SPECTROSCOPY OF THE 2_1^+ STATE IN ^{22}O AND SHELL STRUCTURE NEAR THE NEUTRON DRIP LINE

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One of the major themes of nuclear structure studies with radioactive beams is to examine how changes in the spin-orbit potential near the drip lines affect the shell structure. Here we report measurements of the energy and the $B(E2\uparrow)$ electromagnetic matrix element of the 2_1^+ state in ^{22}O using the technique of intermediate energy heavy-ion inelastic scattering [1]. This nucleus is only two neutrons away from ^{24}O, the heaviest particle-stable oxygen isotope.

The primary beam of 90 MeV/nucleon ^{40}Ar was produced with the NSCL's K1200 cyclotron. Secondary beams were made via fragmentation of the primary beam in a 564 mg/cm^2 ^{9}Be production target located at the mid-acceptance target position of the A1200 fragment separator. The ^{22}O secondary beam was produced with an energy of 55.6 MeV/nucleon. Separation of beam isotopes was enhanced with a 130 mg/cm^2 ^{27}Al achromatic wedge placed at the second dispersive image of the A1200. The momentum acceptance of the A1200 was limited to 1.0% by slits located at the first dispersive image.

A 612 mg/cm^2 ^{197}Au foil was used as the secondary target. The secondary beam slowed down significantly in this target, and the mid-target beam energy was 50.6 MeV/nucleon. The secondary beam was stopped in a cylindrical fast/slow plastic phoswich detector located at zero degrees. Both energy loss in the phoswich detector and time of flight relative to the cyclotron RF signal were used for particle identification. The zero degree detector subtended the scattering angles of 0° to 3.50° in the laboratory. The total integrated secondary beam measured by the zero degree detector was 2.92×10^7 particles.

The γ-rays were detected in an angular range of $56.5^\circ - 123.5^\circ$ in the laboratory by an array of position sensitive NaI(Tl) detectors [5, 6]. The γ-ray spectrum measured in coincidence with beam particles identified as ^{22}O in the zero degree detector appear in Fig. 1.

In the top panel, the laboratory-frame spectrum (uncorrected for the Doppler shift of the projectile) is shown. The 547 keV $7/2^+ \to 3/2^+_{gs}$ γ-ray in the ^{197}Au target nucleus appears strongly in this spectrum. The projectile-frame (Doppler-corrected) spectrum is shown in the bottom panel of Fig. 1. A γ-ray appears at 3170 ± 20 keV, which we assign to be the $2_1^+ \to 0^+_{gs}$ transition in ^{22}O. This result is consistent with that reported in a conference proceeding by Azaiez [2]. A cross section (integrated over the projectile scattering angles 0° to 3.50°) of $10.7 \pm 4.2\ mb$ is obtained for producing this γ-ray, assuming a γ-ray angular distribution corresponding to a pure E2 transition. Another γ-ray at 615 ± 10 keV may come from the decay of an excited state in ^{21}O, produced in a single neutron stripping reaction on the gold target.

To analyze the cross section for the 3.17 MeV γ-ray while accounting for both the Coulomb and nuclear contributions to the reactions, we used the coupled channels code ECIS88 [7], adopting the optical model parameters determined by Barrette *et al.* [8] for the scattering of ^{17}O from ^{208}Pb at a laboratory energy of 84 MeV/nucleon. Details of these calculations can be found in Ref. [10]

There are two coupling strengths (dynamic deformation parameters) involved in the ECIS calculations. The "Coulomb deformation" β_C reflects the deformation of the proton fluid in the nucleus and corresponds to the electromagnetic matrix element $B(E2; 0^+_{gs} \to 2_1^+)$. The quantities $B(E2; 0^+_{gs} \to 2_1^+)$ and β_C are related via the equation [9]

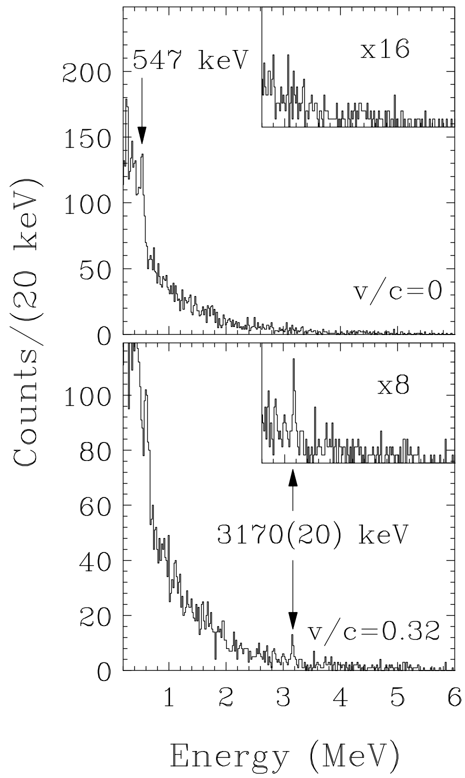

Figure 1: In-beam photon spectra gated on ^{22}O. The top panel shows the spectrum in the laboratory frame (without Doppler correction); the $7/2^+ \rightarrow 3/2^+$ transition in the gold target is visible as a peak. The bottom panel shows the projectile frame (Doppler-corrected) spectrum. The inserts show the same spectra above 2.6 MeV on a different scale.

$$\beta_C = \frac{4\pi}{3ZR_0^2}[B(E2; 0^+_{gs} \rightarrow 2^+_1)/e^2]^{1/2} \tag{1}$$

where the radius R_0 is given by $R_0 = (1.20\ fm)A^{1/3}$.

