Strong Two-Step Contributions in Direct Allowed Two-Nucleon Transfers

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The $h_{9/2}g_{9/2}$ multiplet in ^{210}Bi was populated by ^{208}Pb(α,d) in experiments at 33 and 48 MeV. The strong favoring of the five unnatural-parity states of the multiplet disagrees with one-step transfer distorted-wave Born-approximation predictions. Coupled-reaction-channels calculations explain this effect as interference of direct *np* transfer and successive stripping amplitudes of comparable magnitude. This holds for weak (low-spin) and strong (high-spin) members of the multiplet.

Generally, two-step processes in nuclear transfer reactions have been found to be important in situations where direct, one-step amplitudes are small, or where sensitive details—such as projectile polarization—are involved.[1-7] While some theoretical results imply that two-step contributions may be significant in all two-nucleon transfers,[7,8] direct experimental evidence for these has normally been limited to relatively weak transitions or to nuclei with significant deformation. This experiment presents striking evidence that two-step processes of the sequential stripping type are also important in two-nucleon transfer where the one-step amplitudes are allowed, large, and easily calculated. The presence of large multistep amplitudes here is signaled by a strong interferencelike enhancement of the ^{208}Pb(α, d)^{210}Bi cross sections for certain states in the $h_{9/2}g_{9/2}$ (two-particle) ^{210}Bi ground-state multiplet and a similarly dramatic weakening for others.

$^{208}_{82}$Pb$_{126}$ is a closed-shell, spherical target nucleus. The ten-member $\pi h_{9/2}\nu g_{9/2}$ ground-state multiplet of $^{210}_{83}$Bi is well known and expected to be of very pure two-particle character, a shell-model prediction[9,10] that has been well supported experimentally for all multiplet members[11] (except perhaps the 8$^-$ state). The multiplet excitation energies range from 0 to 0.582 MeV, where-

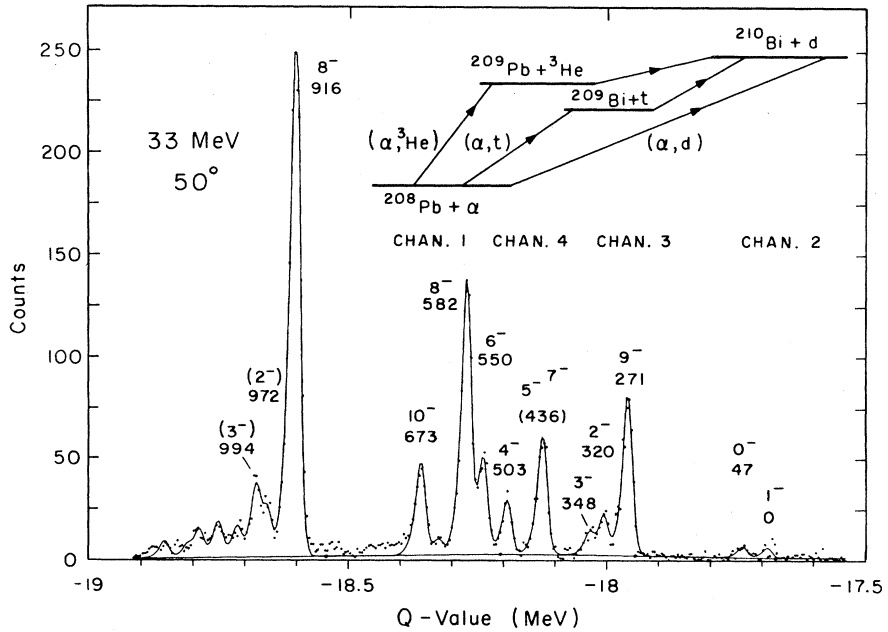

FIG. 1. ^{208}Pb(α,d)^{210}Bi spectrum for states below 1 MeV. All levels up to 582 keV are members of the $h_{9/2}g_{9/2}$ ground-state multiplet. The inset shows the three most important reaction channels through which the multiplet can be populated.

as the first excited state (3^-) of ^{208}Pb lies at 2.61 MeV and is only weakly collective ($\beta = 0.1$). Hence, previous experience would suggest that the reaction ^{208}Pb$(\alpha, d)^{210}$Bi should be well predicted by conventional (one-step) microscopic distorted-wave Born-approximation (DWBA) calculations.[12] However, as shown below, such predictions fail badly and in a systematic way.

