(18) is 1.4 times as large for $^{42}$Ca as for $^{48}$Ca. The corresponding ratio for the right-hand sides of (18), as obtained from one-particle transfer data, is 1.2. We believe that the difference between 1.4 and 1.2 is within the range of uncertainties mentioned above.

Another way to normalize the two-particle DWBA calculation is to fit an individual transition, using reasonable shell-model wave functions for the target and final states. We find that (18) can be satisfied by using a DWBA normalization that is within 30% of what would be needed to fit the $^{48}$Ca$(t,p)^{50}$Ca ground-state transition.

Both of the cases we have just discussed correspond to points on the upper-left-hand segment of Fig. 1. We anticipate obtaining much more information when data from the upper part of the $1f$-$2p$ shell can be analyzed in this way. We regard our preliminary application of (18) as very encouraging, and expect this sum rule to be a valuable tool in the analysis of particle transfer data.

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# $j$ Dependence of Heavy-Ion–Induced Reactions*

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The ($^{16}$O, $^{15}$N) and ($^{12}$C, $^{11}$B) reactions have been studied on targets of $^{54}$Fe, $^{62}$Ni, and $^{208}$Pb at incident $^{16}$O and $^{12}$C energies of 104 and 78 MeV, respectively. The two reactions are observed to populate states in the residual nuclei with different strengths, depending on the $j$ values of the final states. These results are believed to be a consequence of the selection rules for these reactions and suggest that spectroscopic assignments are possible with the use of heavy-ion reactions to complement other measurements.

Studies of heavy-ion–induced single-nucleon–transfer reactions at energies above and below the Coulomb barrier have recently been reported.[1-3] While these studies have added greatly to our understanding of the reaction mechanism, they have also shown such reactions to be somewhat disappointing probes of nuclear structure. The observed angular distributions, for example, have been found to be very nearly independent of $L$, the orbital-angular-momentum transfer.[1-3] Also, uncertainties in the nuclear interactions, bound-state wave functions, and numerical approximations have made extraction of spectroscopic factors using distorted-wave Born approximations (DWBA) subject to question.[4-5]

To date, there are very few experimental data available to provide a good test of one of the more important aspects of the heavy-ion reaction mechanism, the selection rules. These rules will in general differ from those for light ions since the transferred nucleon need not be in a relative $s$ state in the projectile. To obtain more information about these rules we have performed a series of experiments using different targets and projectiles. These measurements reveal a strong $j$ dependence in the relative cross sections for the different projectiles which, apparently, results from the selection rules and can be utilized to provide $j$ assignments.

The experiments were performed with 78-MeV $^{12}C$ and 104-MeV $^{16}O$ beams provided by the Lawrence Berkeley Laboratory 88-in. variable-energy cyclotron. Analyzed beams ($\Delta E/E \cong 0.07\%$) of 200–300 nA of fully stripped ions were typical. We used isotopically enriched targets (> 99%) of $^{54}Fe$, $^{62}Ni$, and $^{208}Pb$, with thicknesses of 100–300 $\mu g/cm^2$. The Ni and Pb targets were on 10–20-$\mu g/cm^2$ carbon backings. The reaction products were momentum analyzed by a magnetic spectrometer[6] with a solid angle of ~ $10^{-3}$ sr and detected in the focal plane by a position-sensitive proportional counter[7] backed by a plastic scintillator. This counter, described in detail elsewhere,[8] provides information on position ($B\rho$), energy loss ($dE/dx$), and time of flight. An on-line computer was used to store single-event parameters both on magnetic tape and in the computer memory for display and analysis. Unambiguous $Z$ and mass determinations of reaction products were made with typical position resolutions corresponding to $\Delta E/E \approx 0.15\%$. We report here the results for single-proton stripping. The data for a number of other reactions recorded simultaneously will be presented at a later date.

