by two PPACs placed upstream of the target. The beam spot size and angular spread were respectively 22 mm and 2.1 degree (FWHM) in the horizontal direction and 14 mm and 3.2 degree (FWHM) in the vertical direction.

Scattered particles were detected and identified by a PPAC and a silicon-detector telescope located about 50 cm downstream of the target. The telescope comprised seven layers with the thicknesses of 0.35, 0.5, 0.5, 0.5, 0.5, 3 and 1 mm, respectively. The active area of the detectors was 48 mm $\times$ 48 mm. Identification of Z was made by the TOF-ΔE method. Inelastic scattered particles of ^{30}Ne are stopped in the fourth, fifth or sixth layer. This large spread of the stopping range is due to the large momentum acceptance ($\pm$3%) of RIPS which set to maximize the ^{30}Ne beam intensity. The ΔE signal was taken from all the layers the particle penetrates. Isotope identification based on the ΔE - E method was difficult because of relatively large number of ions stopped in the dead layers of silicon detectors, which lead to a complicated mass spectrum. The TOF information was obtained between the secondary target and the PPAC.

The DALI setup with sixty-eight NaI(Tl) scintillators [5] was placed around the target to detect the de-excitation γ rays emitted from excited nuclei. Each scintillator crystal was of a rectangular shape with a size of $6 \times 6 \times 12$ cm^3. The setup allowed us to measure the angle of γ ray emission with about a 20 degrees accuracy. The angle information was used to correct for the large Doppler shift. To shield the NaI(Tl) detectors setup from γ rays caused by the silicon telescope and also from room background, the array was surrounded by a 5 cm thick lead blocks. The energy calibration of each NaI(Tl) detectors was made by using standard ^{22}Na, ^{60}Co, ^{88}Y, and ^{137}Cs sources. The energy resolution of the detectors are 8.9% on an averaged for a 662 keV γ ray.

Figure 2 shows the energy spectra of γ rays with the Doppler correction obtained for the ^{29}Ne (a) and ^{30}Ne (b) secondary beams. They were measured in coincidence with the scattered ions with Z =10 (neon isotopes). In Fig. 2(a), γ lines are seen at around 450, 580, and 1310 keV as indicated by the arrows. In addition to those lines, a peak at 791(26) keV was clearly observed for the ^{30}Ne-induced reaction as shown in Fig. 2(b), where the error contains the statistical uncertainty (24 keV) and a systematic one (10 keV). The latter was estimated from the uncertainties arisen in the Doppler correction due to the initial beam energy spread. The energy resolution of the peak was 12%, which includes the 8% resolution for the Doppler correction and the intrinsic resolution 8.9%.

Since only the atomic number Z of the products was identified, the spectra contain the contribution of the neutron-removal reactions as well as the inelastic scattering. It should be noted that the neutron pick-up yield is much smaller than the ones of neutron-removal and inelastic scattering. The line at about 1300 keV observed for both of the ^{29}Ne and the ^{30}Ne beams is attributed to the known $2^+ \rightarrow 0^+$ transition of 1320 keV in ^{28}Ne [30,31], which was populated in one- and two-neutron removal reactions, respectively. The other two lines at 450 keV and 580 keV are plausible to be attributed to unknown transitions in ^{29}Ne. The 791 keV transition was definitively assigned to the line of ^{30}Ne associated with the ^{30}Ne + p inelastic scattering, since it was observed only for the ^{30}Ne beam.

For even-even nuclei in this mass region, the first excited state is expected to be of 2^+ and is excited the most strongly by inelastic scattering. Considering this systematic trend, we assign the 791 keV peak to the $2^+ \rightarrow 0^+$ transition in ^{30}Ne, leading to the first 2^+ energy $E(2^+)$ of 791 keV.

