INELASTIC SCATTERING OF ^{18}Ne AND ISOSPIN PURITY IN A=18 NUCLEI

L.A. Riley[a], P.D. Cottle[b], M. Fauerbach[b 1], T. Glasmacher, K.W. Kemper[b], B. V. Pritychenko, H. Scheit[2]

The degree to which the isospin symmetry is violated in nuclei in the vicinity of $A = 18$ has been shown to play an important role in the understanding of Coulomb energies [1], β-decay matrix elements [2] and nuclear interaction symmetries [3]. Bernstein, Brown and Madsen [4] pointed out that isospin purity in a $T = 1$ multiplet can be tested by comparing corresponding electromagnetic transitions in three members of the multiplet. A systematic study of $0^+ \rightarrow 2^+$ transitions in the $T = 1$ multiplet of the $A = 18$ system provides one example: The isoscalar multipole matrix element M_0 for this transition can be obtained from a comparison of the proton multipole matrix elements M_p in the $|T_z| = 1$ mirror nuclei ^{18}O and ^{18}Ne. If isospin symmetry is satisfied, then the value of M_0 obtained via the comparison of ^{18}O and ^{18}Ne should be equal to that extracted from the $0^+ \rightarrow 2^+$ transition between $T = 1$ states in the $T_z = 0$ nucleus ^{18}F. An analysis of $T = 1$ isospin multiplets for $A = 22 - 42$ recently reported by Cottle *et al.* [5] found suggestions of strong isospin symmetry breaking in the $A = 34, 38, 42$ systems.

While the $B(E2; 0^+_{gs} \rightarrow 2^+_1)$ value in ^{18}O is known with considerable precision, the situation is quite different in the mirror nucleus ^{18}Ne. A measurement of the $B(E2; 0^+_{gs} \rightarrow 2^+_1)$ electromagnetic matrix element in ^{18}Ne was performed by McDonald *et al.* [6] using the Doppler Shift Attenuation Method (DSAM) with the ^{3}He(^{16}O,n) reaction and the ^{3}He implanted in a nickel foil. They arrived at a result of $B(E2; 0^+_{gs} \rightarrow 2^+_1) = 260 \pm 25\ e^2fm^4$ ($M_p = 16.1 \pm 0.8\ fm^2$). However, results from pion scattering measurements on ^{18}O [7] appear to disagree with the conclusion of McDonald *et al.* Under the assumption of isospin symmetry, M_p for a transition in one nucleus should be equal to M_n for the corresponding transition in the mirror nucleus. A comparison of ^{18}O(π^+,$\pi^{+'}$) and ^{18}O(π^-,$\pi^{-'}$) reactions yielded $M_n = 12.4 \pm 0.7$ fm^2 for ^{18}O (assuming the "modified collective model" analysis in Ref. [7]). The authors of ref. [4] warn that a comparison of M_n in ^{18}O and M_p in ^{18}Ne must take into account that the valence protons in ^{18}Ne are less bound than the valence neutrons in ^{18}O. They prescribe that for the $0^+_{gs} \rightarrow 2^+_1$ transition in ^{18}Ne the M_n value should be adjusted upward by 10% before comparison. Nevertheless, the pion scattering measurement yields a value of $M_p = 13.6 \pm 0.8\ fm^2$ (corresponding to $B(E2; 0^+_{gs} \rightarrow 2^+_1) = 186 \pm 23\ e^2fm^4$) for ^{18}Ne.

To study the isospin purity of the $A = 18$ system and resolve the apparent conflict in the experimental results for the electromagnetic matrix element $B(E2; 0^+_{gs} \rightarrow 2^+_1)$ in ^{18}Ne, we measured this value using a beam of radioactive ^{18}Ne ions in an intermediate energy heavy-ion scattering reaction. A review of the experimental technique used in the present study is given in [8].

The experiments were performed at the National Superconducting Cyclotron Laboratory. The primary beam of 80 MeV/nucleon ^{20}Ne was produced with the laboratory's K1200 cyclotron. The ^{18}Ne secondary beam had an energy of 65 MeV/nucleon. A $350\ mg/cm^2$ ^{197}Au foil was used as the secondary target. A description of the array used for detecting γ-rays and details of the analysis of γ-ray spectra can be found in Ref. [9].

