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Finite-range distorted-waves Born-approximation calculations for $^{13}C(^3He, ^6He)^{10}C^\dagger$

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Finite-range distorted-waves Born-approximation calculations, which included recoil effects exactly, were performed for the reaction $^{13}C(^3He, ^6He)^{10}C$ leading to the 0^+, ground state and the 2^+, 3.35 MeV state in ^{10}C for a bombarding energy of 70.3 MeV. The results of the analysis showed that, contrary to the findings of a zero-range distorted-waves Born-approximation study, this reaction can be interpreted as a direct cluster transfer to both of the final states in ^{10}C.

[NUCLEAR REACTIONS $^{13}C(^3He, ^6He)^{10}C$, $E=70$ MeV; calculated $\sigma(\theta)$. Finite range DWBA analysis.]

I. INTRODUCTION

Experiments reported by Kashy *et al.*[1] measured angular distributions for the reaction $^{13}C(^3He, ^6He)^{10}C$ leading to the $J^\pi = 0^+$, ground state and the $J^\pi = 2^+$, 3.35 MeV state in ^{10}C for a 70.3 MeV ^3He beam. The experiments showed that both transitions, despite their low cross sections, were well resolved and displayed rather marked oscillatory structure indicative of a direct transfer reaction. The structures in the experimental differential cross sections for the two transitions were in phase at larger angles (25–43° c.m.) and were out of phase at smaller angles (7–25° c.m.). Furthermore, at the forward angles the observed strength to the 2^+ state in ^{10}C was as much as 40 times greater than that to the 0^+ state. In an attempt to describe these features of the data Kashy *et al.* performed distorted waves Born approximation calculations and in their analysis, to simplify the computations, these authors assumed that the interaction occurring in the expression for the distorted-waves Born-approximation (DWBA) transition matrix amplitude was of zero range. The results of the analysis showed a strong disagreement with experiment, particularly for the relative strengths of the transitions to the 0^+ and 2^+ states, respectively, in ^{10}C. It is not only this discrepancy, found in the previous analysis, which provided the motivation for the present study, but also consideration of features peculiar to the three-neutron pickup. In general, transfer reactions on light nuclei at energies of 10 MeV or more per nucleon are characterized by strong transitions which can be interpreted[2] as transfer of a spatially symmetric cluster $[n]$ of the nucleons. A recent study of two-proton pickup[3] on $1p$-shell targets found that symmetry [2] transfer dominates and that symmetry [11] is very weak even for states calculated to have large nuclear structure amplitudes for such transfer. Three-neutron pickup offers an interesting test in that the Pauli principle forbids symmetry [3] clusters so that symmetry [21] is the most symmetric spatial state allowed.

Kashy *et al.* concluded that nuclear structure considerations would not correct the discrepancy with experiment predicted by the zero-range DWBA analysis, and that the $^{13}C(^3He, ^6He)^{10}C$ reaction mechanism is probably not direct transfer. In the present study a full finite range DWBA analysis, which included recoil effects exactly, was performed and the results indicated that the reaction $^{13}C(^3He, ^6He)^{10}C$ can be interpreted as a direct cluster transfer to both final states in ^{10}C.

II. THEORY

In this section a schematic development of the theory is made to indicate the procedure for the present analysis. The notation is similar to that developed elsewhere[4,5] and expressions are presented which emphasize the features specific to this reaction.

In the pickup reaction $B(b, a)A$ the three transferred neutrons are assumed to be bound as a cluster to the nucleus b with orbital angular momentum $\bar{L}$ and total angular momentum $\bar{J}$, and to the nucleus A with orbital angular momentum L and total angular momentum J. For the reaction $^{13}C(^3He, ^6He)^{10}C$ $\bar{J} = \frac{1}{2}$, and I, the spin of the final nucleus ^{10}C, is 0 or 2. If j denotes the total angular momentum of the cluster, and Q and $\bar{Q}$ the number of oscillator quanta carried in the relative wave functions for the cluster bound to ^{10}C and ^3He, respectively, then the cross section for the

TABLE I. Parentage and amplitudes between the ^{13}C ground state and states I of ^{10}C.

$I\ J\ L_p$	Parentage amplitude
$0\ \frac{1}{2}\ 1$	+0.8396
$2\ \frac{3}{2}\ 1$	−0.5430
$2\ \frac{3}{2}\ 2$	−0.8102
$2\ \frac{5}{2}\ 2$	+1.0854

TABLE II. Expansion coefficients for $(1p)^3$ of carbon into cluster c and c.m. function QL.

