Title

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EVIDENCE FOR RECOIL EFFECTS IN HEAVY ION TRANSFER REACTIONS*

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Abstract:

Data are presented for single proton transfer reactions induced by ^{12}C and ^{16}O ions on ^{208}Pb at high bombarding energies. Analysis using no-recoil DWBA yields spectroscopic factors in marked disagreement with light ion results. Analysis using DWBA theory including first order recoil corrections indicates that the discrepancies are largely, if not entirely, the result of ignoring recoil effects.

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At present it is the uncertainties in reaction theories for heavy ions which have to a large extent thus far limited the spectroscopic information obtainable from heavy ion transfer reactions.[1,2] These uncertainties mainly concern the question of the validity of some of the approximations used in DWBA,[3,4,5,] in particular the "no-recoil" approximation.

The DWBA transition amplitude for a transfer reaction,

$$\underbrace{(c_1 + p)}_{a_1} + c_2 \longrightarrow c_1 + \underbrace{(c_2 + p)}_{a_2} \qquad (1)$$

can be written as;[4]

$$T = \int d\underset{\sim}{r}_i \int d\underset{\sim}{r}_f \; \chi^{(-)*}(\underset{\sim}{k}_f, \underset{\sim}{r}_f) \, \langle a_2 c_1 | V | a_1 c_2 \rangle \, \chi^{(+)}(\underset{\sim}{k}_i, \underset{\sim}{r}_i) \qquad (2)$$

where χ are the distorted waves and the matrix element is the form factor. Computation of the six dimensional integral is lengthy[5] and is usually reduced to a simpler three dimensional integral using the no-recoil approximation, i.e.,[4]

$$\underset{\sim}{r}_i = \underset{\sim}{r} - (m_p/M_{a_1})\underset{\sim}{r}_1 \approx \underset{\sim}{r} \quad , \qquad (3)$$

and,

$$\underset{\sim}{r}_f = (M_{c_2}/M_{a_2})\underset{\sim}{r} + (m_p/M_{a_2})\underset{\sim}{r}_1 \approx (M_{c_2}/M_{a_2})\underset{\sim}{r} \quad , \qquad (4)$$

where $\underset{\sim}{r}$ is the vector between the cores c_1 and c_2, and $\underset{\sim}{r}_1$ and $\underset{\sim}{r}_2$ are the vectors connecting the transferred particle, p, in a_1 and a_2 to the cores c_1 and c_2, respectively. The validity of this approximation is questionable for many reactions.[3,5] In particular it can be shown that, because they are vectors, the inclusion of the recoil terms (i.e., the neglected terms of order $(m_p/M_c)\underset{\sim}{r}_1$) has the effect of introducing additional angular momentum transfer which may significantly change the calculated cross section.[5,6] In the present study we show that the contributions arising from the recoil terms are important and that their effects can be predicted by a simple first order treatment.

The reactions ($^{12}C,^{11}B$) at 78 MeV and ($^{16}O,^{15}N$) at 104 MeV and 140 MeV on ^{208}Pb were studied using the magnetic spectrometer at the Lawrence Berkeley Laboratory 88-inch cyclotron.[7] Sample spectra for ($^{16}O,^{15}N$) are shown in Fig. 1. The proton single particle states in ^{209}Bi, which dominate the spectra, are populated with different relative intensities at the different ^{16}O bombarding energies. As noted previously,[8] the $j = \ell + 1/2(\equiv j_>)$ final states are populated more strongly than the $j = \ell - 1/2(\equiv j_<)$ states in the single proton transfer reactions induced by either ^{12}C or ^{16}O. In the 140 MeV ^{16}O reaction this feature is much less pronounced than at the lower bombarding energy.