We have investigated the population of the $h_{9/2}g_{9/2}$ ground-state multiplet of ^{210}Bi by the reaction ^{208}Pb$(\alpha, d)^{210}$Bi at $E_\alpha = 48$ and at 33 MeV. At both energies, angular distributions ($10° \leq \theta \leq 40°$ and $10° \leq \theta \leq 60°$, respectively) for nine levels of the ten-member multiplet were obtained. The unresolved 5^- level is known from particle-γ work.[11] It lies close to the 7^- level (higher by 6 keV) and is expected to be weaker by a factor of 3–4. The energy spectrum (Fig. 1) of the low-lying ^{210}Bi states (resolution = 16 keV) shows a slight broadening and energy shift of the 7^- peak, and searches with a peak-fitting program indicate that the 5^- state must be weaker by a factor of 2 or more. In both experiments, the reaction products were analyzed by position-sensitive gas proportional counters in the focal plane of quadrupole–triple-dipole spectrographs. The experimental resolution was not limited by the detectors but by contributions from target thickness and beam quality. The 33-MeV experiment was performed with the MP tandem at the Max Planck Institut, Heidelberg, Germany. The 48-MeV experiment was performed with the Princeton University cyclotron. At 33 MeV the angular distributions are flat and unstructured.[13] At 48 MeV the expected structure for small L and strong forward peaking for larger L are seen.[14]

A prominent feature of the cross sections integrated over the observed angular range is the large up-down step pattern as a function of J, as shown in Figs. 2(a) and 2(b). Conventional, microscopic DWBA analyses were made with the zero-range code DWUCK4 and the finite-range code LOLA.[15] For both energies, one-step transfer calculations with suitable optical-model parameters[16] reproduce the angular distributions well for $L < 9$, but fail to explain the step pattern of the relative transition strengths to the individual members of the $h_{9/2}g_{9/2}$ multiplet. Inclusion of the very small predicted admixtures from other configurations[9,10] ($S \leq 0.01$) leads to a general enhancement of all computed cross sections, but leaves the predicted monotonic rise of σ_t with J unchanged. This is shown in Fig. 2(a) where the lines marked DWBA show the results from the

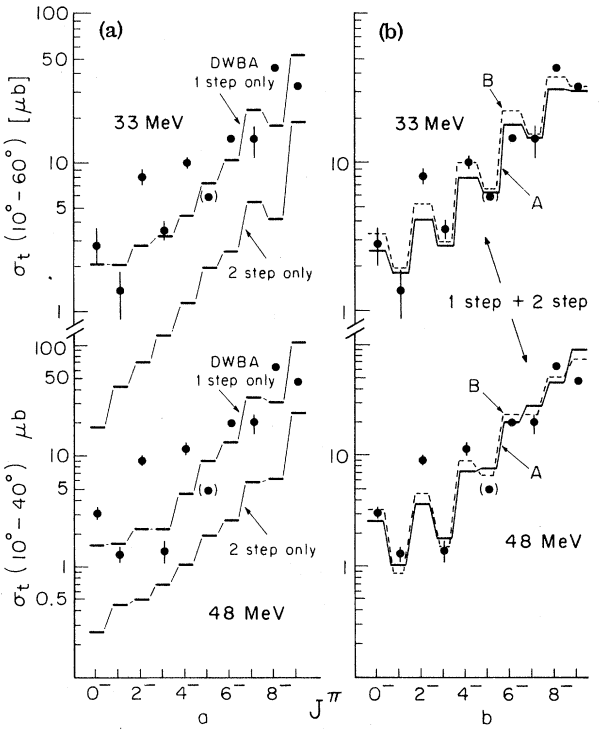

FIG. 2. Integrated experimental ^{208}Pb$(\alpha, d)^{210}$Bi cross sections compared to four sets of transfer calculations. (a) The values obtained from standard microscopic one-step DWBA calculations are connected by the lines labeled DWBA. Cross sections from *pure* two-step CRC lie on the lower lines. (b) Interpretation (saw-tooth-shaped line) of the data obtained through the coherent addition of one-step and two-step amplitudes described in the text and in Fig. 1. Calculated cross sections labeled A (solid lines and solid horizontal bars) are CRC calculations where all parameters were fixed by other reactions. The calculated cross sections labeled B (dashed lines) are obtained if a much less absorptive ^{3}He potential is used or if D_0 for the weak $(\alpha, {}^3\text{He})({}^3\text{He}, d)$ channel is doubled.