The spectra obtained for the reactions ($^{12}C$, $^{11}B$) and ($^{16}O$, $^{15}N$) on $^{62}Ni$ and $^{208}Pb$ are compared in Figs. 1 and 2. Known proton single-particle states in the residual nuclei have been labeled according to their shell-model orbits, and correspond to reactions leaving $^{11}B$ and $^{15}N$ in their ground states. The measured angular distributions peak at angles corresponding to grazing collisions at a radius of ~ $1.7(A_1^{1/3}+A_2^{1/3})$ fm but are otherwise featureless and nearly independent of the final state populated. This is consistent with previous observations of similar reactions.[2,3]

Several features can be noted by comparing the spectra. First, in all cases it is observed that the cross sections to states with $j=l+\frac{1}{2}$ ($\equiv j_>$) in the final nucleus are larger than those to states with $j=l-\frac{1}{2}$ ($\equiv j_<$). This is shown in Fig. 3 where the ratio of the peak cross sections to $j_>$ and $j_<$ states are shown for the two reactions. It is seen that $j_>$ states are populated 2–4 times more strongly than are the corresponding $j_<$ states, and the ratio is noticeably larger in the ($^{16}O$, $^{15}N$) reactions. Second, the same states are populated with different relative intensities in the two re-

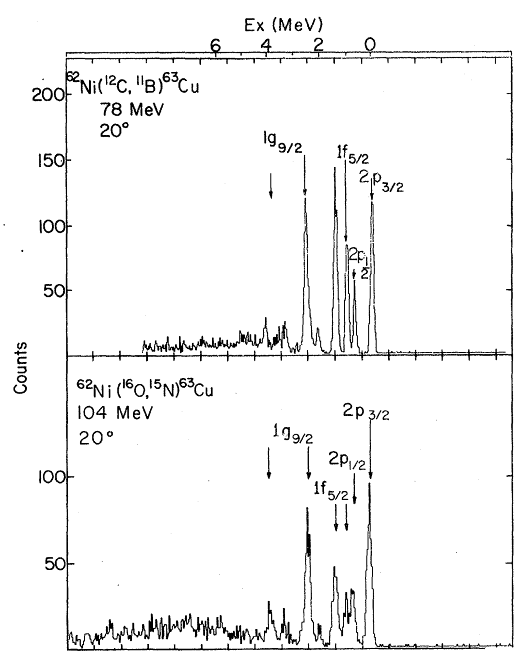


FIG. 1. Spectra for the ($^{12}C$, $^{11}B$) and ($^{16}O$, $^{15}N$) reactions on $^{62}Ni$. The states with the major fragments of the proton single-particle strength are labeled according to their shell-model orbitals.

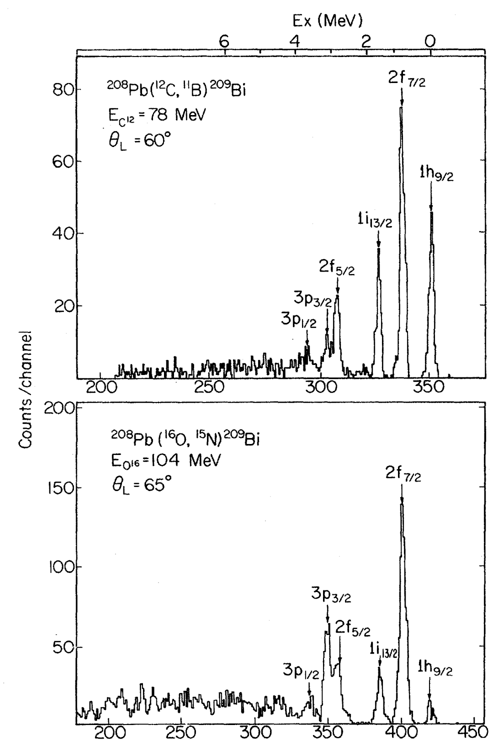


FIG. 2. Spectra for the ($^{12}C$, $^{11}B$) and ($^{16}O$, $^{15}N$) reactions on $^{208}Pb$. The six known proton single-particle states are labeled according to their shell-model orbitals.