The differential cross sections extracted were analyzed with no-recoil DWBA[4,9] using finite range form factors[9,10] and the distorted wave code DWUCK.[11] Optical model parameters were deduced from fitting elastic scattering and bound state parameters were taken from the literature.[12] The fits to the angular distributions are shown by the solid lines in Fig. 2. The DWBA cross sections have the correct shapes, but are shifted back in angle for states at higher excitation, contrary to experiment. These shifts are largest in the 78 MeV ^{12}C reaction, noticeable in the 104 MeV ^{16}O reaction, and not detectable in the 140 MeV ^{16}O reaction. The shapes of the angular distributions for ($^{12}C,^{11}B$) are sufficient to show an L dependence: at large angles the larger L transfers drop more rapidly than the smaller L transfers. DWBA predicts this L-dependence for all but the $i_{13/2}$ state (L = 5,7) whose steep drop is not reproduced.

Relative spectroscopic factors obtained from fitting the integrated cross sections (shown in the figures as dashed curves) are listed in Table I together with the L transfer allowed in the no-recoil formalism.[4] Spectroscopic factors from the (^{16}O,^{15}N) reaction for the $j_<$ states in ^{209}Bi uniformly exceed those for the $j_>$ states (by a factor of ~ 4 at 104 MeV and ~ 8 at 140 MeV). In contrast, those for the $j_<$ states from the (^{12}C,^{11}B) reaction are about half those deduced for the $j_>$ states. The results of no-recoil DWBA analysis are: 1) It is not possible to obtain consistent spectroscopic factors simultaneously for both $j_<$ and $j_>$ states for either reaction. 2) Spectroscopic factors for the $j_<$ and $j_>$ states obtained in the ^{12}C and ^{16}O reactions show opposite deviations. 3) Discrepancies in the spectroscopic factors for the ^{16}O reactions increase with increasing bombarding energies. These results are rather insensitive to variations in optical model and bound state parameters. The (^{16}O,^{15}N) and (^{12}C,^{11}B) reactions on nuclei A = 50 to 100 show similar results.[2,8,13]

To investigate the importance of recoil effects we have extracted spectroscopic factors using a DWBA theory which includes first order recoil corrections in the framework of no-recoil DWBA.[6] A Taylor expansion is made of $\chi^{(+)}(\underset{\sim}{k}_i,\underset{\sim}{r}_i)$ keeping terms of the order $(m_p/M_{c_1})\underset{\sim}{r}_1$. The corresponding terms in the expansion of $\chi^{(-)*}(\underset{\sim}{k}_f,\underset{\sim}{r}_f)$ are neglected here since $m_p << M_{c_2}$. The transfer cross section then contains first order correction terms which are added coherently to the normal no-recoil transition amplitudes and can be written schematically as;

$$\frac{d\sigma}{d\Omega} \propto \sum_L |T_L + K\,T'|^2 = \sum_L \left|T_L + K\left(\sum_{L_R} T_{L_R}\right)\right|^2 \qquad (5)$$

The no-recoil transition amplitude, T_L, obeys the usual no-recoil selection rules. The recoil correction term, T', in a general perturbative treatment would be composed of several no-recoil transition amplitudes calculated with several different L transfers. In this first order treatment the number of transition amplitudes used to evaluate the recoil correction term is greatly reduced and only a single transition amplitude (for $L_R = \ell_2$) is needed. The coefficient K contains a mass factor (m_p/M_{a_1}), the wave number, k_i, at the interaction distance, and a nuclear overlap integral.[6] Under the approximation of a weakly bound final state (made in this calculation) K can be written as;

$$K = k_i(m_p/M_{a_1})(2\ell_1 + 1)/\kappa_2 \quad , \tag{6}$$

where κ_2 is the bound state decay constant for the final state.

Since large L transfers are favored in our reactions (e.g., $\sigma_{L+2} \approx 10\ \sigma_L$), the recoil corrections in this treatment will clearly be most important for those cases where L_R is larger than the allowed no-recoil L transfer. Using the L selection rules[4] one can predict that the recoil contributions will be important for the $(^{16}O,^{15}N)$ transfers to the $j_<$ states $(L_R > L)$, but not so important in the transfer to the $j_>$ states $(L_R < L)$. In the $(^{12}C,^{11}B)$ transfers the recoil corrections will make only small changes in the cross sections for both the $j_<$ and $j_>$ states since $L_R < L$, and significant recoil effects appear only through the interference (5). The magnitude of the recoil effects also depends on the size of the coefficient K which is determined by the mass transferred, the binding energy of the final state populated, and the bombarding energy. It should also be noted that in first order L_R violates the parity selection rule of no-recoil DWBA theory.