$L_p\ c\ \overline{L}\ QL$	$\langle L_p[21]\|cQL\rangle$
$1\ 0\ 1P$	$-2/9$
$1\ 1\ 2S$	$+2/9$
$1\ 1\ 2D$	$-\sqrt{5}/9$
$2\ 1\ 2D$	$+\sqrt{15}/15$

pickup reaction ^{13}C(^{3}He, ^{6}He)^{10}C, in the absence of spin-orbit interactions in the optical model potentials, is given by

$$\frac{d\sigma}{d\Omega}=\frac{\mu_a\mu_b}{(2\pi\hbar^2)^2}\frac{k_a}{k_b}\frac{1}{4}\sum_{J\lambda\mu}\left|\sum_{QL\overline{Q}\overline{L}}B_{IJ\lambda}\beta^{\lambda}_{\mu}(\vec{k}_a,\vec{k}_b)\right|^2, \quad (1)$$

where the dependence of the cross section on the kinematics of the reaction is contained in the factor

$$K\beta^{\lambda}_{\mu}(\vec{k}_a,\vec{k}_b)=\sum_{M\overline{M}}(-1)^{\overline{L}-\overline{M}}\langle L\overline{L}-M\overline{M}\,|\,\lambda-\mu\rangle \times\iint d\vec{r}_{aA}d\vec{r}_{bB}\chi^{*(-)}_{bB}(\vec{k}_b,\vec{r}_{bB})\Phi^{QL*}_{M}(\vec{r}_{xA}) \times V_{bx}\Phi^{\overline{Q}\overline{L}}_{\overline{M}}(\vec{r}_{bx})\chi^{(+)}_{aA}(\vec{k}_a,\vec{r}_{aA}), \quad (2)$$

and the dependence on the nuclear structure in the factor

$$B_{IJ\lambda}=K\sum_{jc}A^{*}_{J}(IjcQL)A_{1/2}(jc\overline{Q}\overline{L})W(j\tfrac{1}{2}L\lambda;\overline{L}J), \quad (3)$$

where c refers to quantum numbers of the cluster other than its total angular momentum. The factor K (where $KK^*=2\lambda+1$) is included here to keep to standard notation[5]: it is clear that it cancels in Eq. (1). The Racah coefficient W exhibits the angular momentum couplings, and λ is the "transferred" orbital angular momentum.

The spectroscopic amplitudes A are defined[5] as coefficients in the expansion of the overlap integrals into internal and center-of-mass (c.m.) functions for the transferred cluster. The integral over the internal coordinates ξ_3 of ^{3}He is

$$\binom{6}{3}^{1/2}\int\Psi^{1/2*}(\xi_3)\Psi^{0}(\xi_6)d\xi_3 =2^{-1/2}\sum_{jc\overline{Q}\overline{L}}A_{1/2}(jc\overline{Q}\overline{L})[\phi^{jc}(\xi_x)\Phi^{\overline{Q}\overline{L}}(\rho_{x3})]^{\overline{J}=1/2}, \quad (4)$$

where ξ_6 and ξ_x are the internal coordinates of ^{6}He and the cluster x, respectively, and ρ_{x3} is the coordinate of c.m. motion of x about ^{3}He. Thus, the amplitude A is analogous to the familiar $CS^{1/2}$ factor of single-nucleon transfer reactions. It is assumed that ^{6}He is represented by a full $0s$ level with two $1p$ neutrons in a ^1S state, and ^{3}He is represented by $0s$ nucleons in a spatially symmetric ^2S state having the same oscillator constant as ^{6}He. Two quanta are thus contained in the transferred nucleons which have spatial symmetry [21] and total orbital angular momentum equal to zero. In the expansion into internal and c.m. motion in Eq. (4) the internal orbital angular momentum must equal the c.m. quantity $\overline{L}$, j equals $\overline{L}\pm\frac{1}{2}$, and the number of oscillator quanta in internal excitation plus the c.m. quantity $\overline{Q}$ must equal two. There are then only three contributing terms possible, one with two internal quanta in a $2s$ state with $j=\frac{1}{2}$, coupled to a $0S$ function for the c.m. motion. The other two terms have one quantum in a $1p$ state with $j=\frac{1}{2}$ or $j=\frac{3}{2}$, and a $1P$ function for the c.m. motion. The spectroscopic amplitudes are given by

$$A_{1/2}(jc\overline{Q}\overline{L})=-\left(\frac{2(2j+1)}{3(2\overline{L}+1)}\right)^{1/2}, \quad (5)$$

since the nature of c is determined by the value of $\overline{L}$.