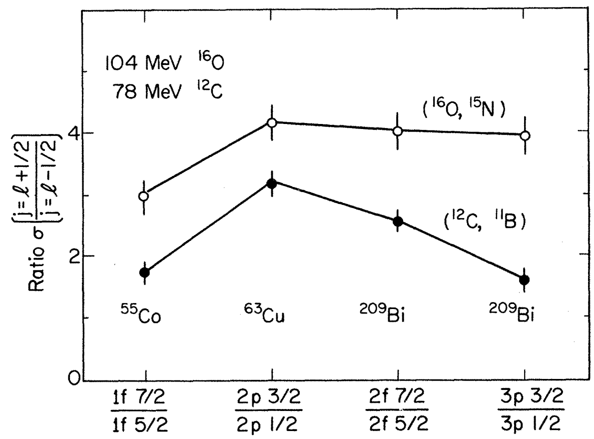


FIG. 3. Peak cross-section ratios for $j=l\pm\frac{1}{2}$ proton single-particle states in the residual nuclei indicated.

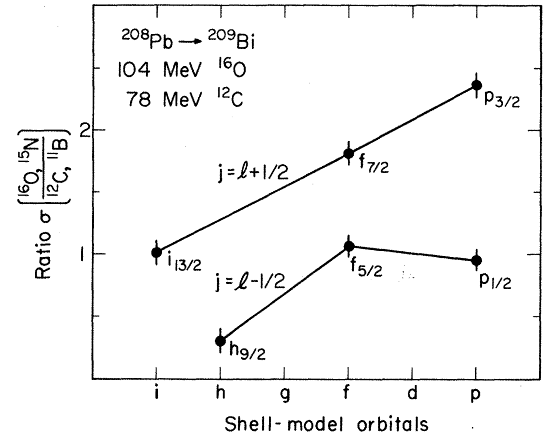


FIG. 4. Peak cross-section ratios for the ($^{16}$O, $^{15}$N) and ($^{12}$C, $^{11}$B) reactions to the same final state in $^{209}$Bi.

actions, depending on whether $j=l+\frac{1}{2}$ or $l-\frac{1}{2}$. This is shown in Fig. 4 where the ratios of the ($^{16}$O, $^{15}$N) to the ($^{12}$C, $^{11}$B) peak cross sections to the same final state are shown versus $l$ for the six single-proton states in $^{209}$Bi. Similar results to those shown in Fig. 4 were obtained for the other nuclei studied. One observes that the $j_>$ states are populated 1.5 to 3.0 times more strongly than the $j_<$ states in ($^{16}$O, $^{15}$N) compared with ($^{12}$C, $^{11}$B). DWBA calculations indicate that the results cannot be explained by $Q$-value effects, which are known to be important for heavy-ion reactions.[1-4] The results can be understood, at least qualitatively, by examining the selection rules.

The DWBA theory has been extended to include transfers between heavy ions.[4,9,5] The cross section for a nucleon transfer,

$$(c_1+p)+c_2 \to (c_2+p)+c_1,\qquad a_1\equiv c_1+p,\quad a_2\equiv c_2+p, \tag{1}$$

can be written in the following form[4,10,11]:

$$\frac{d\sigma}{d\Omega}=\frac{2a_2+1}{2c_2+1}\frac{2j_1+1}{2j_2+1}S_1S_2 \times\sum_L(2L+1)\frac{\langle j_1\tfrac{1}{2}L0|j_2\tfrac{1}{2}\rangle^2}{2j_2+1}\,\sigma_L(\theta), \tag{2}$$

where $L$ is the transferred orbital angular momentum; $c_2$ and $a_2$ are the spins of the target and the residual nuclei, respectively; $S_1, S_2$, $j_1, j_2$, and $l_1, l_2$ are the spectroscopic factors, total angular momenta, and orbital angular momenta respectively, of the transferred nucleon in the projectile (subscript 1) and residual nucleus (subscript 2). The quantity $\sigma_L(\theta)$ is the DWBA cross section for the transition $j_1l_1\to j_2l_2$ proceeding by the transfer $L$. In the above treatment, recoil effects are ignored by neglect of terms of the order of $m_p/m_{a_1}$ in the separation of the variables appearing in the DWBA integrals.[4,5] Based on these assumptions, the following selection rules apply:

$$|l_1-l_2|\le L\le l_1+l_2,\quad |j_1-j_2|\le L\le j_1+j_2,\qquad l_1+l_2+L=\text{even}. \tag{3}$$

