Model for an Effective Q Value for Heavy-Ion–Induced Transfer Reactions

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A model is presented which accounts for the shifts in the energy levels of a transferred nucleon due to the proximity of the colliding ions during the reaction process. Including these shifts through an effective Q value in a distored-wave Born-approximation formalism leads to dramatic improvement of the calculated angular distributions for the reactions induced by 56-MeV ^{16}O on ^{48}Ca.

The angular distributions calculated in the conventional distorted-wave Born approximation (DWBA) for heavy-ion–induced transfer reactions often predict much too low a cross section at forward angles or, if the experimental angular distribution is bell shaped, a grazing peak at too large an angle.[1-3] These forward-peaked or forward-shifted experimental angular distributions are correlated with the overall Q value (and matching) of the reaction,[3] i.e., with the difference in binding energy of the transferred nucleon from its initial state with binding energy E_i to its final state with binding energy E_f; $Q=E_i-E_f$.

It is the purpose of this Letter to demonstrate that an important correction exists to the conventional DWBA analysis for these reactions. This correction accounts for the shifts in the initial and final energy levels of the transferred nucleon from their asymptotic values (E_i and E_f) due to the perturbation introduced by the proximity of the colliding ions during the transfer process. A model, based on a molecular-orbital approach,[4] will be employed to include this correction in a DWBA calculation of the transfer reactions induced by the scattering of ^{16}O on ^{48}Ca at 56 MeV.

Empirical attempts to improve fits to data have yielded valuable insight into the nature of the modification required of the DWBA. One approach[3] arbitrarily increases the diffuseness (a_r) of the real part of the exit-channel distorting potential so that trajectories that skim the nuclear surface are focused to more forward angles. This procedure, when applied to one-nucleon transfer reactions, leads to an exit-channel distorting potential that is state dependent, with large increases in a_r required for transitions populating highly excited states. For two-nucleon transfer reactions, a single increase in a_r often improves the fits for many transitions. A second approach[5] employs distorting potentials that are weakly absorbing in the nuclear surface so that trajectories that contribute to the forward cross section are not attenuated. These empirical procedures prove the efficacy of modifying the exit-channel relative motion through an appropriate change in the exit-channel distorting potential.

A state dependence in the exit-channel distorting potential arises within the molecular-orbital model because the energy levels of the transferred nucleon are a function of the separation (R) of the colliding ions. To lowest order, an *effective* Q value results which depends on the point of transfer, and departs from its asymptotic value (the Q value of the overall reaction). This *effective* Q value can be incorporated into the usual DWBA equations of motion by viewing the transfer process $A(a,b)B$ as the creation of a particle-hole (p-h) pair with respect to a reference state, namely, the entrance channel $(a+A)$:

$$a(\text{projectile})+A(\text{target})\begin{cases} \nearrow b(a+\text{p})+B(A+\text{h}), & \text{pickup} \\ \text{or} & \\ \searrow b(a+\text{h})+B(A+\text{p}), & \text{stripping} \end{cases}. \tag{1}$$

The *effective* Q value becomes $Q_{\text{eff}}(R)=E_{\text{h}}-E_{\text{p}}+\Delta Q(R)$, where E_{p}, and E_{h} are the binding energies of the particle and hole as defined by the shell-model wave functions for the isolated nucleus about which the p or h is bound as $R\to\infty$. $\Delta Q(R)$ is the molecular-orbital correction to the energy difference E_{h}

$-E_p$. For pickup, this correction is due to the interaction of p with A, and h with a:

$$\Delta Q(R) = \langle \mathrm{h} | V_{\mathrm{h},a} | \mathrm{h} \rangle - \langle \mathrm{p} | V_{\mathrm{p},A} | \mathrm{p} \rangle. \tag{2}$$