From the (^{13}C, ^{10}C) overlap expansion analogous to Eq. (4) only those terms are required wherein the internal wave function of the three-neutron cluster is the same as it is in the He overlap. These will arise from transfer of three $1p$ neutrons with spatial symmetry [21], orbital angular momentum $L_p=1$ or 2, and spin equal to $\frac{1}{2}$, i.e., $P_{1/2}$, $P_{3/2}$, $D_{3/2}$, and $D_{5/2}$. The spectroscopic amplitudes between the ground state of ^{13}C and the ^{10}C state with angular momentum I are given by

$$A_J(IjcQL)=\left(\frac{13}{10}\right)^{Q/2}\sum_{L_p}(2L_p+1)(2j+1)^{1/2}W(j\tfrac{1}{2}LL_p;\overline{L}J)\langle\Psi^{1/2}(^{13}\mathrm{C})\|\chi^{J\dagger}(L_p[21])\|\Psi^{I}(^{10}\mathrm{C})\rangle\langle L_p[21]\,|\,cQL\rangle. \quad (6)$$

The next-to-last bracket is the parentage amplitude, which was computed from the wave functions of Cohen and Kurath[6]; values are given in Table I. The last bracket arises from the expansion of the orbital functions into internal and c.m. factors; values are given in Table II, together with the number of quanta Q and the orbital angular momentum L of the c.m. function. The dependence of the spectroscopic amplitudes on j, the total internal angular momentum of the cluster, is given explicitly in Eqs. (5) and (6). Therefore, the summation over j in Eq. (3) can be carried out using the orthogonality relationship of the Racah coefficients which requires that L_p equals λ; thus

$$B_{IJ\lambda} = -K\delta(L_p,\lambda)\left(\frac{1.3^Q}{3\overline{L}+\frac{3}{2}}\right)^{1/2}\langle\Psi^{1/2}(^{13}\mathrm{C})\|\chi^{J^+}(L_p[21])\|\Psi^I(^{10}\mathrm{C})\rangle\langle L_p[21]|cQL\rangle\,. \tag{3'}$$

Since the cross section is incoherent for summation over λ, this property also holds for L_p.

The cross sections for the reaction can thus be expressed in terms of the $\beta^\lambda_\mu(QL,\overline{QL})$, the form factor integrals of Eq. (2), by inserting the numerical values from Tables I and II. For the $I=0$ ground state of ^{10}C only $J=\frac{1}{2}$ with $\lambda=L_p=1$ contributes, so the cross section is proportional to the square of the first parentage amplitude of Table I, and the summation in Eq. (1) becomes

$$\sum_\mu\left|\sum_{QL\overline{QL}}B_{0\,\frac{1}{2}\,1}\beta^1_\mu(QL,\overline{QL})\right|^2 = 0.705\sum_\mu|0.264\beta^1_\mu(2D,1P)-0.236\beta^1_\mu(2S,1P)+0.358\beta^1_\mu(1P,0S)|^2\,. \tag{7}$$

For the 3.35 MeV, $I=2$ state, there is a contribution with $J=\frac{3}{2}$ and $\lambda=L_p=1$ and also contributions for $\lambda=L_p=2$ with $J=\frac{3}{2}$ and $J=\frac{5}{2}$. Thus the summation of Eq. (1) for this case becomes

$$\sum_{J\lambda\mu}\left|\sum_{QL\overline{QL}}B_{2J\lambda}\beta^\lambda_\mu(QL,\overline{QL})\right|^2 = (0.656+1.178)\sum_\mu|0.354\beta^2_\mu(2D,1P)|^2$$
$$+0.295\sum_\mu|0.264\beta^1_\mu(2D,1P)-0.236\beta^1_\mu(2S,1P)+0.358\beta^1_\mu(1P,0S)|^2\,. \tag{8}$$

