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Authors

Kovar, D.G.
Becchetti, P.D.
Harvey, B.C.
et al.

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j-DEPENDENCE OF HEAVY ION INDUCED REACTIONS*

D. G. Kovar, F. D. Becchetti, B. G. Harvey, F. Pühlhofer[†],
J. Mahoney, D. W. Miller^{††}, and M. S. Zisman

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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Abstract:

The ($^{16}\text{O}, ^{15}\text{N}$) and ($^{12}\text{C}, ^{11}\text{B}$) 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 using heavy ion reactions to complement other measurements.

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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 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-inch variable energy cyclotron. Analyzed beams ($dE/E \approx 0.07\%$) of 200-300 nanoamps of fully stripped ions were typical. Isotopically enriched targets (> 99%) of ^{54}Fe , ^{62}Ni , and ^{208}Pb with thicknesses of 100-300 $\mu\text{g}/\text{cm}^2$ were used. The Ni and Pb targets were on 10-20 $\mu\text{g}/\text{cm}^2$ carbon backings. The reaction products were momentum analyzed by a magnetic spectrometer⁶ with solid angle of $\sim 10^{-3}$ sr and detected in the focal plane by a position sensitive proportional counter⁷ backed by a plastic scintillator. This counter, described in detail elsewhere,⁸ provides information on position (Bp), 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 ($^{12}\text{C}, ^{11}\text{B}$) and ($^{16}\text{O}, ^{15}\text{N}$) on ^{62}Ni and ^{208}Pb are compared in Figs. 1-2. Known proton single-particle states in the residual nuclei have been labelled 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 $\sim 1.7(A_1^{1/3} + A_2^{1/3})$ 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 $j = \ell + 1/2$ ($\equiv j_>$) in the final nucleus are larger than those to states with $j = \ell - 1/2$ ($\equiv j_<$). 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 ($^{16}\text{O}, ^{15}\text{N}$) reactions. Second, the same states are populated with different relative intensities in the two reactions, depending on whether $j = \ell + 1/2$ or $\ell - 1/2$. This is shown in Fig. 4 where the ratios of the ($^{16}\text{O}, ^{15}\text{N}$) to the ($^{12}\text{C}, ^{11}\text{B}$) 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 ($^{16}\text{O}, ^{15}\text{N}$) compared with ($^{12}\text{C}, ^{11}\text{B}$). 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 by Buttle and Goldfarb,⁴ Trautmann and Alder,⁹ and Schmittroth, Tobocman, and Golestaneh.⁵ The cross section for a nucleon transfer

$$\begin{array}{ccc} (c_1 + p) + c_2 & \rightarrow & (c_2 + p) + c_1 \\ (a_1) & & (a_2) \end{array} \quad (1)$$

can be written in the following form,^{4,10,12}

$$\frac{d\sigma}{d\Omega} = \frac{2a_2 + 1}{2c_2 + 1} \frac{(2j_1 + 1)}{(2j_2 + 1)} S_1 S_2 \sum_L (2L + 1) \frac{(j_1 \ 1/2 \ L \ 0 | j_2 \ 1/2)^2}{(2j_2 + 1)} \sigma_L(\theta) \quad (2)$$

where L is the transferred orbital angular momentum, c_2 , a_2 are the spins of the target and residual nuclei, and $S_1 j_1 l_1$, $S_2 j_2 l_2$ are the spectroscopic factor, total and orbital angular momentum of the transferred nucleon in the projectile and residual nucleus, respectively. The quantity $\sigma_L(\theta)$ is the DWBA cross section for the transition $j_1 l_1 \rightarrow j_2 l_2$ proceeding by the transfer L . In the above treatment recoil effects are ignored by neglect of terms of the order 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:

$$\begin{aligned} |l_1 - l_2| &\leq L \leq l_1 + l_2 \\ |j_1 - j_2| &\leq L \leq j_1 + j_2 \\ l_1 + l_2 + L &= \text{even} \end{aligned} \quad (3)$$

