^{20}O(p,p') IN INVERSE KINEMATICS AND CORE POLARIZATION NEAR THE DRIP LINE

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The measurement of proton and neutron contributions to transitions between nuclear states provides one of the most important tools for understanding the relative importance of valence and core contributions to these transitions. The competition between valence and core contributions is of particular interest in single-closed-shell nuclei, where the low-lying excitations would be composed exclusively of the valence neutrons or protons if the closed core were truly inert. Methods for determining the proton and neutron multipole matrix elements M_p and M_n generally involve the comparison of measurements of a transition using two experimental probes with different sensitivities to proton and neutron contributions. While studies of $0^+_{gs} \rightarrow 2^+_1$ transitions in stable nuclei have been performed using a variety of combinations of experimental probes (for example, see [1, 2]), it has - until recently - been impossible to examine neutron and proton contributions in this way in short-lived radioactive nuclei. Such studies would be of particular interest because of the relatively small binding energies of the valence nucleons. Data on the electromagnetic matrix elements for $0^+_{gs} \rightarrow 2^+_1$ transitions have been available for some short-lived even-even nuclei for some time [3], and recent advances in intermediate energy Coulomb excitation [4] have made even more information of this type available. These electromagnetic data provide information on the proton contributions to the $0^+_{gs} \rightarrow 2^+_1$ matrix elements. With recent advances in techniques for providing intense beams of radioactive nuclei, inverse kinematics proton scattering provides a way to determine the neutron contributions to these matrix elements. At center-of-mass energies less than 50 MeV - corresponding to radioactive beam energies of less than 50 MeV/nucleon - inelastic proton scattering is much more sensitive to the neutron contributions in transitions than those of the protons, and therefore can be used together with electromagnetic data to understand the relationship between proton and neutron contributions [1, 5].

Here, we report the results of an inverse kinematics proton scattering study of the $0^+_{gs} \rightarrow 2^+_1$ transition in the single-closed-shell radioactive nucleus ^{20}O, which is two neutrons from stability but only four neutrons from the heaviest bound oxygen isotope (^{24}O) [6, 7]. Reliable electromagnetic data are already available for this transition from measurements of the lifetime of the 2^+_1 state (see [3] for a compilation), so the proton scattering data provide a determination of M_n/M_p, the ratio of the neutron and proton multipole matrix elements [2]. The trend of this ratio in the oxygen isotopes provides insight about the role of core polarization in the $0^+_{gs} \rightarrow 2^+_1$ transition.

Angular distributions of protons scattered from the ground state and 1.67 MeV 2^+_1 state of ^{20}O in the p(^{20}O,p') reaction were measured. The 30 MeV/nucleon ^{20}O beam was produced in the A1200 fragment separator [9] at the National Superconducting Cyclotron Laboratory via fragmentation of a 65 MeV/nucleon ^{22}Ne primary beam on a water cooled 360 mg/cm^2 ^{9}Be target. The secondary beam, with a maximum intensity of 30,000 particles/second, was approximately 99% pure. A 3.6 mg/cm^2 polypropylene foil was used as the hydrogen target for the secondary beam. The arrangement for detecting the scattered protons was similar to that used by Kelley *et al.* for the measurement of the p(^{38}S,p') reaction [8].

The computer code CHUCK [10] was used to perform coupled channels calculations from which the strength of the $0^+_{gs} \rightarrow 2^+_1$ transition in the present (p,p') reaction was extracted. The standard vibrational form factor was used for the calculation of the inelastic cross section. The result we extracted was $\beta_2 = 0.50 \pm 0.04$.