In a zero-range DWBA analysis only the $\beta^1_\mu(1P,0S)$ integral is nonvanishing[1] in Eqs. (7) and (8). Since the difference in the DW integrals due to the excitation energy of the $I=2$ state is not expected to be great, the expected ratio of the cross sections is given approximately by the ratio of the squares of the spectroscopic factors

$$\frac{\sigma(2^+)}{\sigma(0^+)}\simeq\frac{0.295}{0.705}=0.418\,.$$

This feature was pointed out in Ref. 1, and the calculated value of that analysis disagreed strongly with the experimental ratio of about 4.5 for the cross sections integrated up to $\theta=45^\circ$ (c.m.). However, it is clear from Eqs. (7) and (8) that if the $\beta(2D,1P)$ integrals are larger than the $\beta(1P,0S)$ integral, the calculation could be closer to the experimental result. Such a possibility is reasonable in a finite range DWBA calculation because the DW integrals not present in the zero-range case arise from the presence of more quanta in the c.m. motion of the transferred cluster. From transfer of α particles and tritons it is known[7] that transfer with the largest possible number of quanta in the c.m. motion is most important at the nuclear surface. The present analysis shows that this feature leads to a large difference between the finite-range and zero-range DWBA calculations for ^{13}C(^{3}He,^{6}He)^{10}C.

III. CALCULATIONS AND RESULTS

Finite-range DWBA calculations which included recoil effects exactly were performed with the code KUNDRY. Details of the code are given in Ref. 8; here, only those points relevant to the reaction under consideration are summarized.

The cluster wave functions were generated by varying the depth of a Woods-Saxon potential of radius $1.25C^{1/3}$ fm, with $C=3$ or 10, and diffuseness 0.65 fm, to reproduce the $3n$ separation energies. The separation energies were 21.55 and 36.80 MeV, respectively, for ^{6}He and ^{13}C, and for the latter the same separation energy is assumed for both transitions. The truncation radii for the cluster wave functions were typically of the order of $r^c_{xA}\simeq 6.3$ fm and $r^c_{bx}\simeq 7.7$ fm, corresponding to the region where the magnitude of the cluster wave functions were of the order of 10^{-4}. Using the relations of Ref. 8 the truncation radii for the double radial integrals evaluated in KUNDRY were $r^c_{aA}\simeq 7.9$ fm and range $\Delta r_{bB}\simeq 4.8$ fm. In contrast to typical single nucleon transfer reactions, the reaction ^{13}C(^{3}He,^{6}He)^{10}C has $2\Delta r_{bB}>r^c_{aA}$, i.e., the transverse region (of the double radial integrals of the DWBA) defined by $r_{bB}=r_{aA}\pm\Delta r_{bB}$ (with only positive values of r_{bB} allowed) is broader than the lateral region 0 to r^c_{aA}. Consequently, without significant losses in accuracy, in evaluating the double radial integrals the squares which have the

TABLE III. Optical model parameters for $^{13}C(^{3}He, ^{6}He)^{10}C$. The potential has the form $C - Vg(v) - iW_v g(wv)$, where $g(x) = \{1 + \exp[(r - r_x A^{1/3})/a_x]\}^{-1}$; C is the Coulomb potential for a uniformly charged sphere of radius $r_c A^{1/3}$, and $A = 13$ and 10, respectively, for the initial and final channels.

Nuclei	$E^{c.m.}$ (MeV)	r_v (fm)	a_v (fm)	V (MeV)	r_{wv} (fm)	a_{wv} (fm)	W_v (MeV)	r_c (fm)
$^{3}He + ^{13}C$	57.07	1.240	0.6650	125.0	1.240	0.6400	20.00	1.260
$^{6}He + ^{10}C$ (0^+)	41.82	1.650	0.9500	175.0	1.400	0.6400	35.00	1.260
(2^+)	38.47	1.460	0.7300	195.0	1.460	0.6400	50.00	1.260