A cross section (integrated over the scattering angles 0° to 4°) of $45 \pm 6\ mb$ was obtained for producing the 1887 keV γ-ray in ^{18}Ne, assuming a γ-ray angular distribution corresponding to a pure E2 transition. It is important to note that this γ-ray production cross section may not be identical to the

[1]Present address: Mississippi School for Mathematics and Science, PO Box W-1627, Columbus, MS 39701
[2]Present address: Max-Planck-Institut für Kernphysik, Postfach 10 39 80, D-69029 Heidelberg, Germany

cross section for directly exciting the 2_1^+ state in the scattering reaction, since this state can be fed by γ-decays from higher-lying states. In particular, it is possible that the 2_2^+ state at 3613 keV is significantly populated in the present scattering reaction since the corresponding 2_2^+ state in the mirror nucleus ^{18}O is strongly populated in proton and neutron scattering reactions [10], in electron scattering [11] and in pion scattering [7]. In addition, $91 \pm 2\%$ of the γ-decays from the 3613 keV state in ^{18}Ne deexcite to the 2_1^+ state via a 1726 keV transition [12]. When this is combined with the observed cross section of $45 \pm 6\ mb$ for producing the 1887 keV γ-ray, we arrive at a cross section of $40 \pm 11\ mb$ for directly populating the 2_1^+ state.

To analyze the scattering cross sections while accounting for both the Coulomb and nuclear contributions to the reactions, we used the coupled channels code ECIS88 [13] with two sets of optical model parameters - the parameters of Mermaz *et al.* [14] from their study of the scattering of ^{16}O from ^{208}Pb at a laboratory energy of 49.5 MeV/nucleon, and the parameters of Barrette *et al.* [15] obtained for the scattering of ^{17}O from ^{208}Pb at a laboratory energy of 84 MeV/nucleon. A comparison of the results we obtained using these two parameters sets provides some understanding of their model dependence. The standard vibrational form factor was used. Cross sections for multiple excitations in intermediate energy heavy-ion scattering are generally negligible [8], so we only considered single-step excitations here.

There are two coupling strengths (dynamic deformation parameters) involved in the ECIS calculations. The first, the "Coulomb deformation" β_C, reflects the deformation of the proton fluid in the nucleus and corresponds to the electromagnetic matrix element $B(E2; 0_{gs}^+ \rightarrow 2_1^+)$. The second 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. To set β_N for the ECIS calculation, we adopt the prescription of Ref. [16] which takes into account not only the difference between the charge and matter deformations but also the sensitivity of the particular probe used in the measurement. We can use the results of a recent measurement of low energy proton scattering on ^{18}Ne in inverse kinematics [17, 18] to constrain the value of β_N for the present experiment so that there is only one free parameter to fit, β_C. With the optical model parameters of Mermaz *et al.*, we obtain $\beta_C = 0.450 \pm 0.036$ (and $\beta_N = 0.481 \pm 0.039$). With this result for β_C and equation 1, we obtain $B(E2; 0_{gs}^+ \rightarrow 2_1^+) = 113 \pm 18\ e^2 fm^4$, corresponding to $M_p = 10.6 \pm 0.9\ fm^2$ Using the optical model parameters of Barrette *et al.* instead, we obtain $\beta_C = 0.496 \pm 0.040$ ($\beta_N = 0.503 \pm 0.040$), giving $B(E2; 0_{gs}^+ \rightarrow 2_1^+) = 137 \pm 22\ e^2 fm^4$, corresponding to $M_p = 11.7 \pm 0.9\ fm^2$.

We also performed a measurement of ^{18}O which supports the reliability of our ^{18}Ne result.

The present results for ^{18}Ne are significantly different from the previous experimental result of McDonald *et al.* [6] ($M_p = 16.1 \pm 0.8\ fm^2$). For this reason, it would seem prudent to repeat their DSAM experiment to take advantage of modern high efficiency Ge detectors. The present result is also significantly below the value for M_p in ^{18}Ne extracted from pion scattering ($13.6 \pm 0.8\ fm^2$), although the pion scattering value also disagrees with the DSAM result.

The present result for the 2_1^+ state in ^{18}Ne provides the opportunity to examine isospin symmetry in the $A = 18$ multiplet. If isospin symmetry is satisfied within a mass multiplet, then the matrix elements of the corresponding electromagnetic transitions in each isobar are related in a straightforward way. The isoscalar multipole matrix element can be extracted from the proton multipole matrix elements of two mirror nuclei with the equation

$$M_0(T_z) = M_p(T_z) + M_p(-T_z) \tag{1}$$

The isoscalar matrix element can also be extracted from the corresponding transition between $T = 1$ states in a $T_z = 0$ nucleus by

$$M_p(T_z = 0) = M_0(T = 1)/2. \tag{2}$$

That is, the hypothesis of isospin purity implies that the value of M_0 extracted from the M_p values in two mirror $T_z = \pm 1$ nuclei should be equal to the value $M_0 = 2M_p$ obtained for the $0^+_{T=1} \to 2^+_{T=1}$ transition in the $T_z = 0$ nucleus. According to [4], this comparison provides an experimental test of isospin purity for $A = 4n + 2$ multiplets.

