INTERMEDIATE-ENERGY COULOMB EXCITATION OF ^{28,29,30}Na

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First evidence on the existence of the so-called "island of deformed nuclei" near the $N = 20$ shell closure was obtained in 1975 by Thibault *et al.* [1] from the mass measurements of sodium isotopes. It has been found that ^{31}Na and ^{32}Na are more tightly bound than expected from spherically symmetrical sd-shell model. In the same year this phenomenon was explained by Campi *et al.* [2] via introduction of neutron $f_{7/2}$ intruder configurations for $Z < 14$ nuclei (i.e., an "inversion" of the standard shell ordering) and Hartree-Fock calculations. For 20 years progress in this field was hampered by lack of experimental information until properties of ^{32}Mg were studied at CERN and RIKEN [3-5]. Motobayashi *et al.* [5] (using the technique of intermediate-energy Coulomb excitation) measured that the reduced transition probability to the first excited 2^+ state in ^{32}Mg was $B(E2; 0^+_{g.s.} \to 2^+_1) =$ 454(78) e^{2}fm^4. A similar result was recently obtained at the NSCL [6]. Recent calculations of Caurier *et al.* [7] predict that intruders dominate ground states in ^{30}Ne, ^{31}Na and ^{32}Mg. To improve our knowledge about the island of deformed nuclei we decided to study ^{28,29,30}Na. Our results represent a first measurement of transition energies and excitation cross sections in ^{28,29,30}Na.

In the present experiment primary beams of ^{48}Ca^{13+} with an energy of 80 MeV/nucleon and intensities as high as 8 particle-nA, and ^{40}Ar^{12+} at 90 MeV/nucleon and 80 particle-nA were produced with the NSCL superconducting electron resonance ion source and the K1200 cyclotron. The secondary beams of sodium isotopes were obtained via fragmentation of the ^{48}Ca (^{40}Ar) primary beam in a 376 mg/cm^2 (564 mg/cm^2) thick ^{9}Be primary target located at the mid-acceptance target position of the A1200 fragment separator [8] and delivered onto a ^{197}Au secondary target. The position and direction of each fragment incident on the secondary target were measured with two parallel plate avalanche counters (PPAC). The time of flight between a thin plastic scintillator located after the A1200 focal plane and plastic phoswich detector at 0° with respect to the beam located after the secondary target was recorded for each fragment and provided positive identification of the fragment after interaction in the target.

Photons were measured in coincidence with the scattered fragments with the NSCL NaI(Tl) array [9]. The time difference between the detection of the photon in the NaI(Tl) detectors and the detection of the scattered fragment in the phoswich detector was recorded for each event so that accidental coincidences could be excluded from the γ-spectrum. The time-gated Doppler-corrected γ-ray spectra obtained with scattered ^{28,29,30}Na nuclei are shown in Figure 1. The photons emitted from fragments, which had velocities of $\approx$ 0.3 c, could be distinguished from those due to target excitations by their Doppler shifts.

Preliminary estimates show that nuclear excitations [10] can account for 10-15% of the excitation cross sections. It is known experimentally that spin and parity for the ground state of ^{28,29,30}Na are 1^+, $3/2$ and 2^+, respectively [11,12]. We are not aware of any theoretical calculations of the nuclear structure of ^{28,29,30}Na. Assuming static deformation and a rotational nature of low-lying excitations we can suggest 2^+ spin and parity assigments for the first excited state in ^{28}Na, $5/2^+$ in ^{29}Na and 3^+ in ^{30}Na. Two peaks are observed in the Doppler corrected spectrum of ^{30}Na. Our data analysis indicates that only the 433(16) keV transition belongs to ^{30}Na, and the 701(20) keV line originates from the neutron-stripping reaction and further deexcitation of ^{29}Na. In fact, a weak peak at this energy can be seen in the ^{29}Na data. However, the current experiment has poor statistics for this isotope. Observation of a neutron-stripping reaction in ^{30}Na