Inelastic proton scattering at low energies (≤ 50 MeV) is much more sensitive to neutron contributions to a transition than proton contributions. If $b_{n(p)}^{(p,p')}$ is the external-field neutron (proton) interaction strength for low-energy proton scattering, then the ratio $b_n^{(p,p')}/b_p^{(p,p')}$ is approximately 3 [2]. In contrast, the electromagnetic matrix element $B(E2; 0^+_{gs} \to 2^+_1)$ measures the proton matrix element M_p. We use the prescription given in [2] to extract a value for the ratio M_n/M_p. The compilation of Raman *et al.* [3] gives $\delta_{em} = 0.850(29)$ fm for ^{20}O. To calculate $\delta_{(p,p')}$, we use the radius parameter from the real part of the optical model potential, $r_R = 1.10$ fm, so that $R = 2.99$ fm. This gives $\delta_{(p,p')} = \beta_2 R = 1.49(12)$ fm. From a simple comparison of these two deformation lengths, it is clear that there is an isovector component to this transition and that the neutrons are playing a disproportionately large role, as is expected for a nucleus with a closed proton shell. We arrive at the result M_n/M_p=2.9(4), which can be compared to the value $M_n/M_p = N/Z = 1.5$ that would be expected for a purely isoscalar transition.

One of the primary motivations for the present efforts in nuclear structure physics with radioactive beams is to observe the evolution of nuclear structure effects as the drip lines are approached. The transition from stability to particle instability occurs over a relatively small change in neutron number in the oxygen isotopes. While ^{18}O is stable, it appears from an exhaustive search for ^{26}O that ^{24}O is the heaviest bound isotope [6, 7]. Hence, the oxygen isotopes provide an excellent opportunity to track changes that occur in the structure of the 2^+_1 state as the neutron drip line is approached.

In this context, it is interesting to compare the values of M_n/M_p for the $0^+_{gs} \to 2^+_1$ transitions in ^{18}O and ^{20}O to look for suggestions of a trend. Several methods have been employed to extract the M_n/M_p value for the $0^+_{gs} \to 2^+_1$ transition in ^{18}O, and a significant range of results has been obtained. However, we begin by comparing the present M_n/M_p result for ^{20}O with a value for ^{18}O extracted using an identical analysis of low energy proton scattering and electromagnetic results. From the compilation of [3], we obtain an electromagnetic deformation length of $\delta_{em} = 1.12(3)$ fm for ^{18}O. Proton inelastic scattering data for ^{18}O were taken at 24.5 MeV by Escudie *et al.* [11], but were reanalyzed by Grabmayr *et al.* [12] using an optical model potential formulated to systematically reproduce the available neutron and proton scattering data for ^{16,18}O at energies between 14 and 25 MeV. Hence, the result of the distorted-wave Born approximation (DWBA) analysis of the ^{18}O(p,p') data in [12] ($\beta_2 = 0.45(4)$) is adopted, giving $\delta_{(p,p')} = 1.30(12)$ fm. Using these values with equation (4), we obtain $M_n/M_p = 1.50(17)$ for ^{18}O, a value which is significantly smaller than the result for ^{20}O and is not so far from the result we would expect for an isoscalar transition, $M_n/M_p = N/Z = 1.25$. This comparison of results extracted using the same experimental probes in both nuclei suggests a trend in which M_n/M_p is increasing as a function of mass.

Values of M_n/M_p for the $0^+_{gs} \to 2^+_1$ transition in ^{18}O have been extracted using a variety of methods, including the comparison of intermediate energy proton scattering with electron scattering [13], the comparison of the electromagnetic result for ^{18}O with the corresponding electromagnetic result in the mirror nucleus ^{18}Ne [14], the comparison of low energy proton scattering with low energy neutron scattering [12], and the comparison of the scattering of π^+ and π^- [15, 16]. Results using these methods, as well as the values for ^{18}O and ^{20}O extracted using the comparison of low energy proton scattering and electromagnetic data, are shown in Fig. 1 (The mirror nucleus result of [14] has been updated with matrix elements compiled in [3]; the result shown for the pion scattering data of [15] is that cited in [14]; and the value shown for the (p,p') vs. (n,n') analysis of [12] is that cited in the compilation of [1]).