48 point quadrature[8] are approximately 2×2 fm. The two-dimensional form factors of the double radial integrals, containing the respective overlaps, need only to be evaluated once. Subsequent calculation of the DWBA amplitudes for different optical model parameters (OM) required only the evaluation of the double radial integrals, computation of the transition matrix amplitudes, their summation, and formation of the cross section. The computation times for this stage of the calculation were approximately 2.8 and 8.5 sec for the 0^+ and 2^+ transitions, respectively. These rapid computation times made possible an extensive analysis of the dependence of the DWBA cross sections on the choice of OM parameters, particularly for the $^{6}He + ^{10}C$ channel. This was necessitated by the lack of elastic scattering data for ^{3}He on ^{13}C at 70 MeV bombarding energy, and because it is not possible to obtain elastic scattering data for ^{6}He on ^{10}C at the two energies corresponding to the two different transitions in the reaction under study. Initially a sequence of 14 DWBA calculations were performed for both transitions using identical OM parameters for both channels. The parameters used were taken from the literature.[9-15] A review of these calculations revealed that the most promising results for both transitions came from using the OM parameters of the system nearest in energy, i.e., elastic scattering of ^{4}He on ^{12}C at 56 MeV.[15] The results for the parameter sets A, B, C, and D of Gaillard *et al.* showed that set A yielded cross sections which bore no resemblance to the data whatever, whereas, to varying degrees, Sets B, C, and D were more successful. Of the latter three sets, C was the most promising and was used as the basis for extensive grid searches on the DWBA calculations to determine the optimum parameters. For the ground state transition a large number of DWBA calculations were performed in the grid searches varying the OM parameters away from parameter set C of Gaillard *et al.* In the $^{3}He + ^{13}C$ channel the strength of the real potential was decreased from 152 to 125 MeV (a trend expected with increasing bombarding energy of ^{3}He), and the strength of the imaginary potential was decreased from 28 to 20 MeV. For the $^{6}He + ^{10}C$ channel both the real and imaginary parts of the interaction were made considerably stronger. The OM parameters determined for the ground state transition are given in Table III, and the corresponding cross section is shown in Fig. 1. The predicted shape and magnitude are reasonably close to experiment for the ground state cross section. Also shown in Fig. 1 is the cross section

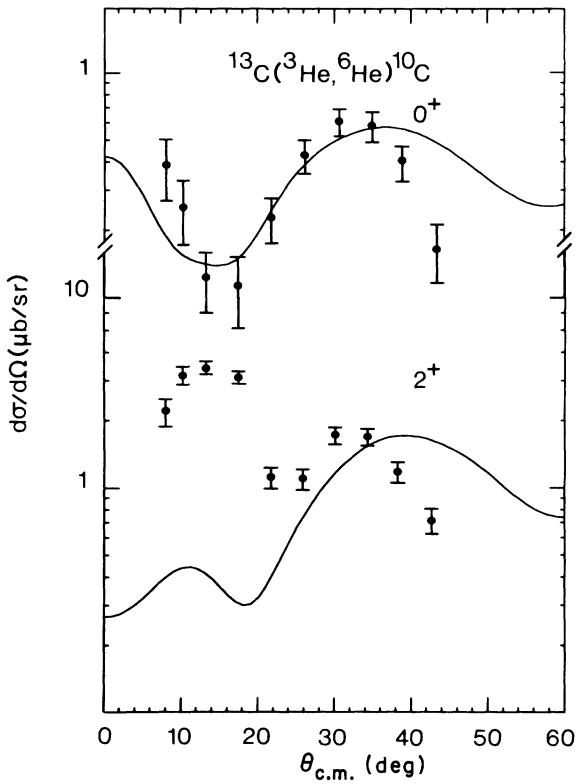

FIG. 1. Exact finite-range DWBA calculations for the reaction $^{13}C(^{3}He, ^{6}He)^{10}C$ for a 70.3 MeV ^{3}He beam. The upper curve is the transition to the 0^+ ground state in ^{10}C, and the lower curve the transition to the 2^+, 3.35 MeV state in ^{10}C for the same set of optical model parameters in the $^{6}He + ^{10}C$ channel (the parameters are those given in the second line of Table III). The data are those of Ref. 1.