The allowed L transfers for the reactions studied here are listed in Table 1. One finds that for ($^{16}_O, ^{15}_N$), where $p_{1/2}$ proton is transferred from the projectile, only one L value is allowed with $L = \ell_2 \pm 1$ for $j_2 = \ell_2 \pm 1/2$. 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: $L = \ell_2 + 1$ and $\ell_2 - 1$ for either $j_2 = \ell_2 \pm 1$. In a light ion reaction $\ell_1 = 1$, $j_1 = 1/2$ so that only $L = \ell_2$ 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 reactions¹¹ 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 $\sigma_{L+2} \approx 10 \sigma_L$ for a given $n_1 \ell_1 j_1$ and $n_2 \ell_2 j_2$. 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 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 σ_L 's (Eq. (2)):

$$\frac{\sigma(^{16}_O, ^{15}_N)}{\sigma(^{12}_C, ^{11}_B)} \propto \frac{\sigma_{\ell_2 \pm 1}}{(A\sigma_{\ell_2 \pm 1} + B\sigma_{\ell_2 - 1})} \quad \text{for } j_2 = \ell_2 \pm 1 \quad (4)$$

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 DWBA¹² and have found that the observed j -dependent effects (Figs. 3,4) are overestimated by a factor of 2-10. Expressed in terms of relative spectroscopic factors ($S_{j_1} = S_{j_2}$) we find for $^{208}\text{Pb}(^{16}\text{O}, ^{15}\text{N})^{209}\text{Bi}$ that the spectroscopic factors, which should be close to unity, fall into two distinct groups with $S_{j_1} \approx 3 S_{j_2}$, whereas for $(^{12}\text{C}, ^{11}\text{B})$, $S_{j_1} \approx 1/2 S_{j_2}$. The DWBA calculations for each reaction can be renormalized to give, $S_{j_1} \approx 1$, however. Similar results were obtained for the reactions on ^{54}Fe and ^{62}Ni . A recent DWBA analysis³ for $(^{16}\text{O}, ^{15}\text{N})$ considered primarily j_1 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.^{4,14} These terms can affect the magnitude⁴ of σ_L and perhaps more importantly they can introduce contributions to the cross section with L transfers different¹³ 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.¹³

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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FOOTNOTES AND REFERENCES

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† Present Address: Universität Marburg, Marburg, Germany.

†† Present Address: Indiana University, Bloomington, Indiana 47401.

1. See for example: Nuclear Reactions Induced by Heavy Ions, ed. by R. Bock and W. Hering (North-Holland, Amsterdam, 1970); Proceedings of the International Conference on Heavy Ion Physics (Dubna, 1971); J. Phys. (Paris) Suppl. 11-12, Tome 32 (1971).
2. A. R. Barnett, P. J. A. Buttle, L. J. B. Goldfarb, and W. R. Phillips, Nucl. Phys. A176, 321 (1971).
3. G. C. Morrison, H. J. Körner, L. R. Greenwood, and R. H. Siemssen, Phys. Rev. Letters 28, 1662 (1972).
4. P. J. A. Buttle and L. J. B. Goldfarb, Nucl. Phys. A176, 299 (1971) and references cited therein.
5. F. Schmittroth, W. Tobocman, and A. A. Golestaneh, Phys. Rev. C1, 377 (1970).
6. D. L. Hendrie, J. R. Meriwether, and F. B. Selph, to be published. J. B. Selph, UCID-3388, LBL Report (1969) unpublished.
7. C. J. Borkowski and M. K. Kopp, IEEE Trans. Nucl. Sci., NS-17, No. 3, 340 (1970).
8. B. G. Harvey, J. Mahoney, F. G. Pühlhofer, F. S. Goulding, D. A. Landis, J.-C. Faivre, D. G. Kovar, M. S. Zisman, J. R. Meriwether, S. W. Cosper, and D. L. Hendrie, to be published in Nucl. Instr. Methods.
9. D. Trautmann and K. Alder, Helv. Phys. Acta 43, 363 (1970).
10. T. Kammuri, private communication.
11. L. L. Lee, Jr. and J. P. Schiffer, Phys. Rev. Letters 12, 108 (1964).