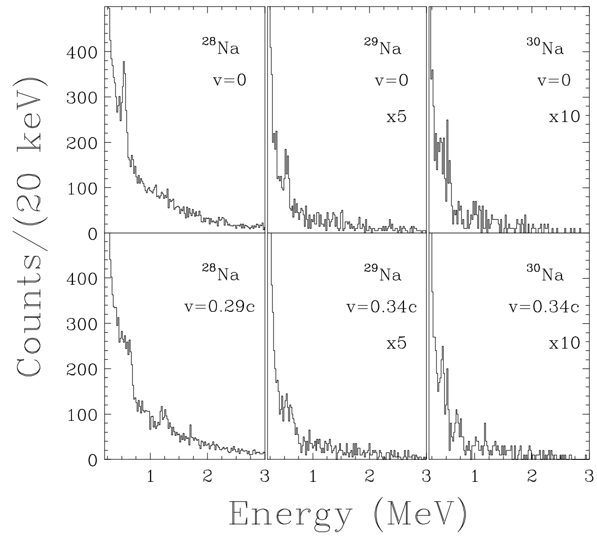

Figure 1: Upper panels contain photon spectra in the laboratory frame. The 547.5 keV ($7/2^+ \rightarrow g.s.$) transition in the gold target is visible as a peak, while transitions in each projectile are very broad. Lower panels contain Doppler-corrected γ-ray spectra.

Table 1: Experimental parameters and results. The secondary fragments were positively identified on an event-by-event basis and only desired fragments were analyzed. The energy spread of the secondary beam was ±2%.

Primary beam	Secondary beam	$E_{beam}^{midtarget}$ (MeV/A)	Total beam particles/10^6	^{197}Au target (mg/cm^2)	E_γ (keV)	σ (mb)	$B(E2\uparrow)$ (e^{2}fm^4)	θ_{cm}^{max} (deg)
^{40}Ar	^{28}Na	43.11	82.44	518	1240(11)	26(6)	87(19)	4.52
^{48}Ca	^{29}Na	59.97	12.96	702	701(20)	26(21)	48(35)	3.21
^{48}Ca	^{30}Na	55.56	3.30	702	433(16)	42(14)	186(63)	3.23

is consistent with the one-neutron separation energies for ^{28,29,30}Na, which are 3520(80) keV, 4420(120) keV and 2100(130) keV [12], respectively. In the ^{28}Na data, the 1240(11) keV transition is observed. The experimental results for these nuclei are presented in Table 1.

Assuming that all cross section can be attributed to excitations of the first excited state, we compare our data with the measured values of the ground state electric quadrupole moments [13]. The corresponding intrinsic quadrupole moments can be extracted using the standard formalism described in [14], the experimental knowledge of the ground state spins, and the assumption of axial symmetry:

$$Q_{JK} = \frac{3K^2 - J(J+1)}{(J+1)(2J+3)} Q_0, \tag{1}$$

where K is the spin projection along the symmetry axis ($J = K$ for the ground state) and Q_0 is the intrinsic quadrupole moment. The same quantity for the transition moments can be obtained [15,16] from our experimental cross sections assuming static deformations and pure $E2\uparrow$ excitations:

$$B(E2; I_i \rightarrow I_f) = \frac{5}{16\pi} Q_0^2 < I_i K 20 | I_f K >^2, \tag{2}$$

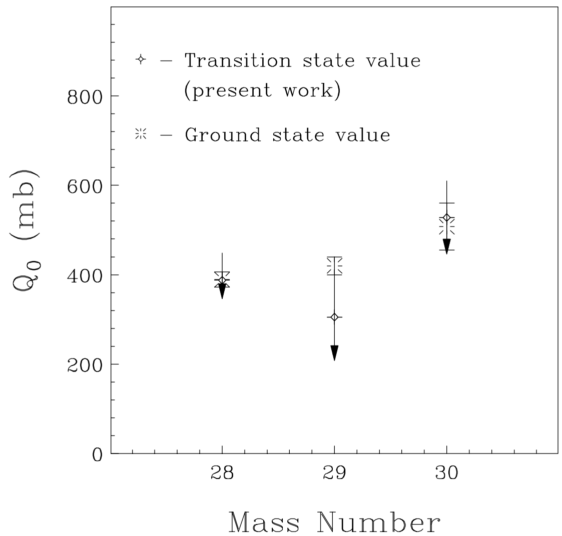

Figure 2: The intrinsic electric quadrupole moments for the ground and transition states in sodium isotopes (ignoring possible feeding from the higher-lying states).

where $< I_i K 20 | I_f K >$ are the corresponding Clebsch-Gordan coefficients. The intrinsic quadrupole moments for sodium isotopes are presented in Figure 2. The agreement between the two definitions for ^{28,29,30}Na suggests that these nuclei are indeed statically deformed.

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