In Fig. 3, the present result of ^{30}Ne is compared with the $E(2^+)$ values of neighboring $N = 20$ nuclei together with theoretical predictions. The measured $E(2^+)$ values for ^{30}Ne and ^{32}Mg are considerably smaller than those for other $N = 20$ isotones. This implies large deformation of ^{30}Ne and ^{32}Mg in contrast to ^{36}S and ^{34}Si with spherical shapes. The energy of 791 keV obtained in the present study for ^{30}Ne is even smaller than that of ^{32}Mg (885 keV), which suggests a larger deformation of ^{30}Ne. The theoretical predictions [11–14,16] of $E(2^+)$ for ^{30}Ne are categorized into two gropes as $0\hbar\omega$ and $2\hbar\omega$ models. In the $0\hbar\omega$ models [13,14], the $N = 20$ *sd*-closed shell is assumed. Predicted $E(2^+)$ values for ^{30}Ne and ^{32}Mg appear at around 1800 keV. On the other hand, the $2\hbar\omega$ models [11–14,16] allow $2p$ - $2h$ excitations of neutrons across the gap between the *sd*- and *pf*-shells. As shown in the figures, these models predict the 2^+ energies of around 800 keV for ^{30}Ne and ^{32}Mg. Obviously the experimental data favor the $2\hbar\omega$ models, suggesting that the $N = 20$ shell closure disappears for ^{30}Ne as well as for ^{32}Mg, and the nucleus ^{30}Ne belongs to the 'island of inversion'.

In summary, we have measured the first excited state in the very neutron-rich nucleus ^{30}Ne for the first time. The in-beam γ spectroscopy technique was applied by employing proton inelastic scattering with a liquid hydrogen target. Despite of the low ^{30}Ne beam intensity of 0.2 cps, the $2^+ \rightarrow 0^+$ gamma-transition was clearly observed. The $E(2^+)$ value of ^{30}Ne (791 keV) is the lowest among the ones of even-even $N = 20$ isotones, suggesting a large deformation of ^{30}Ne. It evidently indicates that the ^{30}Ne nucleus belongs to the 'island of inversion'. The present study also demonstrates the usefulness of the proton inelastic scattering. In particular, a liquid hydrogen target considerably facilitates spectroscopic studies with low-intensity radioactive beams by its large number of available hydrogen nuclei.