The second deformation parameter in the calculation is the "nuclear deformation parameter" β_N. While the Coulomb deformation parameter is used to calculate the electromagnetic interaction between target and projectile, the nuclear deformation parameter is used in the nuclear potential to determine the matter interaction. The relationship between β_C and β_N depends on the proton and neutron contributions to the transition being studied and the sensitivity of the particular experimental probe used in the measurement to the proton and neutron contributions. The relationship between the proton and neutron contributions to the transition can be expressed as the ratio M_n/M_p of the neutron and proton multipole matrix elements. In the absence of data on ^{22}O from a second experimental probe, we adopt a value for M_n/M_p (2.6) calculated using standard sd-shell calculations with the USD interaction [3].

The fit to the ^{22}O cross section data using ECIS yielded $\beta_C = 0.21 \pm 0.04$ ($B(E2\uparrow) = 21 \pm 8\ e^2 fm^4$) and $\beta_N = 0.31 \pm 0.06$.

Figure 2 shows the data on the energies and $B(E2\uparrow)$ values for the $N > 8$ even-even isotopes of oxygen (the data on ^{16,18}O are taken from Ref. [11]) as well as the results of shell model calculations which are described below.

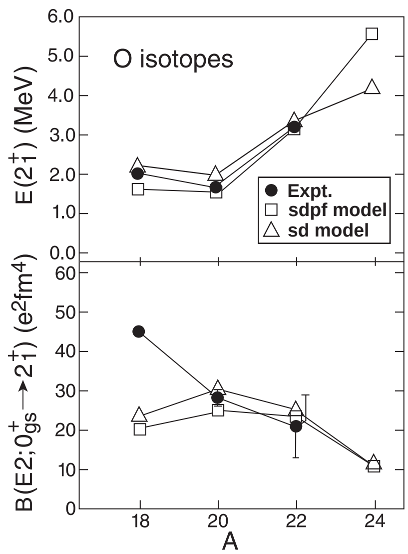

Figure 2: The top panel shows the excitation energies of the 2_1^+ states in the $N > 8$ even-even oxygen isotopes. The measured values (taken from [11] and the present work) are shown as solid shapes, and the calculated values for the standard sd-shell calculations [3] and the shell model calculations with an expanded space [4] are shown as open shapes. The bottom panel depicts the $B(E2\uparrow)$ values for the same nuclei.

A comparison of the data on ^{18}O and ^{20}O demonstrates the importance of having data on *both* the energy and $B(E2\uparrow)$ value to judge the collectivity of the 2_1^+ state. The energy of the 2_1^+ state in ^{20}O is somewhat lower than in ^{18}O, which might imply a greater degree of collectivity in ^{20}O. However, the $B(E2\uparrow)$ value in ^{20}O is considerably lower, leading to the correct conclusion that the 2_1^+ state in ^{18}O is more collective. In ^{22}O, the energy of the 2_1^+ state is significantly higher than in ^{20}O and ^{18}O, suggesting that the $N = 14$ subshell gap that results from the filling of the $d_{5/2}$ neutron orbit is present in ^{22}O. In this case, the $B(E2\uparrow)$ value for ^{22}O provides confirmation of the conclusion suggested by the 2_1^+ state energy, since it is is less than or equal to the $B(E2\uparrow)$ value in ^{20}O. Thus the present results provide strong evidence for the existence of the $N = 14$ subshell closure in ^{22}O even though this nucleus is only two neutrons away from the drip line nucleus ^{24}O.

The experimental results have been compared with the standard sd-shell calculations with the USD interaction [3] and expanded space calculations of $Z = 8 - 14$ nuclei described by Utsono *et al.* [4] which incorporate the $f_{7/2}$ and $p_{3/2}$ orbitals in addition to the sd shell with an interaction which starts with USD and then makes modifications to the monopole interaction. The USD calculations predict a 2^+ energy of 3.38 MeV and a $B(E2\uparrow)$ value of $25\ e^2fm^4$ (with a standard neutron effective charge of 0.5 [3]), successfully reproducing our experimental results. The MCSM calculations give similar results of 3.13 MeV and $23\ e^2fm^4$, respectively, indicating that the pf-shell admixtures are small. The results of these calculations for $^{18-24}$O are compared to the experimental data in Figure 2, demonstrating that the present data for ^{22}O can be understood using the standard sd shell model with an effective interaction derived from nuclei in and near the valley of stability. The calculations for ^{24}O also predict a high 2_1^+ state energy and small $B(E2\uparrow)$ value. These results reflect the fact that $N = 16$ also gives a subshell closure, this time from the filling of the $s_{1/2}$ neutron orbit.

It is clear that an experimental determination of M_n/M_p is critical for a thorough understanding of the structure of the low-lying states of ^{22}O. The new generation of radioactive beam facilities coming online shortly will be able to provide beams of ^{22}O intense enough to make inverse kinematics proton scattering experiments feasible.

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