12. The DWBA form factors were calculated using program RDRC (W. Tobocman, unpublished). The DWBA cross sections were calculated using program DWUCK (P. D. Kunz, unpublished).
13. M. Nagarajan, submitted to Nucl. Phys.
14. K. R. Greider, Nuclear Reactions Induced by Heavy Ions, ed. by R. Bock and W. Hering (North-Holland, Amsterdam, 1970).

Table 1. Allowed L Values

Residual nucleus	$(^{12}\text{C}, ^{11}\text{B})$		$(^{16}\text{O}, ^{15}\text{N})$
	$n_2 l_2 j_2$	$n_1 l_1 j_1 = 1p_{3/2}$ Allowed L ^a	$n_1 l_1 j_1 = 1p_{1/2}$ 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

^aSee Eq. (3) of text.

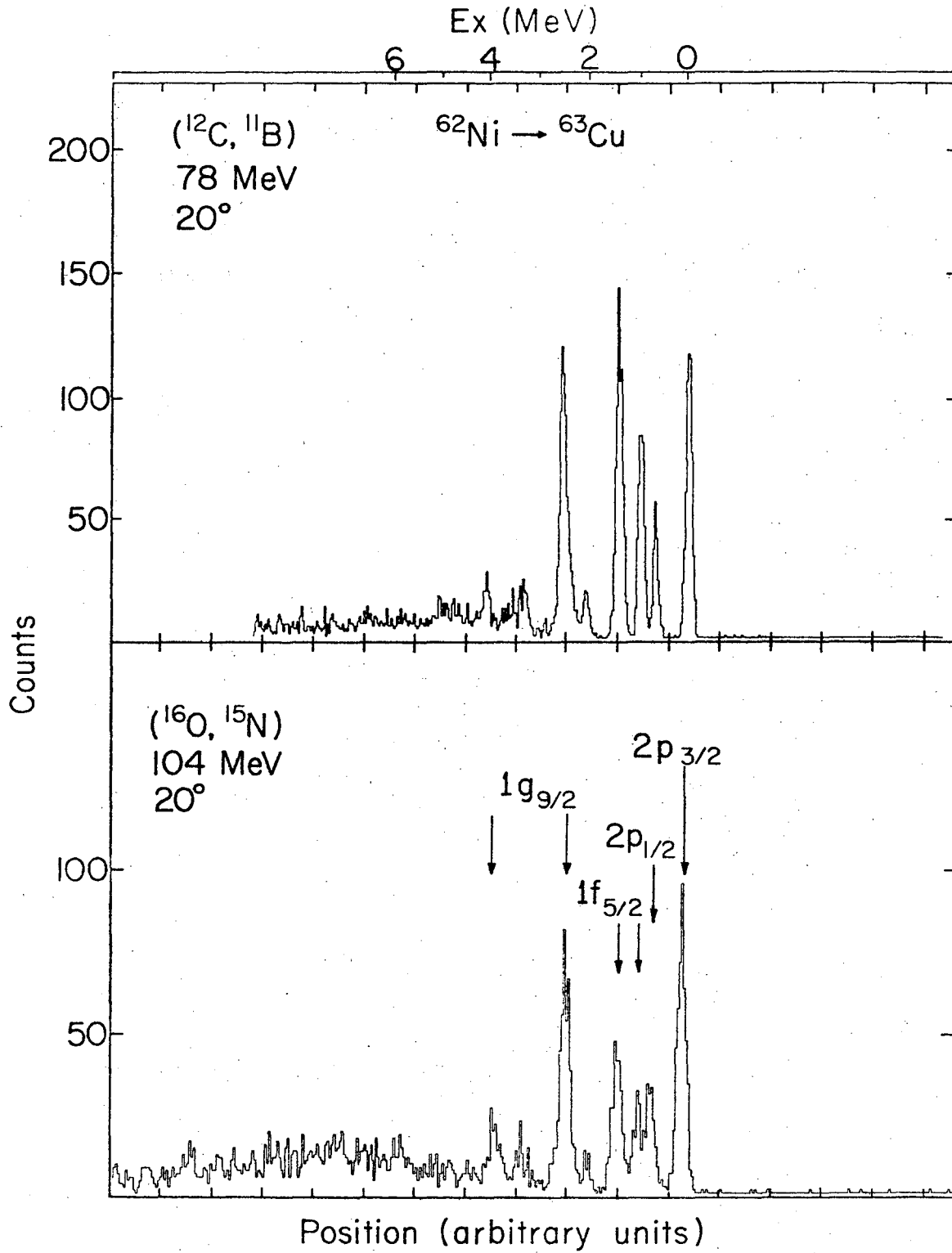
FIGURE CAPTIONS

Fig. 1. Spectra for the ($^{12}\text{C}, ^{11}\text{B}$) and ($^{16}\text{O}, ^{15}\text{N}$) 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 ($^{12}\text{C}, ^{11}\text{B}$) and ($^{16}\text{O}, ^{15}\text{N}$) reaction on ^{208}Pb . The six known proton single-particle states are labeled according to their shell model orbitals.

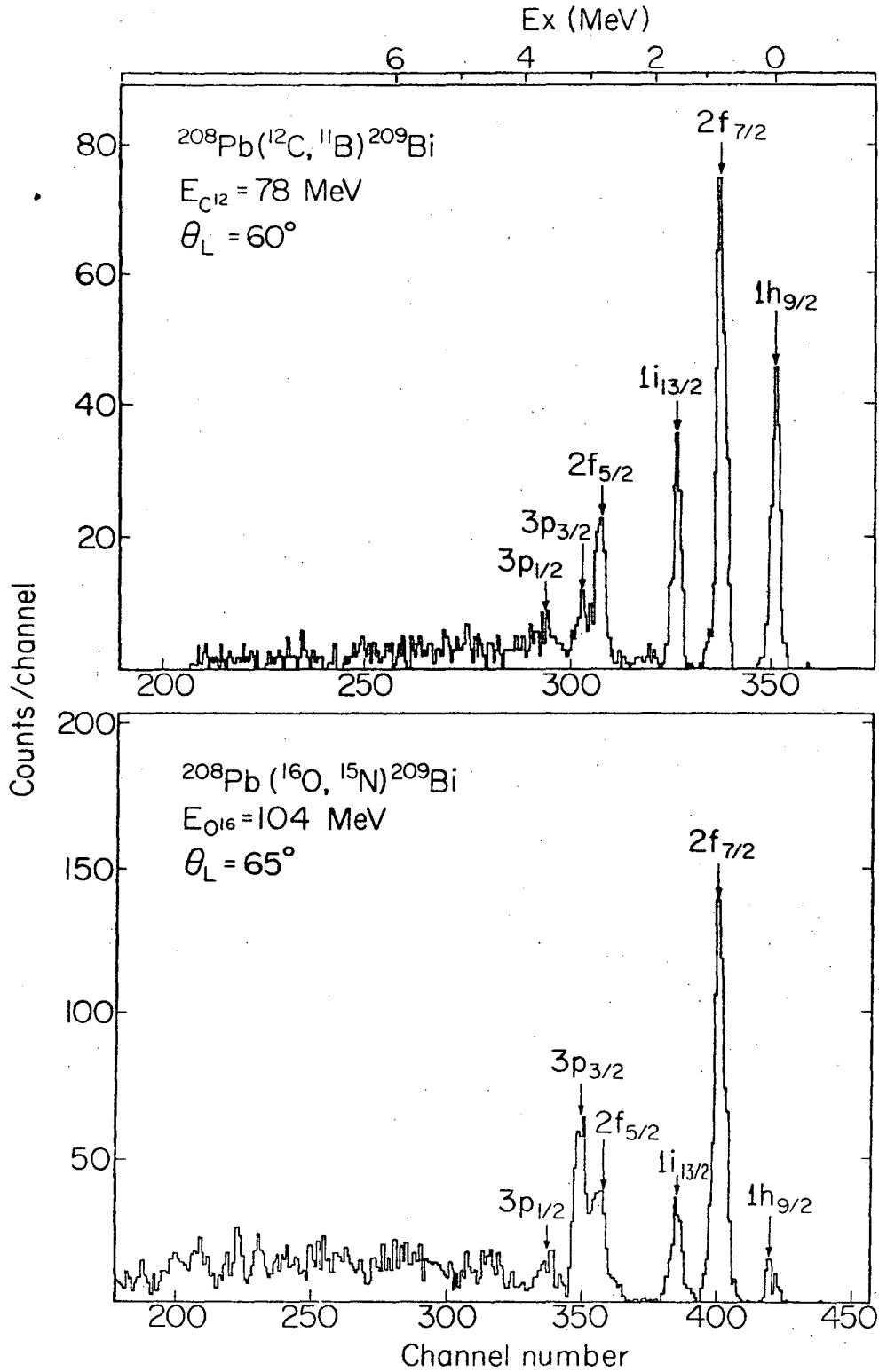
Fig. 3. Peak cross section ratios for $j = \ell + 1/2$ and $j = \ell - 1/2$ proton single-particle states in the residual nuclei indicated.