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FIGURES

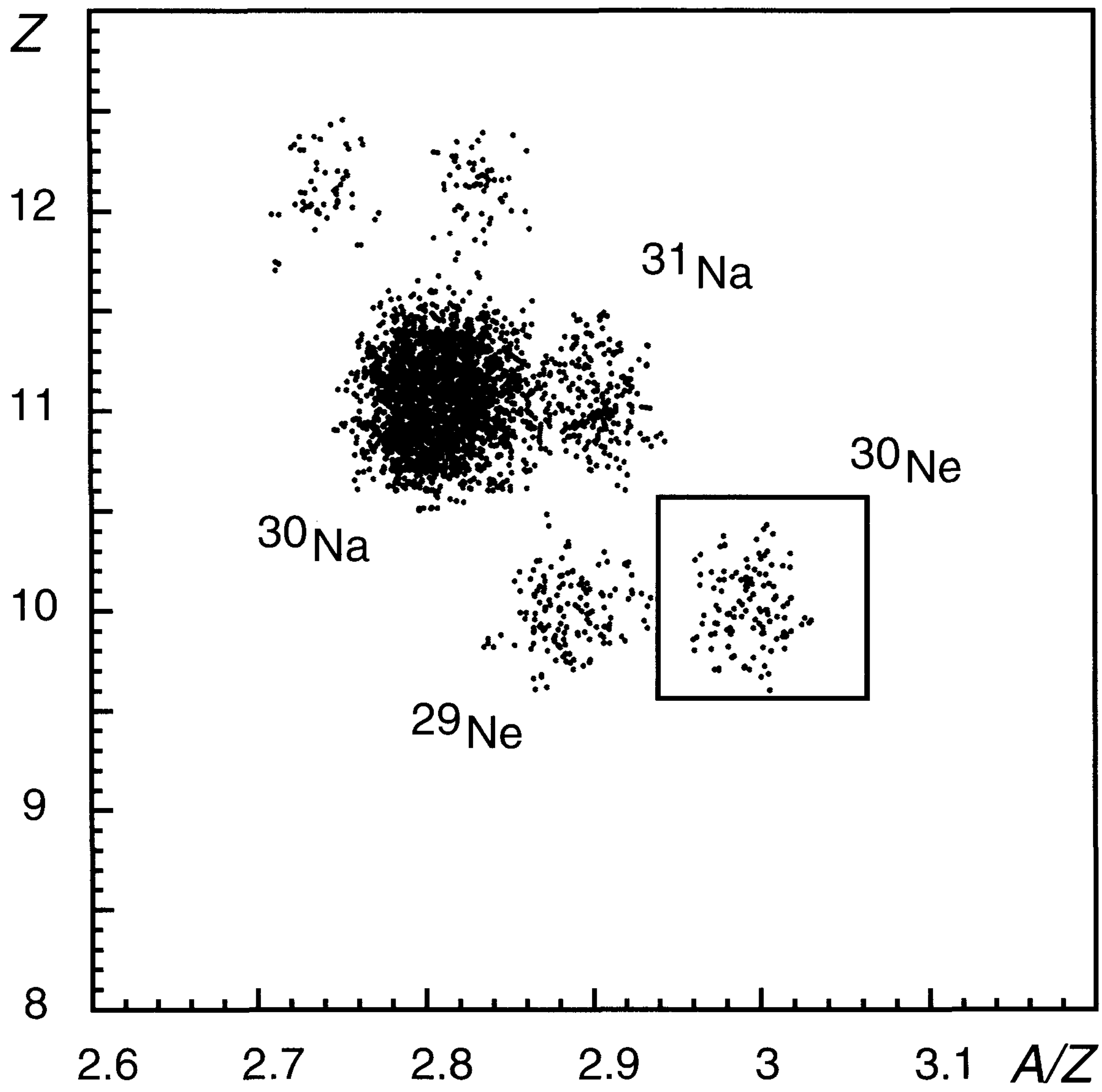

FIG. 1. Two-dimensional A/Z versus Z plot, which was obtained for the reaction products of a 94 MeV/nucleon ^{40}Ar beam on a ^{181}Ta target.

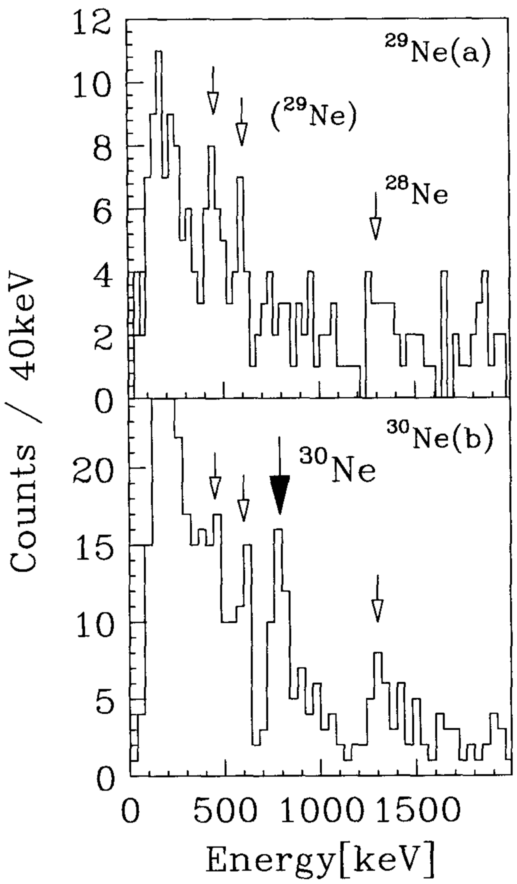

FIG. 2. Doppler-corrected energy spectra of γ-rays detected in coincidence with Ne isotopes measured with the ^{29}Ne (a) and ^{30}Ne (b) secondary beams. The 791(26) keV line is the correspond to the $2^+ \rightarrow 0^+$ transition in ^{30}Ne. The 1300 keV line is in agreement with the earlier experimental result for the $2^+ \rightarrow 0^+$ transition in ^{28}Ne [30,31].