For $A = 18$, the results obtained with the parameter sets of Mermaz *et al.* (2.84 ± 0.23 single particle units, or spu) and Barrette *et al.* (3.13 ± 0.20 spu) for ^{18}Ne, when taken with the corresponding value for ^{18}O from the compilation of Ref. [19], $M_p = 1.82 \pm 0.02$ spu, yield $M_0 = 4.66 \pm 0.23$ spu and 4.95 ± 0.25 spu, respectively. In the $T_z = 0$ nucleus ^{18}F, the $T = 1$ 0^+ and 2^+ states are located at 1042 and 3062 keV, respectively. The 3062 keV state decays predominantly to the $T = 0$ states at 0 keV ($J^\pi = 1^+$) and 937 keV ($J^\pi = 3^+$) via $M1$ transitions. Only $0.11 \pm 0.03\%$ of the decays of the 3062 keV state populate the 1042 keV state. The $M1$ decays cause the lifetime of the 3062 keV to be quite short, and only an upper limit (the mean life $\tau < 1.2$ fs) has been determined [12]. The measurement of the branch ratio and the upper limit of the lifetime allow a lower limit on the reduced matrix element, $B(E2; 0^+ \to 2^+) > 5.8$ spu, to be obtained (this value is calculated with the lower 1σ limit, 0.08%, of the measured branch ratio). This, in turn, gives $M_p > 2.40$ spu and $M_0 > 4.80$ spu. Hence, the values of M_0 obtained from ^{18}O and the present results for ^{18}Ne are consistent with the lower limit extracted from the available data on ^{18}F. Therefore, the data on these $0^+_{T=1} \to 2^+_{T=1}$ transitions are consistent with the assumption of isospin purity. This conclusion is valid for both sets of optical model parameters adopted here. It is worth noting that the ^{18}Ne result of McDonald *et al.* [6] gives $M_p = 4.30 \pm 0.20$ spu, yielding a ^{18}O/^{18}Ne M_0 result of 6.12 ± 0.20 spu.

Comparisons between M_0 values taken from $T_z = \pm 1$ nuclei and the $T = 0$ states of the $T_z = 0$ isobars for $4n + 2$ nuclei in the mass range $A = 18 - 42$ are shown in Fig. 1 (data are taken from [5, 22] and the present work).

Cottle *et al.* [5] noted that the error bars for the $T_z = 0$ and $T_z = \pm 1$ M_0 values do not overlap in the cases of $A = 34, 38$ and 42, suggesting the possibility of measurable isospin purity violation in these nuclei. These cases merit further study, as does the case of $A = 22$, where the experimental uncertainties for both $T_z = 0$ and $T_z = \pm 1$ M_0 values are large.

A more complete report of this work is in press in Phys. Rev. C.

a. Department of Physics and Astronomy, Earlham College, Richmond, Indiana 47374
b. Department of Physics, Florida State University, Tallahassee, Florida 32306

References

1. R. Sherr and H.T. Fortune, Phys. Rev. **C58**, 3292 (1998).
2. D.J. Millener, Phys. Rev. **C55**, R1633 (1997).
3. D.B. Kaplan and M.J. Savage, Phys. Lett. B **365**, 244 (1996).
4. A.M. Bernstein, V.R. Brown, and V.A. Madsen, Phys. Rev. Lett. **42**, 425 (1979).
5. P.D. Cottle, M. Fauerbach, T. Glasmacher, R.W. Ibbotson, K.W. Kemper, B. Pritychenko, H. Scheit, and M. Steiner, Phys. Rev. **C60**, 031301 (1999).
6. A.B. McDonald, T.K. Alexander, C. Broude, J.S. Forster, O. Hauser, F.C. Khanna, I.V. Mitchell, Nucl. Phys. **A258**, 152 (1976).