In the calculations that follow, the effective Q value was included in the DWBA calculations of the transfer process by using, as equations for the relative motion,

$$\begin{aligned} &[T_R + U_{\mathrm{ref}}(R) - E_{\mathrm{c.m.}}]\varphi_{\mathrm{ent\text{-}el}}^{(+)}(R) = 0, \\ &\{T_{R'} + U_{\mathrm{ref}}(R') \\ &\qquad - [E_{\mathrm{c.m.}} + Q_{\mathrm{eff}}(R')]\}\varphi_{\mathrm{exit}}^{(-)}(R') = 0 \end{aligned} \tag{3}$$

for the entrance (elastic) and exit channels; each reaction channel now is considered an elementary (p-h) excitation with respect to the reference state. Furthermore, $\Delta Q(R)$ can be interpreted as the correction necessary to relate the exit-channel distorting potential to the entrance-channel elastic potential in the DWBA. Thus these exit potentials are *not* simply related to a potential that describes elastic scattering.

For all the reactions considered in this Letter, the *R dependence* and the *relative strength* of $\Delta Q(R)$ can be well represented by the matrix element

$$\Delta Q(R) \iint d^3r_p d^3r_h \rho_p(\vec{r}_p)\rho_h(\vec{r}_h)\upsilon(\vec{r}_p + \vec{R} - \vec{r}_h), \tag{4}$$

where ρ is the spherically averaged single-particle (or -hole) density around its respective center (a or A) and is calculated from a Woods-Saxon wave function corresponding to a binding energy E_p or E_h; υ is a residual interaction. υ is taken as a Gaussian interaction with a range of 1 fm. The calculations are not sensitive to this choice, however, and results similar to those described below were obtained with a zero-range interaction. (Recall that in the shell-model description of nuclei, the first-order correction to the excitation energy of a p-h state is a similar matrix element.)

Since an adequate theory of the effective interaction for valence nucleons in a molecular-orbital model does not exist, the *absolute strength* of the matrix element, Eq. (4), was adjusted (through the residual interaction) to produce the required ΔQ necessary to fit the ^{48}Ca(^{16}O, ^{17}O)^{47}Ca ground-state transition. The $\Delta Q(R)$'s for all other transitions are then completely specified by the corresponding p and h densities. Hence, a *single strength parameter* characterizes all the reaction channels considered in this Letter. The $\Delta Q(R)$ at $R = 9.3$ fm, approximately the strong absorption radius, is given for each of the transitions in the figures. The relative size and the radial behavior of $\Delta Q(R)$ from Eq. (4) depend critically on the magnitude and exponential decay (binding energy) of the p and h densities at the nuclear surface. The increase in ΔQ for the excited-state transitions ($\frac{3}{2}^-$ of ^{49}Sc and $\frac{1}{2}^+$ of ^{17}O) reflects *both* the decreased binding energy and the extra radial node of the single-particle orbitals ($2p_{3/2}$ and $2s_{1/2}$) associated with these states. In this manner, densities with greater radial extent produce more diffuse optical potentials, thus enhancing the forward scattering compared to potentials used in conventional DWBA calculations which neglect this effect.

The success of this approach for one-nucleon transfer reactions is shown in Figs. 1 and 2, where the solid lines are DWBA calculations employing the correction $\Delta Q(R)$ of Eq. (4) in the description of the exit-channel relative motion, Eq. (3). The reference potential was obtained by fitting the elastic scattering of ^{16}O + ^{48}Ca at 56