DWBA cross sections were calculated as outlined above using finite range form factors with DWUCK. The shapes of the angular distributions are nearly the same as those obtained from no-recoil calculations. The relative spectroscopic factors extracted are listed in Table I together with the L transfer and the L_R used to calculate the recoil correction terms. The effect of the recoil corrections is to significantly reduce the differences in the spectroscopic factors for the $j_<$ and $j_>$ states in both the ^{12}C and ^{16}O induced reactions. While there are still problems, such as the predicted energy dependence of the (^{16}O,^{15}N) transfers to the $j_>$ states, the agreement with the light ion results is much improved. Even better agreement is probably hindered by the approximations made in the present treatment. Most serious is our approximation for the overlap integral which is valid only for weakly bound states.[6] Nevertheless, the results demonstrate that the largest part of the discrepancies can be removed by including recoil effects.

We conclude from our study that recoil effects in heavy ion transfer reactions can be large and that they must be treated properly before spectroscopic information can be extracted reliably.

FOOTNOTES AND REFERENCES

[*] Work performed under the auspices of the U. S. Atomic Energy Commission.

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Table I. Spectroscopic factors obtained from analysis using no-recoil DWBA and no-recoil DWBA including recoil effects in first order.

Ex (MeV)	nlj	No-Recoil Spectroscopic Factors					Recoil Spectroscopic Factors (First Order)					
		(^{16}O,^{15}N)[a]			(^{12}C,^{11}B)[b]		(^{16}O,^{15}N)[a]			(^{12}C,^{11}B)[b]		(^{3}He,d)
		L	104 MeV	140 MeV	L	78 MeV	L	104 MeV	140 MeV	L	78 MeV	Ref. 14
0.00	$1h_{9/2}$	4	3.04	3.84	4,6	0.63	4,(5)[d]	1.32	1.28	4,(5)[d],6	0.78	1.00
0.90	$2f_{7/2}$	4	0.80	0.48	2,4	0.99	(3),4	1.00[c]	0.57	2,(3),4	1.00[c]	1.12
1.61	$1i_{13/2}$	7	0.66	0.40	5,7	0.86	(6),7	0.80	0.48	5,(6),7	0.86	0.94
2.84	$2f_{5/2}$	2	3.20	3.20	2,4	0.56	2,(3)	1.12	0.77	2,(3),4	0.75	1.14
3.12	$3p_{3/2}$	2	0.92	0.48	0,2	1.56	(1),2	1.28	0.59	0,(1),2	1.72	1.08
3.64	$3p_{1/2}$	0	2.80	4.80	2	0.47	0,(1)	0.82	0.84	(1),2	0.66	0.7-0.9

[a,(b)] Normalization factor N = 1.25(3.20) used in obtaining (^{16}O,^{15}N) and (^{12}C,^{11}B) spectroscopic factors, respectively.

[c] Normalization factors obtained by normalizing these spectroscopic factors to unity.

[d] The L values in parentheses are the L_R used in recoil corrections. The others are those allowed in no-recoil DWBA theory.

FIGURE CAPTIONS

Fig. 1. Spectra obtained for the ^{208}Pb(^{16}O,^{15}N)^{209}Bi reaction at ^{16}O energies of 104 MeV and 140 MeV. The proton single-particle states are labelled by their shell model orbitals.

Fig. 2. The predicted DWBA cross sections for the (^{16}O,^{15}N) transfers to the six proton single-particle states in ^{209}Bi are shown by the solid curves. The dashed curves are the DWBA predictions shifted so as to fit the integrated cross sections.