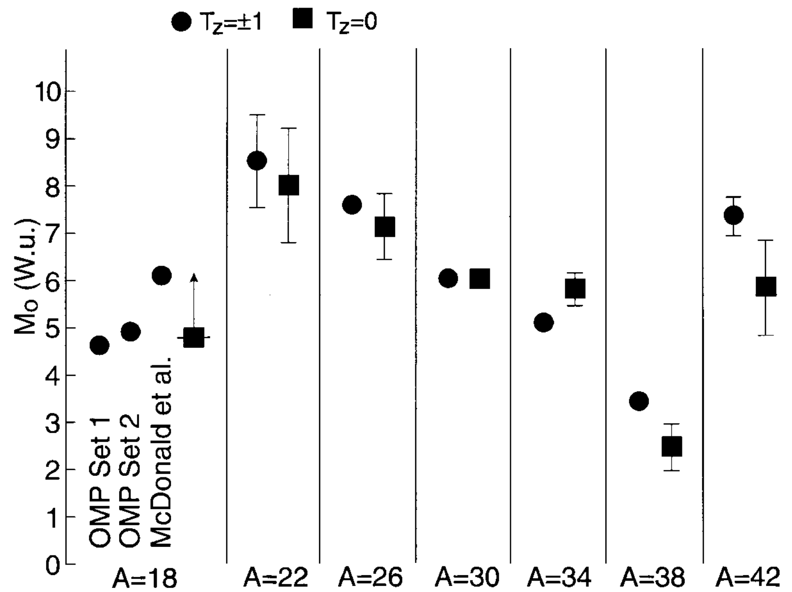

Figure 1: A comparison of isoscalar multipole matrix elements M_0 extracted from the comparison of M_p values for $0^+_{gs} \rightarrow 2^+_1$ transitions in $T = 1$ nuclei to the M_0 values taken from transitions between $T = 1$ states in $T_z = 0$ nuclei. This comparison allows a test of isospin purity in $A = 4n + 2$ systems. Three $A = 18$ $T_z = \pm 1$ values are shown, corresponding to the results obtained in the present work with the two optical model parameter sets and the result of McDonald *et al.* [6].

7. S.J. Seestrom-Morris, D. Dehnhard, M.A. Franey, D.B. Holtkamp, C.L. Blilie, C.L. Morris, J.D. Zumbro, and H.T. Fortune, Phys. Rev. **C37** (1988) 2057.
8. T. Glasmacher, Ann. Rev. Nucl. Part. Sci., **48**, 1 (1998).
9. H. Scheit, T. Glasmacher, R.W. Ibbotson, and P.G. Thirolf, Nucl. Inst. and Meth. **A422**, 124 (1999).
10. P. Grabmayr, J. Rapaport, and R.W. Finlay, Nucl. Phys. **A350**, 167 (1980).
11. B.E. Norum, M.V. Hynes, H. Miska, W. Bertozzi, J. Kelly, S. Kowalski, F.N. Rad, C.P. Sargent, T. Sasanuma, W. Turchinetz, and B.L. Berman, Phys. Rev. **C25**, 1778 (1982).
12. D.R. Tilley, H.R. Weller, C.M. Cheves, and R.M. Chasteler, Nucl. Phys. **A595**, 1 (1995). (updated: http://www.tunl.duke.edu)
13. J. Raynal, Phys. Rev. **C23**, 2571 (1981).
14. M.C.Mermaz, B.Berthier, J.Barrette, J.Gastebois, A.Gillibert, R.Lucas, J.Matuszek, A.Miczaika, E.Van Renterghem, T.Suomijarvi, A.Boucenna, D.Disdier, P.Gorodetzky, L.Kraus, I.Linck, B.Lott, V.Rauch, R.Rebmeister, F.Scheibling, N.Schulz, J.C.Sens, C.Grunberg, W.Mittig, Z.Phys. **A326**, 353 (1987).
15. J. Barrette, N. Alamanos, F. Auger, B. Fernandez, A. Gillibert, D.J. Horen, J.R. Beene, F.E. Bertrand, R.L. Auble, B.L. Burks, J.G. Del Campo, M.L. Halbert, R.O. Sayer, W. Mittig, Y. Schutz, B. Haas, and J.P. Vivien, Phys. Lett. B **209**, 182 (1988).
16. A.M. Bernstein, V.R. Brown, V.A. Madsen, Comments Nucl. Part. Phys., **11**, 203 (1983).
17. L.A. Riley, Dissertation, Florida State University (1997).
18. L.A. Riley, J.K. Jewell, P.D. Cottle, T. Glasmacher, K.W. Kemper, N. Alamanos, Y. Blumenfeld, J.A. Carr, M. Chromik, S.E. Hirzebruch, R.W. Ibbotson, F. Marechal, D.J. Morrissey, W.E. Ormand, F. Petrovich, H. Scheit, T. Suomijarvi, Phys. Rev. Lett. **82**, 4196 (1999)
19. S. Raman, C.H. Malarkey, W.T. Milner, C.W. Nestor, Jr., and P.H. Stelson, At. Data Nucl. Data Tables **36**, 1 (1987).
20. G.C. Ball, T.K. Alexander, W.G. Davies, J.S. Forster, I.V. Mitchell, J. Keinonen, and H.B. Mak, Nucl. Phys. **A386**, 333 (1982).
21. C. Rolfs, Can. J. Phys. **50**, 1791 (1972).
22. P.M. Endt, Nucl. Phys. **A521**, 1 (1990).