full microscopic DWBA calculations, obtained for the ^{210}Bi wave functions of Ref. 9. The measured integrated cross sections and the DWBA calculations are in systematic disagreement. If the (zero-range) DWBA calculations are normalized so that they agree best for the natural-parity levels, the five well-resolved unnatural-parity states are underpredicted by factors 3 to 6 at 48 MeV and by 2 to 4 at 33 MeV. Much stronger mixing of the $h_{9/2}g_{9/2}$ multiplet with the neighboring $f_{7/2}g_{9/2}$ configuration would reduce the discrepancy for the 8^- state, but not for the other levels. In any case, no available shell-model calculation predicts mixing stronger than that of Ref. 9, and after a detailed investigation of the

effects of different ^{210}Bi wave functions, finite range, other optical-model parameters, etc., it had to be concluded that one-step DWBA could not reproduce the data at either energy.

Motivated by the known importance of two-step processes in many weaker transitions, we computed two-step transition amplitudes for the reaction channels ^{208}Pb$(\alpha,t;t,d)^{210}$Bi and ^{208}Pn$(\alpha,{}^3\mathrm{He};{}^3\mathrm{He},d)^{210}$Bi with the coupled-reaction-channels (CRC) code CHUCK2[17] (see inset in Fig. 1). Well-matched global deuteron parameters and deep α potentials, similar to those of Ref. 16, were used. The intermediate-state ^{3}He and t wave functions were generated by global potentials[18] for free ^{3}He and t projectile scattering at the appropriate energies. In the physical context emphasized in the second paragraph (inert ^{208}Pb core) these calculations are straightforward, with well-known spectroscopic amplitudes, because for each two-step process there is only one important intermediate state: the $g_{9/2}$ ground state of ^{209}Pb or the $h_{9/2}$ ground state of ^{209}Bi. We used zero-range normalization constants D_0 very close to the conventional values which, for the optical parameters used here, fitted the known[19] reactions ^{208}Pb(α,t), ^{208}Pb$(\alpha,{}^3\mathrm{He})$, ^{208}Pb(t,d), and ^{208}Pb$({}^3\mathrm{He},d)$. The two-step *cross sections* obtained lie a factor of 3 below the one-step results and show the *same* monotonic J dependence [compare curves labeled "2 step only" in Fig. 2(a)]. This means, however, that with predicted two-step *amplitudes* near 60% of one-step amplitudes, maximal "interference" effects could modify total cross sections by factors of 0.2–2.5.

The $\sigma_t(J)$ "saw-tooth" patterns in Fig. 2(b) are theoretical cross sections resulting from a coherent addition of the one- and two-step transfer amplitudes identified in Fig. 1. The solid line connects the cross sections for calculations with no adjustable parameters. The phase prescribed by theory for the individual reaction channels that are not part of the code CHUCK2 and the products of the spectroscopic amplitudes $CS^{1/2}D_0$ are shown in Table I. In (α,d) the two sequential modes are not identical, as they have different intermediate states ($\pi h_{9/2}$ vs $\nu g_{9/2}$). If the neutron transfer precedes the proton transfer, reordering (from np to pn) in the ^{210}Bi wave function is required. There is no corresponding reordering phase in the projectile wave functions. Hence this operation produces the (structure related) phase factor $-(-1)^{j_1+j_2-J}$ in the $(\alpha,{}^3\mathrm{He};{}^3\mathrm{He},d)$ channel only. There is an additional minus sign in both two-step paths that comes from antisymmetry considerations of the particle reordering. The i^L factors (from the spherical harmonics) must be entered because the code CHUCK2 expects them to be used in the structure wave functions.

TABLE I. Externally entered phases and amplitudes for CHUCK2 for different configurations $(l_1 j_1 l_2 j_2)$ and c.m. angular momenta L [after converting ^{210}Bi shell-model wave functions to reaction-code convention (positive tail at $r\to\infty$)].

Channel	(phase) $\times (CS^{1/2}D_0)_1 \times (CS^{1/2}D_0)_2$
(α,d)	$i^L(-4800)$
$(\alpha,t;t,d)$	$-i^{l_1+l_2}(-705)(-225)$
$(\alpha,{}^3\mathrm{He};{}^3\mathrm{He},d)$	$i^{l_1+l_2}(-1)^{j_1+j_2-J}(+700)(-240)$

The phase evaluations were checked against simpler cases where the answers are known from independent symmetry considerations. They were also found to produce results consistent with other, similar CRC calculations.[5,20] We note that a significant systematic improvement is obtained through the coherent addition of the three channels.