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



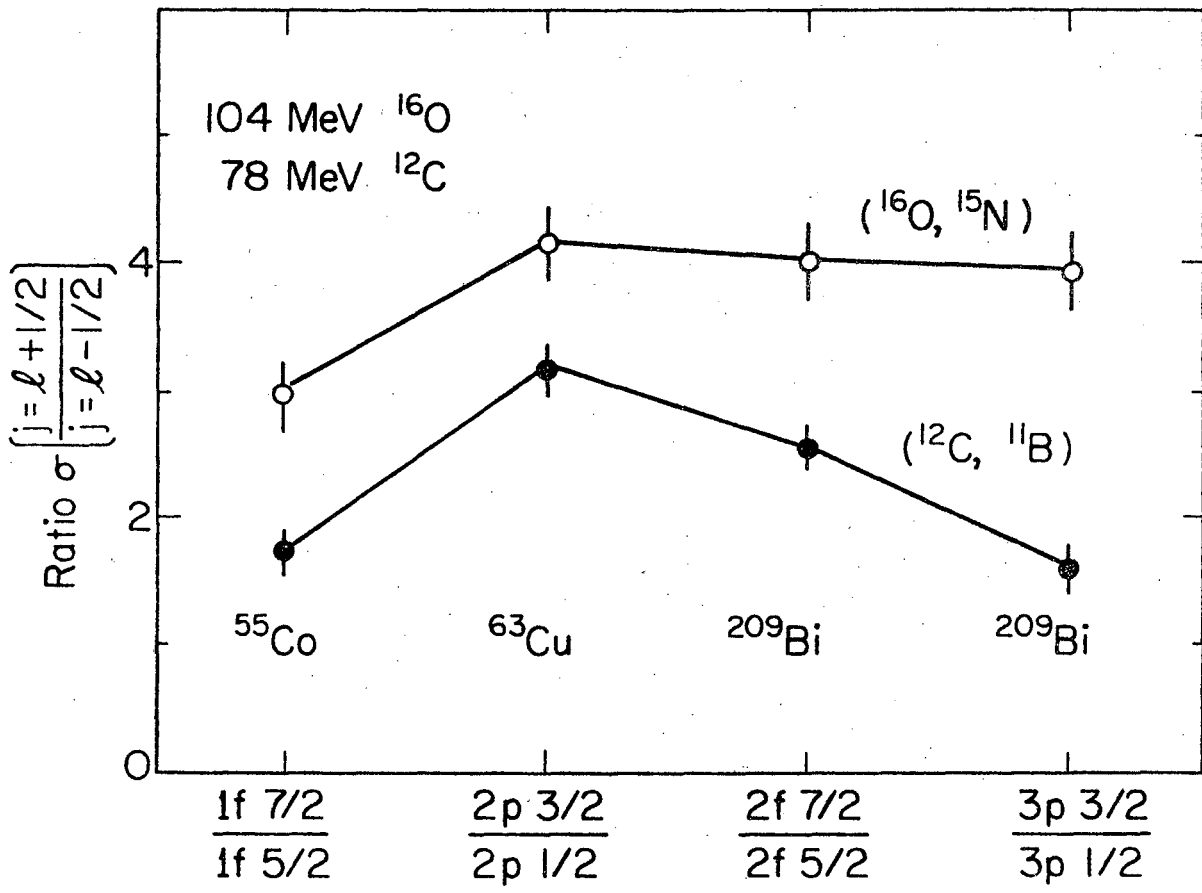
XBL726-3229

Fig. 1



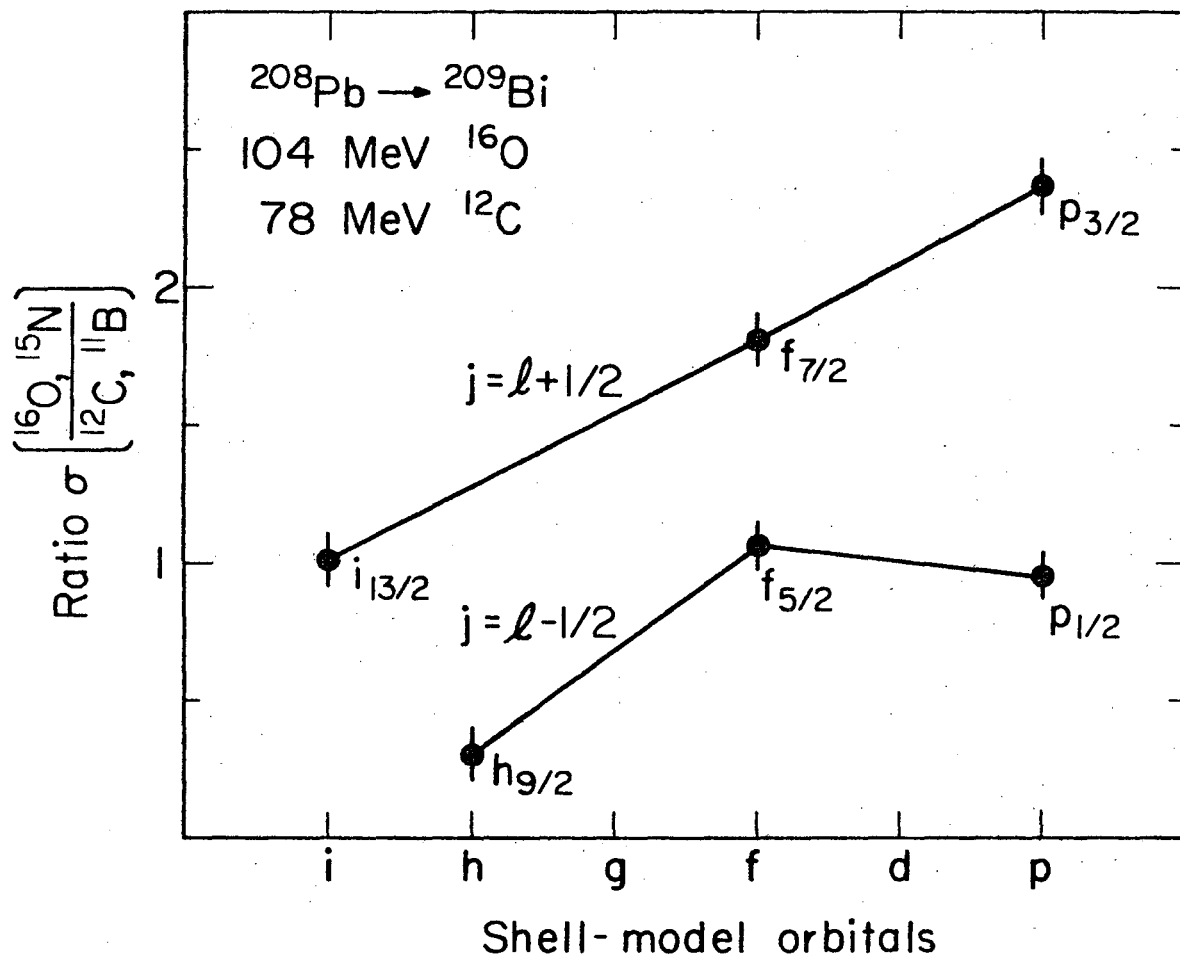
XBL726-3221

Fig. 2



XBL 726-3225

Fig. 3



XBL726-3224

Fig. 4

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720