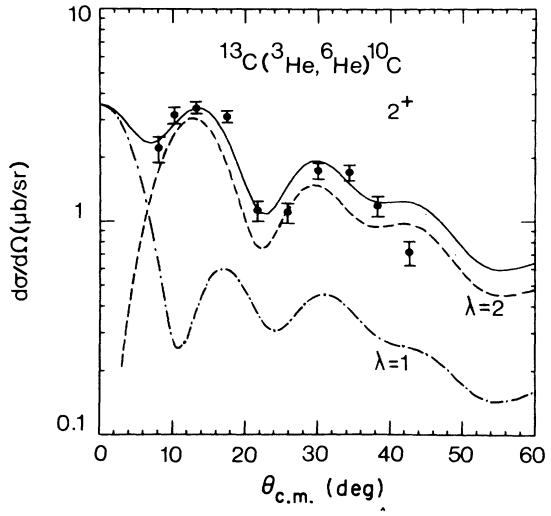

FIG. 2. Exact finite-range DWBA calculations for the reaction $^{13}C(^3He,^6He)^{10}C$ leading to the 2^+, 3.35 MeV state in ^{10}C for a 70.3 MeV ^3He beam. The optical model parameters for the $^6He+^{10}C$ channel are given in the third line of Table III. The broken curve is the $\lambda=2$ component of the cross section and the dashed-and-dotted curve is the $\lambda=1$ component. The final cross section is the unbroken curve. The data are those of Ref. 1.

calculated for the 2^+ transition with the same OM parameters. Above 25° the 2^+ cross section also resembles experiment, but while the calculation differs from that for the ground state at forward angles, the nascent peak is much too small. Nevertheless, the ratio of integrated cross sections is about 2.7, much larger than the zero-range result of 0.4.

In the parameter searches for the $^6He+^{10}C$ channel, good fits to both transitions with the same OM parameters were not found. However, it is possible to fit the shape and magnitude of the 2^+ cross section with the OM parameters given in the last line of Table III, as shown in Fig. 2. Also shown in Fig. 2 are the separate contributions for the two values of the transferred orbital angular momentum λ. As can be seen from Fig. 2, the $\lambda=2$ contribution, corresponding to the $\beta_\mu^2(2D,1P)$ term of Eq. (8), dominates the cross section. This feature of the finite range DWBA calculations is true for all our OM parameter variations. As is manifest in Eqs. (7) and (8), the shape of the ground state cross section is the same as that of the $\lambda=1$ contribution to the 2^+ cross section. Furthermore, the magnitude of the latter should equal 0.418 times the ground state cross section (this ratio is calculated to be ~0.55 rather than 0.418 due to the difference in Q values). These relationships can be used to find the weak $\lambda=1$ contribution to the 2^+ cross section of Fig. 1, or to find the 0^+ cross section from Fig. 2.

Thus, while the difference in OM parameters between the last two lines of Table III is greater than would normally be expected on the basis of differences in energy of the outgoing ^6He in the two transitions, the analysis indicates that one could select a set of OM parameters in the range spanned by these limiting values. Such a choice would then give crude fits to cross section shapes for both transitions and still display the dominance of the 2^+ transition magnitude which is found at both limits of the OM parametrization.

IV. CONCLUSIONS

Finite-range DWBA calculations, which included recoil effects exactly, were performed for the reaction $^{13}C(^3He,^6He)^{10}C$ at 70 MeV, assuming transfer of a three-neutron cluster to the 0^+, ground state and 2^+, 3.35 MeV state in ^{10}C. After some variation of the relatively unknown optical model parameters, a range of values was found within which it is possible to represent the qualitative features of the observed cross section shapes and magnitudes of the two transitions. In view of the approximations involved in the basic assumptions, e.g., restricting the interaction of the three-neutron cluster with ^3He to a dependence on the relative spatial coordinate, the degree of agreement with experiment is quite encouraging.

These results are in contradiction to those obtained with the DWBA in the zero-range approximation. In particular, an important result of the present analysis is that the ratio of the integrated cross sections, $\sigma(2^+)/\sigma(0^+)$, is calculated to be of the order of two to three even when the same set of OM parameters is used for the $^6He+^{10}C$ channel in both transitions. This ratio differs substantially from the value of 0.4 given by the DWBA in the zero-range approximation, and is also much closer to experiment. The difference arises because the transition amplitudes present in the zero-range DWBA calculation play only a minor role in the finite-range case. In the present calculations it is other transition amplitudes which dominate, namely, those corresponding to more oscillator quanta in the c.m. motion. The preference for transfer to the $I=2$ state in the calculation arises from the dominance of transfer with orbital angular momentum λ equal to 2, a term that is absent in the zero-range DWBA.

The present finite-range DWBA analysis shows that it is possible to interpret the reaction $^{13}C(^3He,^6He)^{10}C$ as proceeding by direct cluster transfer to both the 0^+, ground state and the 2^+, 3.35 MeV state in ^{10}C.

All the finite-range DWBA calculations reported in this study were performed at the Lawrence Berkeley Laboratory computer center.

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