# Where is the $(2s_{1/2})^2$ $T=1$ Strength in Mass 18?*

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A doublet at 4.5-MeV excitation energy in $^{18}$Ne has been studied via the reactions $^{16}$O($^3$He,$n$)$^{18}$Ne and $^{20}$Ne($p$,$t$)$^{18}$Ne. The states are found to have excitation energies of $4.518 \pm 0.008$ and $4.590 \pm 0.008$ MeV with spin and parity $1^-$ and $0^+$, respectively. The difference between the excitation energy of the $0^+$ state and that of the analogous state at 5.34 MeV in $^{18}$O gives strong evidence for the predominantly $s_{1/2}{}^2$ character of the state.

In a previous study of $^{18}$Ne using the reaction $^{16}$O($^3$He,$n$), Adelberger and McDonald[1] observed a doublet at 4.5 MeV excitation and, from a comparison with the reaction $^{16}$O($t,p$), suggested that it consisted of the analogs of the 4.46-MeV $1^-$ and 5.34-MeV $0^+$ states of $^{18}$O. As discussed below, the existence of a $0^+$ state at 4.5 MeV would directly indicate a strong $s_{1/2}{}^2$ component in the state since the analogous state in $^{18}$O has an excitation energy 0.8 MeV greater, a difference most easily attributed to the large Coulomb shift associated with $s$-wave particles. Since the position of the $s_{1/2}{}^2$ ($0^+$) strength in mass 18 is a centrally important and heretofore unresolved issue in shell-model calculations, we have given the 4.5-MeV doublet special attention in a study of the reactions $^{16}$O($^3$He,$n$) and $^{20}$Ne($p,t$), which will be reported in greater detail elsewhere. We have confirmed the suggestion of Ref. 1, identified which member of the doublet is $0_3{}^+$ (the third $0^+$ state), and shown that the measured Coulomb energy implies a largely $s_{1/2}{}^2$ configuration. This is inconsistent with several calculations[2-4] which place the $s_{1/2}{}^2$ strength in the $0_2{}^+$ state and supports those[5-7] which place it in $0_3{}^+$.

Our $^{16}$O($^3$He,$n$) studies used the Stanford University time-of-flight spectrometer to detect neutrons from a gaseous $O_2$ target bombarded by 10-20-MeV $^3$He beams. Measured excitation energies are summarized in Table I. As seen in the 10.5-MeV spectrum of Fig. 1, well-known states below 4 MeV in $^{18}$Ne are prominent, and groups at 4.5 and 5.1 MeV are doublets. At 13.8 MeV, where angular distributions to the 4.5-MeV states may be meaningfully compared with the distorted-wave Born approximation (DWBA), the states are unresolved, and the yield to the unresolved group

TABLE I. $^{18}$Ne excitation-energy measurements.[a]

| $^{16}$O($^3$He,n)$^{18}$Ne | $^{20}$Ne(p,t)$^{18}$Ne |
|---|---|
| | 1886(10) |
| | 3375(10) |
| | 3580(10) |
| | 3612(10) |
| 4513(13) | 4522(10), ≤40 |
| 4587(13) | 4592(10), ≤40 |
| 5075(13), ≤60 | 5095(15), ≤80 |
| 5135(12), ≤60 | 5149(15), ≤50 |
| | 5453(10), ≤50 |
| 6291(30), 180 ± 60 | 6297(10), ≤60 |
| | 6353(10), ≤60 |
| 7062(12), 180 ± 50 | |
| 7712(20), ≤50 | 7713(10), ≤60 |
| 7915(12), ≤50 | |
| | 7949(10), ≤60 |
| 8100(14), ≤50 | |
| 8500(30), ≤120 | |
| | 9198(10), ≤50 |

[a]Given in keV are the excitation energy (uncertainty) and width.

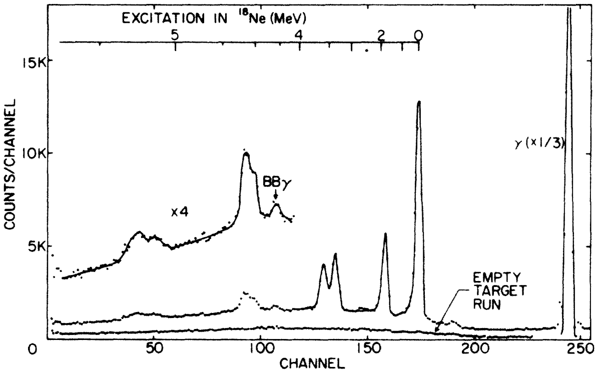


FIG. 1. Time spectrum for $^{16}O(^3He,n)^{18}Ne$ at $E(^3He) = 10.52$ MeV and $\theta_{lab} = 5°$ for a flight path of 3.0 m. BBγ is due to prompt γ rays from an out-of-phase beam burst. The background run was accumulated for less integrated beam than the foreground run.