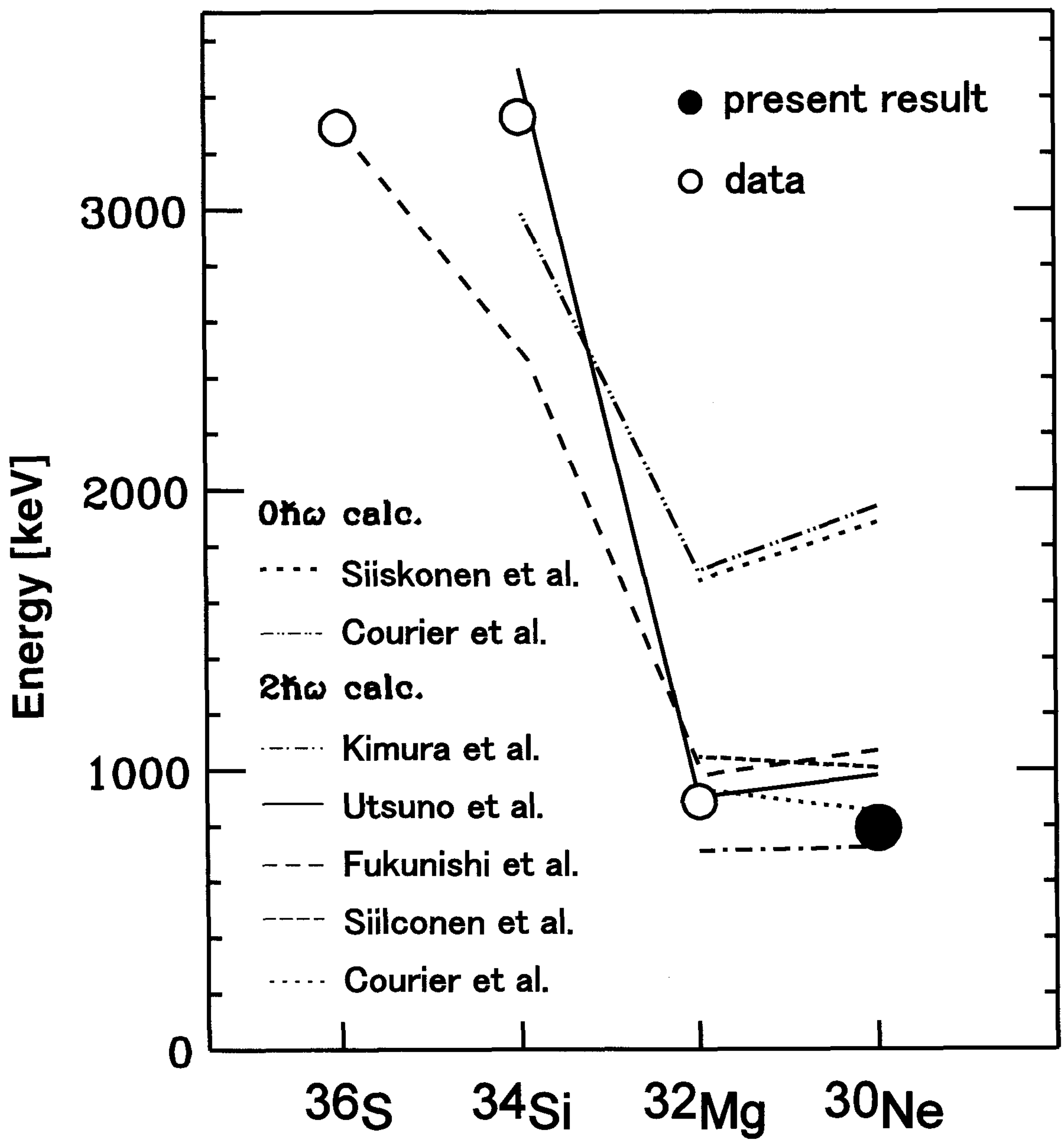

FIG. 3. Plots of energies of the measured first 2^+ states in even-even $N = 20$ isotones (closed circles) together with theoretical predictions [11-14,16]. The represent data are shown by the closed circle.