The allowed $L$ transfers for the reactions studied here are listed in Table I. One finds that for ($^{16}$O, $^{15}$N), where a $p_{1/2}$ proton is transferred from the projectile, only one $L$ value is allowed with $L=l_2\pm1$ for $j_2=l_2\pm\frac{1}{2}$. In contrast, the ($^{12}$C, $^{11}$B) reaction, which involves a $p_{3/2}$ proton transfer from $^{12}$C, usually proceeds by two $L$ values: $L=l_2\pm1$ for either $j_2=l_2\pm1$. In a light-ion reaction, $l_1=0$ and $j_1=\frac{1}{2}$, so that only $L=l_2$ is allowed. Thus, nucleon transfer between heavy ions contains an inherent dependence on the value of $j_2$, which appears explicitly in the selection rules. This is in contrast to the $j$ dependence observed in light-ion reactions,[12] which arises from the spin-orbit part of the projectile-nucleus potential and is a small effect except for polarization phenomena.

It is unfortunate from the point of view of studying nuclear structure that the shape for $\sigma_L(\theta)$ in heavy-ion transfers is nearly independent of $L$. The magnitude, however, depends sensitively on $L$. The DWBA calculations used here typically predict $\sigma_{L+2}\approx10\sigma_L$ for a given $n_1l_1j_1$ and $n_2l_2j_2$. This strong $L$ dependence leads to a marked $j$ dependence in the magnitude of the transfer cross section. To isolate this effect the variations in

TABLE I. Allowed $L$ values.

| Residual nucleus | $n_2l_2j_2$ | ($^{12}C$, $^{11}B$) $n_1l_1j_1 = 1p_{3/2}$ Allowed $L$ [a] | ($^{16}O$, $^{15}N$) $n_1l_1j_1 = 1p_{1/2}$ Allowed $L$ [a] |
|---|---|---|---|
| $^{55}Co$ | $1f_{7/2}$ | 2, 4 | 4 |
| | $1f_{5/2}$ | 2, 4 | 2 |
| $^{65}Cu$ | $2p_{3/2}$ | 0, 2 | 2 |
| | $2p_{1/2}$ | 2 | 0 |
| | $1f_{5/2}$ | 2, 4 | 2 |
| | $1g_{9/2}$ | 3, 5 | 5 |
| $^{209}Bi$ | $1h_{9/2}$ | 4, 6 | 4 |
| | $2f_{7/2}$ | 2, 4 | 4 |
| | $1i_{13/2}$ | 5, 7 | 7 |
| | $2f_{5/2}$ | 2, 4 | 2 |
| | $3p_{3/2}$ | 0, 2 | 2 |
| | $3p_{1/2}$ | 2 | 0 |

[a]See Eq. (3) of text.

the cross section due to changes in the bound-state wave function and $Q$ values must be minimized. This can be done by comparing cross-section ratios such as those shown in Figs. 3 and 4. The cross-section ratio ($^{16}O$, $^{15}N$)/($^{12}C$, $^{11}B$), for example, is expected to be proportional to a ratio of $\sigma_L$'s [Eq. (2)]:

$$\frac{\sigma(^{16}O, ^{15}N)}{\sigma(^{12}C, ^{11}B)} \propto \frac{\sigma_{l_2+1}}{A\sigma_{l_2+1} + B\sigma_{l_2-1}}, \text{ for } j_2 = l_2 \pm 1, \qquad (4)$$

where $A$ and $B$ are statistical and coupling coefficients ($A, B \approx 1$). The $j$ dependence of the cross-section ratios exhibited in Figs. 3 and 4 can be explained, at least qualitatively, by the fact that $\sigma_{L+2} \gg \sigma_L$.

We have analyzed our data using DWBA[11] and have found that the observed $j$-dependent effects (Figs. 3 and 4) are overestimated by a factor of 2–10. Expressed in terms of relative spectroscopic factors ($S_j = S_2$), we find for $^{208}Pb(^{16}O, ^{15}N)^{209}Bi$ that the spectroscopic factors, which should be close to unity, fall into two distinct groups with $S_{j<} \approx 3S_{j>}$, whereas for ($^{12}C$, $^{11}B$), $S_{j<} \approx \frac{1}{2}S_{j>}$. The DWBA calculations for each reaction can be renormalized to give $S_{j>} \approx 1$, however. Similar results were obtained for the reactions on $^{54}Fe$ and $^{62}Ni$. A recent DWBA analysis[3] for ($^{16}O$, $^{15}N$) considered primarily $j_>$ states, and thus relative spectroscopic factors which were in agreement with those deduced using light ions could be obtained. In view of our results the reported agreement is probably fortuitous. A better understanding of the reaction mechanism is needed before one can use DWBA reliably to extract spectroscopic factors from heavy-ion nucleon transfers.