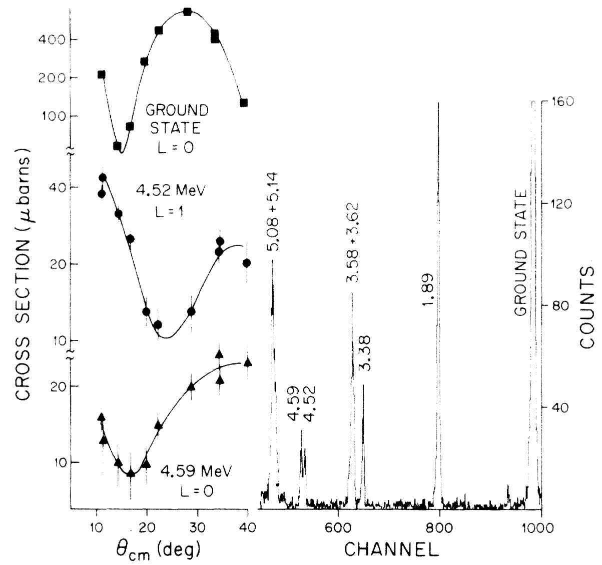


FIG. 2. Triton spectrum from $^{20}Ne(p,t)^{18}Ne$ at $E_p = 41.8$ MeV and $\theta_{lab} = 20.0°$; angular distributions to the 4.5-MeV doublet and to the ground state. The cross-section scales have a ± 15% uncertainty. Smooth curves are to guide the eye.

is found to be consistent with either $L = 0$ or $L = 1$, with the forward-angle points favoring $L = 0$. The width of the group is found to *increase* as $\theta_{lab}$ is changed from 20° to 30°, and the excitation energy appears to *decrease* by about 30 keV. This indicates that at forward angles the bulk of the strength is due to the higher-lying member of the doublet; at larger angles, where the observed cross section is small, neither of the states dominates. In the analogous reaction[8] $^{16}O(t,p)^{18}O$, the 4.46-MeV $1^-$ state was very weakly populated with an angular distribution not characteristic of a direct reaction. The $0_3^+$ state at 5.34 MeV was strongly populated with a typical $L = 0$ angular distribution. Thus our $^{16}O(^3He,n)$ data are consistent with a $1^-$ state at 4.513 MeV and a $0^+$ state at 4.587 MeV.

The reaction $^{20}Ne(p,t)$ was studied with the Princeton University azimuthally varying field cyclotron at $\theta_{lab} = 10°$ to 45° where $L = 0$ and 1 transfers can be distinguished easily. A 41.8-MeV proton beam bombarded a gaseous $^{20}Ne$ target and tritons were detected in a solid-state counter telescope. The experimental resolution of 50 keV clearly resolved the 4.5-MeV doublet. Previous $(p,t)$ work[9-11] with poorer resolution had not supported the existence of a doublet at 4.5 MeV, and had even excluded[10] the possibility of significant $L = 0$ stength to the 4.5-MeV group. Our 20° spectrum (Fig. 2) shows a well-defined 4.5-MeV doublet; the slower rise on the high-channel-number side of the 5.1-MeV group verifies that it is a doublet. Table I gives measured excitation energies from this study. Angular distributions to the ground state and the states at 4.5 MeV are shown in Fig. 2. The summed yield to the 4.5-MeV states agrees with previous reresults.[10] The 4.52-MeV angular distribution agrees well with an $L = 1$ transfer: A minimum occurs at $\theta_{c.m.} = 25°$. Yield to the 4.59-MeV state is characteristic of $L = 0$ in that a mimimum occurs at $\theta_{c.m.} < 25°$.[12]

The existence of states at 4.518 ± 0.008 and 4.590 ± 0.008 MeV is thus established. The $(p,t)$ work clearly indicates that the lower of these is populated by $L = 1$ transfer; the $(^3He,n)$ favors an $L = 0$ assignment for the upper, and the $(p,t)$ results confirm this. We conclude that these states have $J^\pi = 1^-$ and $0^+$, respectively. We also note the existence of states at 5.085 ± 0.010 and 5.141 ± 0.010 MeV, supporting the suggestion[10] that a 5.10-MeV group is populated by both $L = 2$ and 3 transfers. These are presumably the analogs of the 5.09-MeV $3^-$ and 5.25-MeV $2^+$ states of $^{18}O$.

