COULOMB EXCITATION OF ODD-A NEUTRON-RICH π(s-d)- AND ν(f-p)-SHELL NUCLEI

R.W. Ibbotson, T. Glasmacher, P.F. Mantica, H. Scheit

Several recent studies have revealed a region of large quadrupole collectivity for N=20, Z<14. This collectivity has been interpreted in terms of a quadrupole deformation arising from the intrusion of the $\nu f_{7/2}$ orbital into the $s-d$ shell [1,2,3]. Another region of large quadrupole collectivity has been discovered for $N \approx 28$, $Z \approx 16$ nuclei [4] although this collectivity has been predicted to be vibrational (based on a spherical ground state) in some models and rotational (based on a deformed ground state) in others [4,5].

Very little information about these very neutron-rich nuclei which might aid in the interpretation of this collectivity is known. This region of collectivity lies at the edge of the region of measured mass excess ($N - Z \leq 11$), and J^{π} assignments have been made for the ground-states of odd nuclei only out to $N - Z \leq 7$ [6]. In stable nuclei, the low-lying excitations in odd-mass nuclei have proven useful in interpreting the nature of the low-lying collective excitations in neighboring even-even nuclei through the coupling of the odd nucleon to the collective excitations in the even-even core. By the same means, a measurement of the lowest excitations in the odd-mass nuclei near $N \approx 28$, $Z \approx 16$ may prove useful in interpreting the collectivity found in the even-even nuclei in this region.

In a previous experiment, a group of nuclei with neutron excesses of 9--11 in the $13 \leq Z \leq 17$ region has been produced and studied by Coulomb excitation in order to determine the energies and excitation cross-sections for the lowest excited states. The data for the odd-mass systems in this group has been studied in an effort to provide information which may aid in the interpretation of the collectivity in this region. A determination of the excited states in these nuclei also provides information necessary for further studies by $\beta - \gamma$ and $\gamma - \gamma$ coincidence methods.

The nuclei studied in the present work were produced simultaneously by fragmentation of a 70 MeV/A ^{48}Ca beam provided by the K1200 cyclotron at the NSCL at Michigan State University in a 285 mg/cm^2 ^{9}Be target and separated in the A1200. A thin 5 mg/cm^2 plastic wedge was used to reduce the number of light fragments reaching the focal plane of the A1200. A set of 18 nuclei in the range $12 \leq Z \leq 17$ with $7 \leq N - Z \leq 12$ reached the focal plane at rates of 30 particles per second or greater, where they were identified by energy-loss in a 300μm Si PIN detector and by time of flight with respect to the cyclotron radiofrequency. The momentum spread of these fragments was limited to $\pm$1.5% through the use of a slit at the first dispersive image of the A1200. This large acceptance was chosen in order to maximize the observed number of the most neutron-rich fragments, while still restricting the momenta enough to allow for unique identification of the fragments.

This mixed-particle beam was transported to the experimental station where it impinged on a 532 mg/cm^2 ^{197}Au target. Scattered beam particles were detected in a fast/slow plastic phoswich detector in coincidence with γ rays. The scattered fragments were identified by energy-loss in the 0.6mm fast-plastic portion of the phoswich and by time-of-flight from the end of the A1200. Since the goal of this study was to measure Coulomb excitation cross-sections, the maximum scattering angle from the target was restricted to $\theta_{lab} < 3.8°$ (the angular extent of the phoswich detector used for identification of the scattered fragments). This angular restriction corresponds to a distance of closest approach at least 3.1 fm larger than the sum of the nucleiar radii (assuming R=1.25A$^{1/3}$ fm) in all cases, which ensures that the effect of the nuclear interaction is small. An array of 39 cylindrical NaI(Tl) detectors centered about the target position was used for detection of γ rays in coincidence with scattered projectile ions (described in detail in [7]). Due to the low rate of detected particles, the entire array was enclosed in a 16.5 cm thick shielding wall of lead to reduce detected γ-rays from room background.