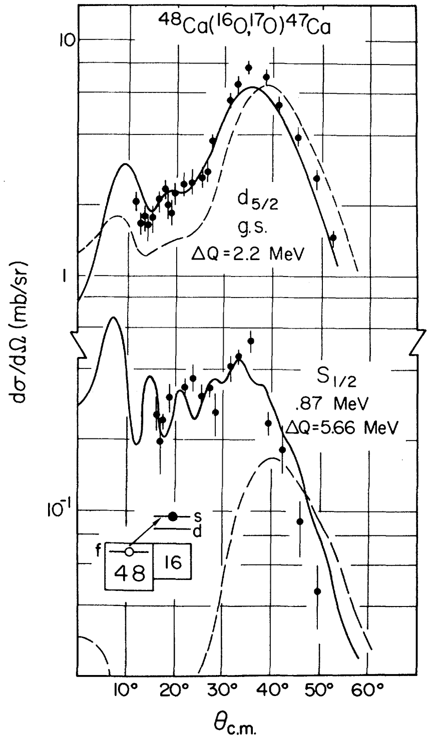

FIG. 1. Angular distributions for the one-neutron pickup reactions induced by ^{16}O + ^{48}Ca at 56 MeV. Solid lines are DWBA calculations including the effective Q value. The curves have normalized to the data. For reference, the dashed lines are conventional DWBA calculations from Ref. 3 with the same normalization applied.

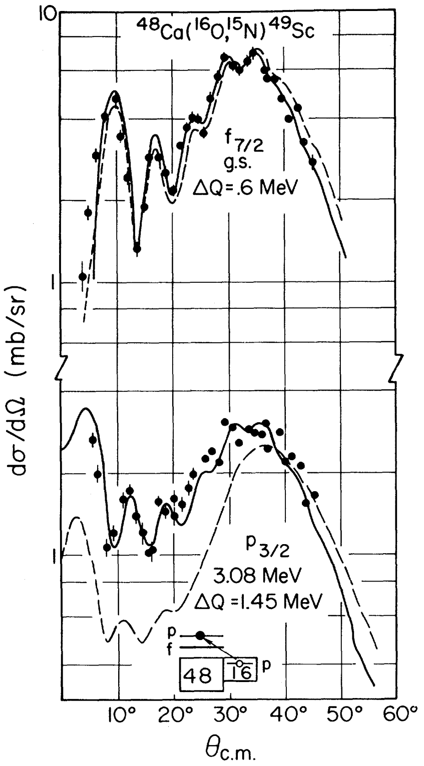

FIG. 2. Same as Fig. 1 for one-proton stripping reaction.

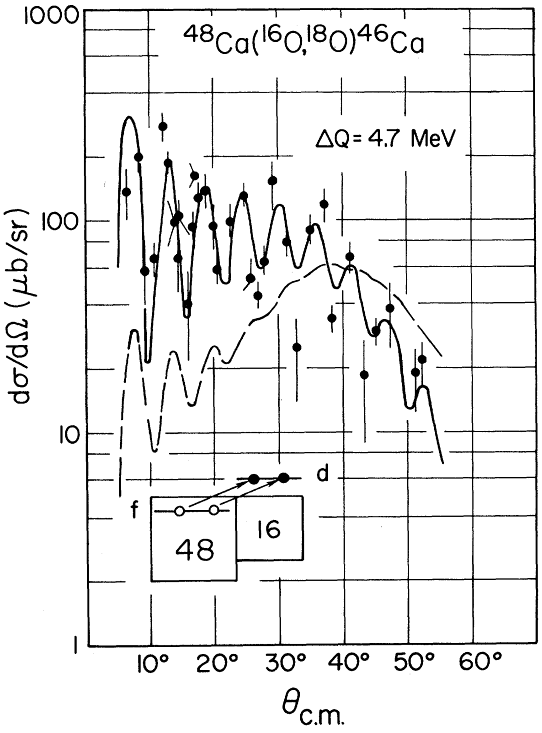

FIG. 3. Same as Fig. 1 for two-neutron pickup reaction.

MeV. The dashed lines are the conventional DWBA calculations of Ref. 3. The dramatic change in the shape of the angular distributions [with $\Delta Q(R)$ included] for the excited states demonstrates the importance of including this explicit dependence on the valence orbitals involved in the transfer process.