In looking at the individual two-step channels we noticed that for almost identical k, l, and Q values, the predicted $(\alpha,{}^3\mathrm{He};{}^3\mathrm{He},d)$ cross section was a factor of 10–20 weaker than the analogous $(\alpha,t;t,d)$ branch. This is due in large part to the effect of the different optical potentials used for ^{3}He and tritons. Heuristically, this asymmetry seems large since there is no *physical* triton or ^{3}He outside the Coulomb barrier and inside, where they are assumed to exist briefly, they differ only in their charge. We tested the effect of this possibly artificial suppression of the $(\alpha,{}^3\mathrm{He};{}^3\mathrm{He},\alpha)$ channel by multiplying its amplitude by 2, and obtained the dashed saw-tooth prediction in Fig. 2(b). (A similar effect is achieved by using less absorptive optical-model potentials for ^{3}He.) Interestingly, the shapes of the angular distributions are hardly affected by the two-step contributions.

We conclude that the strong J_{even} enhancement in the ^{210}Bi ground-state multiplet is a signature of an interference effect and that it should be explained by coherent addition of one-step and two-step contributions. The *two-step processes are strong and do not diminish as the cross sections increase.* We see some evidence that the customary use of ordinary elastic-scattering potentials for the intermediate "projectiles" may have to be refined. There are other known shortcomings in

the current sequential particle-transfer formalisms; however, it appears that currently available coupled-reaction-channels codes (such as CHUCK 2) give qualitatively correct results even without nonorthogonality corrections.[20] Our study thus gives strong support to the idea that two-step processes are large in allowed two-nucleon transfer, and may have to be considered explicitly in all quantitative analyses.

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[1]N. Austern, R. M. Drisko, E. Rost, and G. R. Satchler, Phys. Rev. 128, 733 (1962).

[2]T. Tamura, Rev. Mod. Phys. 37, 679 (1965).

[3]J. L. Yntema and G. R. Satchler, Phys. Rev. 161, 1137 (1967).

[4]H. H. Duhm *et al.*, Phys. Lett. 48B, 1 (1974).

[5]W. R. Coker, T. Udagawa, and J. R. Comfort, Phys. Rev. C 10, 1130 (1974).

[6]K. Yagi *et al.*, Phys. Rev. Lett. 40, 161 (1978).

[7]N. B. DeTakacsy, Nucl. Phys. A231, 243 (1974).

[8]R. J. Ascuitto and N. V. Glendenning, Phys. Rev. C 2, 1260 (1970).

[9]T. S. Kuo and G. H. Herling, U. S. Naval Research Laboratory Report No. 2258, 1971 (unpublished).

[10]Y. E. Kim and J. O. Rasmussen, Nucl. Phys. 47, 184 (1963); C. W. Ma and Wm. W. True, Phys. Rev. C 8, 2313 (1973).

[11]T. R. Canada *et al.*, Nucl. Phys. A205, 145 (1973).

[12]N. K. Glendenning, Phys. Rev. 137, B102 (1965).

[13]W. W. Daehnick, H. Hafner, H. H. Duhm, R. Seehars, and M. Goldschmidt, Bull. Am. Phys. Soc. 19, 1020 (1974).

[14]W. W. Daehnick, M. J. Spisak, R. M. DelVecchio, and W. Oelert, Phys. Rev. C 15, 594 (1977).

[15]Written by R. DeVries, University of Rochester (unpublished).

[16]R. M. DelVecchio and W. W. Daehnick, Phys. Rev. C 6, 2095 (1972).

[17]Written by P. D. Kunz, University of Colorado (unpublished).

[18]F. D. Becchetti and G. W. Greenlees, in *Proceedings of the Third International Symposium on Polarization Phenomena in Nuclear Reactions, Madison, Wisconsin, 1970,* edited by H. H. Borschall and W. Haeberli (Univ. of Wisconsin Press, Madison, Wis., 1971), p. 682.

[19]J. S. Lilley and N. Stein, Phys. Rev. Lett. 19, 709 (1967), for (α,t); R. Tickle and W. S. Gray, Nucl. Phys. A247, 187 (1975), for $(\alpha,{}^3\mathrm{He})$; G. Igo *et al.*, Phys. Rev. 177, 1831 (1969), for (t,d); J. Bardwick and R. Tickle, Phys. Rev. C 171, 1305 (1968), for $({}^3\mathrm{He},d)$.

[20]N. Hashimoto and M. Kawai, to be published, and Phys. Lett. 59B, 223 (1975).