For each of the 18 nuclear species in the beam, the spectrum of Doppler-corrected γ rays in coincidence with the scattered nucleus of interest was collected. For the observed γ-ray peaks, centroids and peak areas were extracted. In the present work, each γ-ray peak which was observed has been interpreted as corresponding to the excitation of one excited state by an E2 excitation. With this assumption, the measured excitation cross-sections can be used to deduce a B(E2) value for exciting the state (or an upper limit, if no decay is observed). The B(E2) values in the present work have been extracted using the method of Winther and Alder [8].

The γ-ray data taken for 5 of the even-even nuclei in this group have been analyzed separately [4,9]. Of the remaining 13 nuclei for which > 5 million fragments were produced, projectile γ-rays were observed in 8 cases. The total number of fragments detected during this experiment for each nucleus is listed with the observed γ-ray centroids in Table 1. In two of these 8 cases, however, the observed γ rays

Nucleus	N_{obs} (10^6)	E/A (MeV)	E_γ (keV)	B(E2↑) (e^2fm^4)
^{33}Al	7.9	50.3		
^{34}Al	10.6	46.9		
^{35}Al	10.2	43.8	1006 (8)	142 (52)
^{37}Si	21.1	45.1	1437 (13)	101 (45)
^{38}P	51.0	49.3		
^{39}P	119.0	46.3	976 (4)	97 (30)
^{40}P	28.6	43.5		
^{41}P	5.6	40.9		
^{41}S	75.1	47.4	449 (3)	167 (65)
			904 (4)	232 (56)
^{43}S	22.2	42.0	≈940	175 (69)
^{44}Cl	71.1	45.6		
^{45}Cl	170.8	43.0	929 (6)	87 (24)
^{46}Cl	5.8	40.6		

Table 1: Odd-A and odd-Z fragments produced at rates greater than 30/sec, listed with the total number observed and average energy per nucleon (accounting for energy-loss in 1/2 the 532 mg/cm^2 ^{197}Au target.

were unresolved. For the ^{38}P case, a large number of unresolved γ rays were observed between 700 KeV and 1400 KeV. The large energy-range for which these γ rays was observed prohibits the estimation of a reasonable background. A summed E2 strength for these decays is therefore not quoted. For one other case, (^{43}S) unresolved γ rays were observed at $\approx$ 940 keV; the summed E2 strength is given in Table 1. Since the energy resolution of the detectors is typically 8%, the transitions observed in the present work may of course consist of more than one γ-ray separated by less than 8%.

The known energy levels below 4 MeV in the sulfur isotopes between $N = 20$ and $N = 28$ are plotted in Figure 1 along with the summed B(E2) strength $\sum_{J^\pi} B(E2; g.s. \rightarrow J^\pi)$. The level energies and B(E2) values for the even-even sulfur isotopes may indicate that $N = 28$ is not as strong a shell closure as $N = 20$ for $Z = 16$. The presence of an excited state at very similar excitation energies (≈900 keV) for ^{40,41,42}S is unexpected, and may be important in understanding the structure of these nuclei. It is interesting to compare the total B(E2) strength measured in the odd-A nuclei with the B(E2;$0^+ \rightarrow 2^+$)