This model can easily be extended to two-nucleon transfer reactions by viewing the process as a two-particle, two-hole excitation of the reference state. The correction $\Delta Q(R)$ for the (^{16}O, ^{18}O) reaction is completely determined from the matrix elements used for the (^{16}O, ^{17}O) reaction. Figure 3 demonstrates the consistency of this approach as well as the critical importance of this correction for two-nucleon transfer. Similar results hold for transitions populating the 2^+ and 4^+ states of ^{18}O.

In summary, a restricted, but crucial, aspect of the general, molecular-orbital[6] description of nuclear reactions has been explored, namely the R dependence of the single-particle energy levels as the nuclei are brought into proximity. This R dependence in a transfer reaction can be incorporated into an effective, R-dependent Q value *or* it can be associated with a state-dependent, exit-channel distorting potential used in a DWBA [via Eqs. (2) and (3)]. (Again, the exit-channel distorting potential should not be associated with elastic scattering in the exit channel.) The effective Q value can significantly alter the relative motion of the ions and thus angular distributions. For the case of the scattering of ^{16}O on ^{48}Ca, both of which are closed-shell nuclei, the important quantity $\Delta Q(R)$ can be calculated as a particle-hole interaction matrix element. These matrix elements, when they are included [via Eq. (3)] in a DWBA calculation, substantially improve the fits to the experimental angular distributions. The examples considered here, furthermore, illustrate how the ΔQ correction becomes increasingly important for the excited-state transitions. A similar analysis[7] using the correction $\Delta Q(R)$ from Eq. (4) (and the same strength parameter) has been applied to the reactions initiated by ^{12}C +^{208}Pb at 77.4 and 97.9 MeV.[8] Again, dramatic improvement over the conventional DWBA is obtained with this model.

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Survival of Fast Molecular Ions Traversing a Thin Foil

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Measured yields and energy distributions of H_2^+ emerging at 0° from the breakup of 2.2-MeV H_3^+ in 1.5–7-μg/cm^2 carbon foils suggest that, in traversing a solid at the same velocity, the lifetime for survival with the original electron is the same for H and H_2^+. Seen for the first time is a reversal in the 0° intensity asymmetry between the leading and trailing H_2^+ breakup fragments with changing target thickness which we interpret as the result of competing wake alignment and enhanced destruction mechanisms.

Recent studies[1,2] of neutral H atoms emerging from very thin carbon foils bombarded with MeV beams of H, H_2^+, and H_3^+ have suggested that an electron can be bound to a fast moving proton in solid and that such a system has a lifetime for survival of $(2.0\pm 0.1)\times 10^{-16}$ s.[1] In a further attempt to understand the implications of such a lifetime, we have studied the survival of H_2^+. Like the H atom, H_2^+ has only one bound electron of comparable binding energy but is presumably more fragile because of the presence of lower-energy dissociation channels. Rather than measuring the transmission of an H_2^+ beam in solid foils, we observed instead H_2^+ fragments from the breakup of H_3^+. In so doing we shed additional light on the H_3^+ breakup mechanisms as well as on the specific effects on molecular fragments caused by the perturbed electronic density behind a moving ion. We report here the new observed features.

In our measurements, a magnetically selected 2.2-MeV H_3^+ beam from a Van de Graaff accelerator was collimated to a total angular divergence of ≤ 0.2 mrad before striking the target consisting of carbon foils with thicknesses ranging from 1.5 to 7 μg/cm^2. Fragments of H_2^+ emerging within a 0.5-mrad cone centered in the beam direction were detected by a high-resolution magnetic spectrometer ($\Delta E/E \simeq 2\times 10^{-4}$).

Typical energy spectra of H_2^+ fragments emerging at 0° are displayed in Fig. 1 for three target thicknesses. The two outer peaks correspond to the trailing and leading H_2^+ fragments of the H_3^+ Coulomb explosions into $H_2^+ + H^+$. Noting that H_3^+ has a triangular shape,[3] the H_2^+ here are constrained by the detection geometry to be those whose internuclear axis is perpendicular to the beam direction. A new feature which has hereto-