Among the many uncertainties in DWBA are the effects of recoil. Recoil effects can be included as correction terms in the no-recoil DWBA amplitudes.[4,13] These terms can affect the magnitude[4] of $\sigma_L$, and perhaps more importantly they can introduce contributions to the cross section with $L$ transfers different[14] from those allowed by the standard no-recoil DWBA expression [Eq. (3)]. These additional contributions appear qualitatively to be of the right magnitude to explain our results.[14]

Despite the uncertainties in the reliability of DWBA, the $j$ dependence observed in the present experiment indicates that nucleon transfers between heavy ions can provide spectroscopic information complementary to that obtained using light ions.

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# Mirror Asymmetry of Fermi $\beta$ Decay

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Half-lives and branching ratios for the Fermi $\beta$ decays of $^{18}$Ne, $^{22}$Mg, $^{26}$Si, and $^{34}$Ar have been studied in experiments which employed a gas-transport system. The $ft$ values for the last two are compared with the mirror decays of $^{26}$Al$^m$ and $^{34}$Cl. A difference of $(4.6 \pm 1.7)\%$ is observed for mass 34 and may be attributable to unexpectedly large charge-dependent mixing. Possible implications are discussed with respect to Cabibbo theory and the existence of an intermediate vector boson.

The intensity of a $\beta$ transition between $0^+$ analog states is determined by the Fermi matrix element connecting the states and by $G_V$, the vector coupling constant of nuclear $\beta$ decay. In the absence of charge-dependent effects—that is, if the states were exact analogs—the $ft$ values for all such transitions from states of a particular isospin would be identical, and the experimental values could be used to determine $G_V$. In practice, the accurately measured decays of $T = 1$ nuclei have intensities scattered over a range of 3%, although the experimental uncertainties for the best cases are a factor of 10 smaller than that. The scatter has been attributed to charge-dependent mixing, which would cause the initial and final states to differ from one another and in general reduce the transition strength (i.e., increase the $ft$ value), but by a different amount in each case. Because the extent of mixing has not been directly measured, the strongest accurately determined transition of this type—that of $^{26}$Al$^m$—has been chosen as being least influenced by mixing and, further, it has been assumed that what mixing effects remain can be neglected.[1] It would be of no little significance to learn if this assumption is correct since the derived value o $G_V$ may have important implications for the form factors of the $K_{l3}$ decay,[2] or for the existence of the intermediate vector boson.[1]

We report here the first accurate experimental measurements that allow comparison of mirror Fermi transitions, the results of which suggest the possibility of much greater mixing effects than have previously been believed. We have measured the decays of $^{18}$Ne, $^{22}$Mg, $^{26}$Si, and $^{34}$Ar. The last two, which will be emphasized here, are mirrors to the well-studied decays of $^{26}$Al$^m$ and $^{34}$Cl. While the measured $ft$ value for $^{26}$Si agrees with that for $^{26}$Al$^m$, the difference between $^{34}$Ar and $^{34}$Cl is $(4.6 \pm 1.7)\%$. Since many of the uncertainties in radiative and other corrections disappear for comparison within a multiplet, it appears that such a large difference must reflect significant charge-dependent mixing.

The species being studied were produced through the reactions $^{16}$O($^3$He, $n$)$^{18}$Ne, $^{20}$Ne($^3$He, $n$)$^{22}$Mg, $^{24}$Mg($^3$He, $n$)$^{26}$Si, and $^{32}$S($^3$He, $n$)$^{34}$Ar initiated by 12-MeV $^3$He particles from the Chalk River MP tandem. Targets were oxygen, neon, and hydrogen-sulfide gases and $^{24}$Mg foil, the recoil atoms