The 4.59-MeV state, the analog of the 5.34-MeV $0^+$ $^{18}O$ state, lies 0.75 MeV lower in excitation energy, a much larger shift than in other mass-18 multiplets. However, such shifts in excitation energy occur as the proton number of a state changes[13] and can be striking if the $s_{1/2}$ orbital is important, since the additional Coulomb energy easily alters the $s_{1/2}$ radial wave function, which extends particularly far from the nuclear center. Kahana[4] recently applied this notion in a two-particle model of mass 18. He finds that such a model, by placing most of the $s_{1/2}{}^2$ strength in the $0_2{}^+$ state, implies a much larger Coulomb shift for the $0_2{}^+$ state than is observed experimentally. It is known, moreover, that a model space based on two particles in $2s_{1/2}$ and $1d_{5/2}$ orbitals outside a $^{16}$O core cannot reproduce the number or properties of low-lying levels in mass 18. To yield the third $0^+$ and $2^+$ states observed near 5 MeV and to explain large observed $E2$ transition rates, a model must include configurations (usually "deformed") resembling $^{20}$Ne less two $p$-shell particles.[2,5] The manner in which these "hole" configurations mix with the two-particle configurations is not established. The $T=1$ ground state is known to be predominantly $d_{5/2}{}^2$ $(0^+)$; but distribution of the $s_{1/2}{}^2$ and hole strength between the second and third $0^+$ states is in dispute as may be seen in Refs. 2-7. We suggest that the present observation of a large downward shift of the third $0^+$ state of $^{18}$Ne, rather than the second, selects among available sets of wave functions for mass 18 in that it *requires* that most of the $s_{1/2}{}^2$ strength lie in $0_3{}^+$.

We briefly describe a model to calculate relative Coulomb shifts in terms of the radial-wave-function differences in the two-particle components of the state vectors. We write the state $\alpha$, with spin $J$, as

$$|\alpha J\rangle = \sum_{j_2 \geq j_1} c_{j_1 j_2}{}^{\alpha J} |j_1 j_2 J\rangle + \sum_i d_i{}^{\alpha J} |p^{-2} iJ\rangle,$$

where $j_1$ and $j_2$ refer to nucleons in the $sd$ shell and the second group are hole configurations. We assume that the Hamiltonian in the two-particle subspace is $H_{nn} = T_1 + T_2 + V_1 + V_2 + V_{12}$ for $^{18}$O and $H_{pp} = H_{nn} + W_1 + W_2 + W_{12}$ for $^{18}$Ne, where the $V$'s and $W$'s are nuclear and Coulomb potentials, respectively, and assume that configuration amplitudes remain the same across $T=1$ mutiplets, but that radial wave functions may change, particularly in the surface and external regions. Forming the difference, $\langle \alpha J^{nn} | H_{pp} | \alpha J^{pp}\rangle - \langle \alpha J^{pp} | H_{nn} | \alpha J^{nn}\rangle$, integrated out to a radius near the nuclear surface, we are led to an approximation for the Coulomb energy difference for the state $|\alpha J\rangle$,

$$E_{pp} - E_{nn} = \sum_{j_2 \geq j_1} (c_{j_1 j_2}{}^{\alpha J})^2 (\Delta_{j_1} + \Delta_{j_2}) + 2\delta \sum_i (d_i{}^{\alpha J})^2 + \langle \alpha J | W_{12} | \alpha J\rangle,$$

where $\Delta_j$ is $(E_p - E_n)_j$, the *one*-particle Coulomb difference for the $j$ orbital. An equivalent single-particle shift $\delta$ is assigned to all of the hole configurations. Calculation of the relatively noncritical $W_{12}$ term will be discussed in a subsequent paper. We evaluate the $\Delta_j$ from a potential model, including the "dominant" terms of Ref. 13, with parameters appropriate to the separation of a nucleon from a mass-17 core. As an example, $E_p - E_n$ for the $s_{1/2}{}^2$ component in a $0^+$ wave function is evaluated by adjusting the nuclear well depth to produce the *observed* binding, with respect to $n + {}^{17}\mathrm{O}(\frac{1}{2}^+)$, of an $s_{1/2}$ neutron in the $^{18}$O state in question. The Coulomb potential is then added to this nuclear part, and the binding of a proton is *calculated*, yielding $\Delta_j$. Given the experimental $^{18}$O spectrum and a set of wave functions, $E_{pp} - E_{nn}$ is evaluated as a function of $\delta$ for each $^{18}$O state. The $^{18}$Ne spectrum thus generated is compared with experiment, adjusting $\delta$ to obtain best agreement.