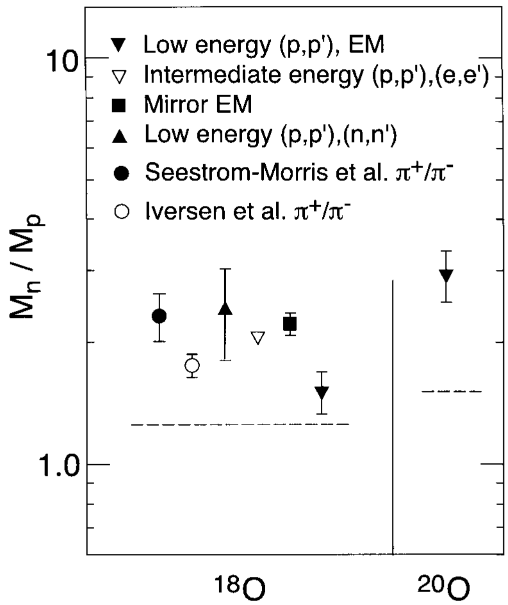

Figure 1: M_n/M_p values for the $0^+_{gs} \to 2^+_1$ transitions in ^{18}O and ^{20}O. The results illustrated here are described in the text. The dashed lines correspond to $M_n/M_p = N/Z$.

The weighted mean of all the results shown for ^{18}O in Fig. 1 is $M_n/M_p = 2.03(3)$. Once again, the results suggest that M_n/M_p is larger in ^{20}O than in ^{18}O.

We can examine the role of core polarization in the $0^+_{gs} \to 2^+_1$ transition to understand the physical significance of the difference between M_n/M_p values in ^{18}O and ^{20}O. A simple understanding of the roles of the valence nucleons and core polarization in the $0^+_{gs} \to 2^+_1$ transition can be achieved by writing M_n and M_p in terms of valence-space matrix elements $M_n^{'}$ and $M_p^{'}$ and core-polarization contributions as [2]

$$M_n = M_n^{'}(1 + \delta^{nn}) + M_p^{'}\delta^{np}, \tag{1}$$

and

$$M_p = M_n^{'}\delta^{pn} + M_p^{'}(1 + \delta^{pp}), \tag{2}$$

where δ^{xy} is the core-polarization parameter corresponding to core x's polarization by valence y's. That is, δ^{xy} reflects the amount of core polarization *per unit of contribution from the valence nucleons*. The connection of the core-polarization parameters and the usual electromagnetic effective charges is given by $e_n = \delta^{pn}$ and $e_p = 1 + \delta^{pp}$. The oxygen isotopes have no valence proton contribution because of the closed proton shell, so that $M_p^{'} = 0$. Therefore, the ratio M_n/M_p is given by

$$M_n/M_p = (1 + \delta^{nn})/\delta^{pn}. \tag{3}$$

That is, M_n/M_p depends only on the core polarization parameters and *not* on the number of valence neutrons. If these parameters - and, therefore, the effective charges - are constant, then M_n/M_p should be constant as well. Conversely, any change in M_n/M_p would be due to changes in the polarization parameters.

As discussed above, such an increase would not be a simple consequence of the increase in the number of valence neutrons, since the increase in the valence neutron contribution $M_n^{'}$ cancels out of

M_n/M_p. Instead, it appears that either the interaction of the valence neutrons with the core neutrons (as reflected in δ^{nn}) is stronger in ^{20}O than in ^{18}O or that the interaction of the valence neutrons with the core protons (δ^{pn}) is becoming weaker with increasing mass. Confirmation of this trend will require inverse kinematics proton scattering measurements of the corresponding transitions in the heavier even-A isotopes ^{22,24}O. These measurements will become possible as new radioactive beam facilities come on line. Futhermore, a microscopic study of the trends suggested by the macroscopic analysis presented here would likely lend new insights regarding the core polarization mechanisms at work in the oxygen isotopes.

A more detailed report of this work can be found in Ref. [17].

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