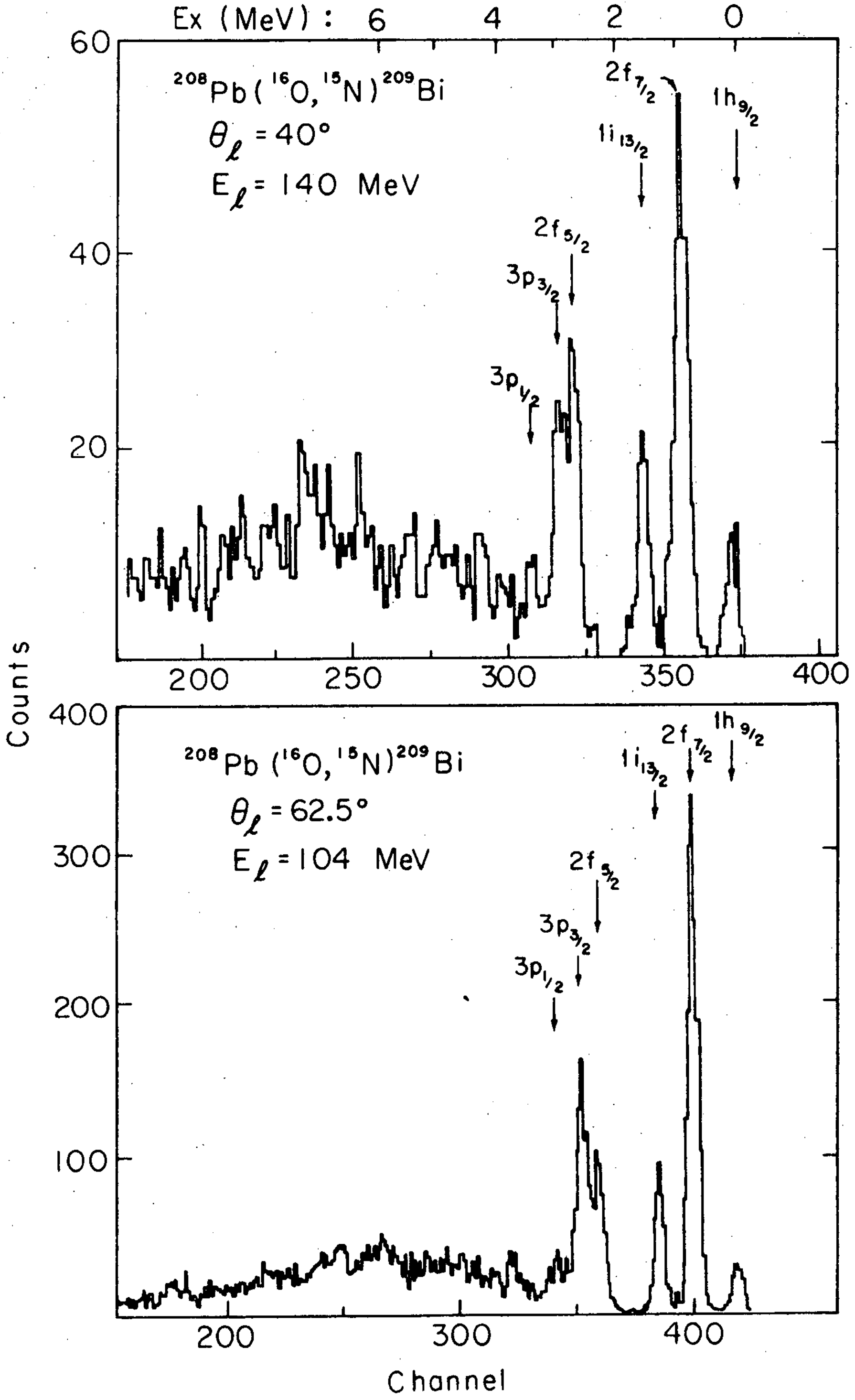

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Fig. 1

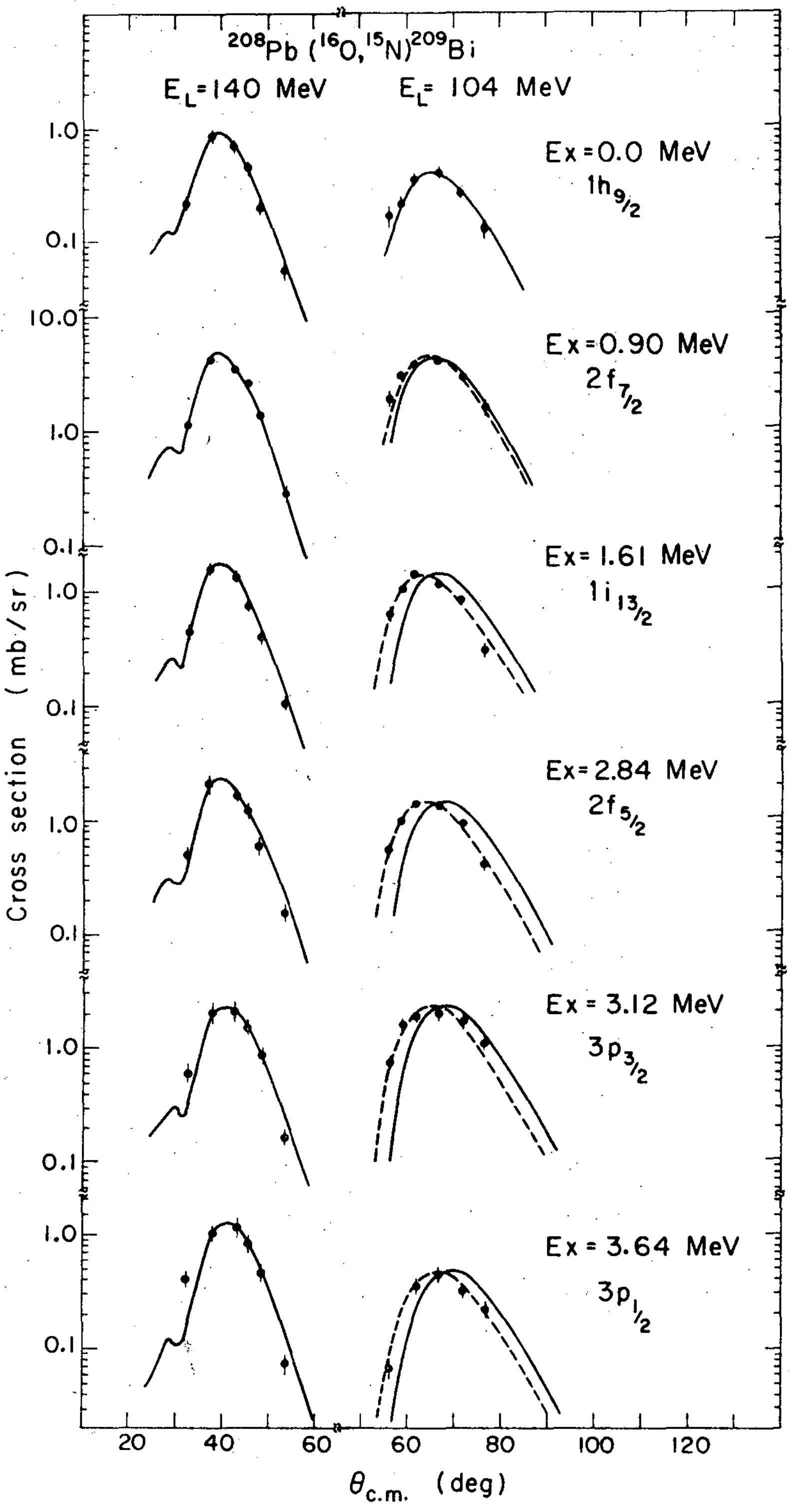

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Fig. 2

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