The wave functions of Benson and Flowers,[6] which place most of the $s_{1/2}{}^2$ strength in $0_3{}^+$, have been used to generate the $^{18}$Ne spectrum given in Table II. In spite of differences in experimental excitation energies as large as 750 keV, the calculation reproduces the $^{18}$Ne energies quite well, the maximum and average absolute discrepancies being 140 and 55 keV, respectively. Corresponding numbers for the wave functions of Engeland,[2] which concentrate the $s_{1/2}{}^2$ strength in the $0_2{}^+$ state, are 350 and 170 keV. The observed Coulomb energy of the $0_3{}^+$ state strongly favors mod-

TABLE II. Excitation energies of $T=1$ states.[a]

| $J^\pi$ | $^{18}\mathrm{O}_{\mathrm{expt}}$ [b] | $^{18}\mathrm{Ne}_{\mathrm{expt}}$ | $^{18}\mathrm{Ne}_{\mathrm{calc}}$ [e] | $\Delta$ [f] |
|---|---|---|---|---|
| $0_1{}^+$ | 0 | 0 | 140 | +140 |
| $2_1{}^+$ | 1982 | 1887 [c] | 1911 | + 24 |
| $4_1{}^+$ | 3555 | 3376 [c] | 3325 | − 50 |
| $0_2{}^+$ | 3634 | 3576 [c] | 3546 | − 28 |
| $2_2{}^+$ | 3921 | 3616 [c] | 3575 | − 41 |
| $2_3{}^+$ | 5260 | 5113 [d] | 5055 | − 58 |
| $0_3{}^+$ | 5336 | 4590 [d] | 4550 | − 40 |

[a] All energies in keV.
[b] From J. W. Olness, E. K. Warburton, and J. A. Becker, Phys. Rev. C 7, 2239 (1973).
[c] From F. Ajzenberg-Selove, Nucl. Phys. A190, 1 (1972).
[d] From present work. 5113 is the mean of states in the 5.1-MeV doublet.
[e] $\delta = 3450$ keV; see text.
[f] $\Delta = {}^{18}\mathrm{Ne}_{\mathrm{calc}} - {}^{18}\mathrm{Ne}_{\mathrm{expt}}$.

els which place most of the $s_{1/2}$ strength in that state.

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## Can the Charge Symmetry of Nuclear Forces be Confirmed by Nucleon-Nucleon Scattering Experiments?*

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The Coulomb interaction is subtracted from the proton-proton scattering data in the $^1S_0$ partial wave. Contrary to traditional belief, the resulting nuclear effective-range parameters depend strongly on the unknown nuclear potential at small distances. The comparison between proton-proton and neutron-neutron data is therefore ambiguous.

Nucleon-nucleon scattering is believed to provide direct and reliable evidence on the isospin properties of the nuclear interaction. Whereas proton-proton ($pp$) and neutron-proton ($np$) experiments have been performed with great precision at a variety of energies, no corresponding neutron-neutron ($nn$) experiment has been carried out by now. All available $nn$ information is extracted from the final-state interaction in few-body reactions. Only the $^1S_0$ effective-range parameters, scattering length $a_{nn}$, and effective range $r_{nn}$ have been determined this way, and even their best values,[1]

$$a_{nn} = -16.4 \pm 0.9 \text{ fm}, \quad r_{nn} = 2.8 \pm 0.5 \text{ fm}, \qquad (1)$$

are still plagued with large uncertainties. The scarcity of experimental $nn$ data and their uncertainty are usually blamed for the missing detailed comparison between $pp$ and $nn$ scattering and for the lack of a rigorous experimental confirmation of charge symmetry.

However, charge symmetry solely applies to the hadronic part of the nucleon-nucleon interaction. Even in the advent of accurate and abundant $nn$ data, nucleon-nucleon scattering will experimentally prove charge symmetry only to the extent that electromagnetic effects can theoretically be removed from the data in an unambiguous manner. The traditional belief is that this can be done. However, this claim is questioned in the present paper.

The subtraction of the Coulomb force is our concern. It is the most important correction of $pp$ data for electromagnetic effects, though a sophisticated comparison[2] between $pp$ and $nn$ scattering should also take vacuum polarization, the magnetic-moment interaction, and the neutron-proton mass difference into account. The technique for subtracting the Coulomb force is standard: A nuclear potential is fitted to the data such that together with the Coulomb potential $V_C$ it reproduces the experimental phase $\eta_{pp}{}^C(k)$ well.