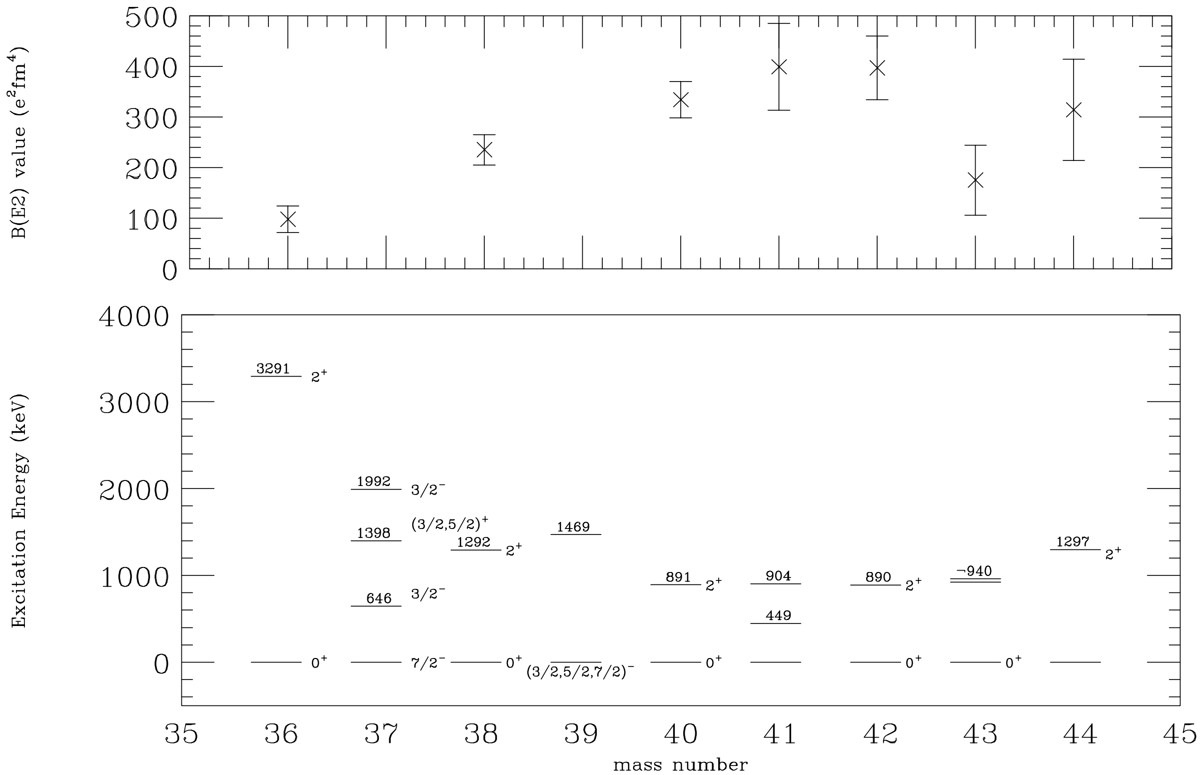

Figure 1: Level-energies and B(E2;$g.s. \rightarrow J^{\pi}$) values for sulfur isotopes between the $N = 20$ and $N = 28$ shell closures. For ^{41,43}S, the B(E2) values are summed over the observed E2 strength.

value in the even-even neighbors. If the odd-A nucleus can be described as a particle (or hole) weakly coupled to the A-1 (or A+1) core nucleus, the sum B(E2) strength should equal the B(E2;$0^+ \rightarrow 2^+$) value in the core nucleus, regardless of the nature of the core 2^+ excitation. If the odd particle couples strongly to the excitation, of course, this assumption is not valid. It is interesting that for ^{41}S, 110% of the B(E2) strength in the even-even neighbors is observed in two clearly resolved states at 449 keV and 904 keV. In ^{43}S and ^{45}Cl (both neighbors of the $N = 28$ nucleus ^{44}S), however, less than half of the B(E2) strength in the neighboring nuclei was observed in this experiment. While this may be indicative of a change in the particle-core coupling near $N = 28$, a clear interpretation is not possible with the limited information available. It must be pointed out that the experiment discussed was not sensitive to γ-rays of energy less than $\approx$300 keV. A measurement of the spins and parities of these observed states (or a restriction of the possible values) would be extremely useful in interpreting these results.

References

1. C. Thibault et al., Phys. Rev. **C12** 644 (1975).
2. T. Motobayashi et al., Phys. Lett. **B346** 9 (1995).
3. D. Guillemaud-Mueller et al., Nucl. Phys. **A426** (1984) 37.
4. T. Glasmacher et al., Phys. Lett. **395B** 163 (1997).
5. T.R. Werner et al., Phys. Lett. **B335** 259 (1994).
6. P.M. Endt, Nucl. Phys. **A521** 1 (1990).
7. H. Scheit et al., to be submitted to Nucl. Instr. and Meth. **A**.

8. A. Winther and K. Alder, Nucl. Phys. **A319** 518 (1979).
9. R.W. Ibbotson et al., Phys. Rev. Lett. **80** (1998) 2081.