Direct cluster transfer in ^{3}He bombardment of ^{13}C at sub-barrier energies

M. A. Eswaran, Suresh Kumar, and E. T. Mirgule
Nuclear Physics Division, Bhabha Atomic Research Centre, Bombay 400 085, India
(Received 11 May 1989)

The angular distributions of cross sections for the reaction ^{13}C(^{3}He,^{4}He)^{12}C leading to ground state and first excited 4.44 MeV, 2^+ state of ^{12}C have been measured at sub-Coulomb energies of $E_{c.m.}=1.20$ and 1.05 MeV. The angular distributions are asymmetric with respect to 90° and anisotropies are also found to be much larger than those expected from compound nuclear processes. Analyses of the data, with assumptions of direct transfer processes, by exact finite range distorted wave Born approximation calculations show the presence of interference of two modes of direct transfer mechanisms of neutron transfer and ^{9}Be cluster transfer from the target ^{13}C to the projectile ^{3}He. These direct transfer calculations are in good agreement with the angular distributions and yield the value of the ratio of three nucleon spectroscopic strengths of first excited state to ground state of ^{12}C in good agreement with the value predicted from structure calculations.

I. INTRODUCTION

The study of nuclear reaction mechanism at sub-Coulomb energies is of significant interest. The process of direct transfer of a nucleon in nuclear reactions induced by either light ions or heavy ions at sub-Coulomb energies is well known.[1-3] Observation of direct transfer of a cluster of nucleons in reactions of light ions or heavy ions at sub-barrier energies is rare. However, the investigations of the occurrence of such cluster transfer reactions at sub-Coulomb energies, though difficult because of possible low cross sections, are of interest both from the point of view of reaction mechanism as well as the study of clustering in nuclei. In this article we report on our experiment of ^{3}He bombardment of ^{13}C at lowest ever sub-barrier energies, in which we could deduce evidence of direct cluster transfer.

II. EXPERIMENTAL MEASUREMENTS

In the present work the reactions ^{13}C(^{3}He,^{4}He)^{12}C$_{g.s.}$ ($Q=15.625$ MeV) and ^{13}C(^{3}He,^{4}He)^{12}C* (4.44 MeV, $J^\pi=2^+$) leading to the ground state and first excited state of ^{12}C have been studied at sub-Coulomb energies with a momentum analyzed beam of singly ionized ^{3}He from Model CN Van de Graaff accelerator at Bhabha Atomic Research Centre at Bombay. Preliminary results of this work on the reaction leading to the ground state of ^{12}C were reported earlier in an international seminar.[4]

A natural carbon target (1.11% ^{13}C) of 165 or 135 μg/cm^2 thickness was used. Four surface barrier detectors of 300 μm thickness were employed for the detection of alpha particles from the reaction at different angles. Because of the high Q value of 15.625 MeV (for the ground state) of this reaction there was no need of a particle identification system to detect the alpha particle from this reaction unambiguously. The Q value of the (^{3}He,^{4}He) reaction on the abundant isotope, ^{12}C, being only 1.401 MeV, this reaction does not interfere in the study of (^{3}He,^{4}He) on ^{13}C. Examples of alpha particle spectra from the reaction ^{13}C(^{3}He,^{4}He)^{12}C are shown in Fig. 1 recorded at laboratory angles of 24° and 160° at a bombarding energy of 1.40 MeV.

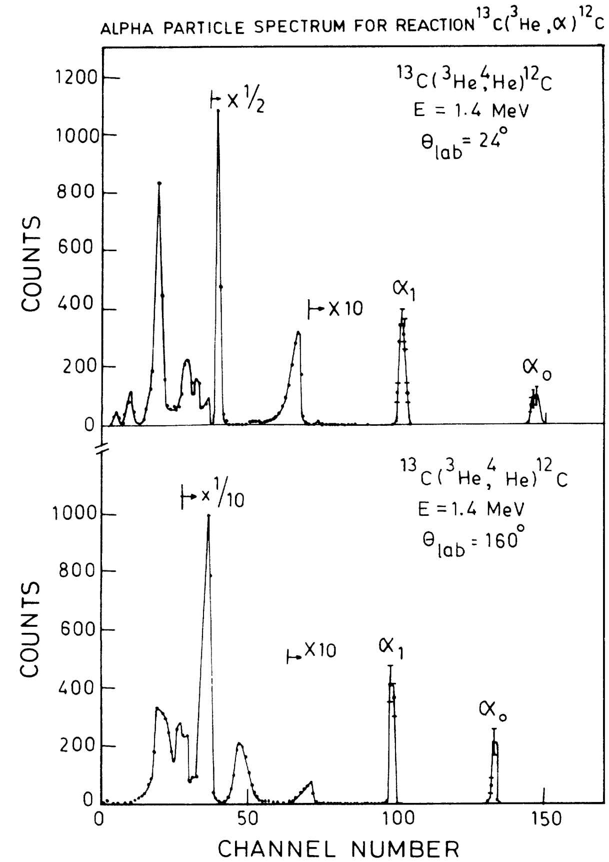

FIG. 1. Alpha particle spectrum from the reaction ^{13}C(^{3}He,α)^{12}C at $\theta_{lab}=24°$ and 160°, respectively, at $E_{^3He}=1.40$ MeV. The peaks marked α_0 and α_1 are the alpha particle peaks corresponding to ground state and first excited state of ^{12}C.

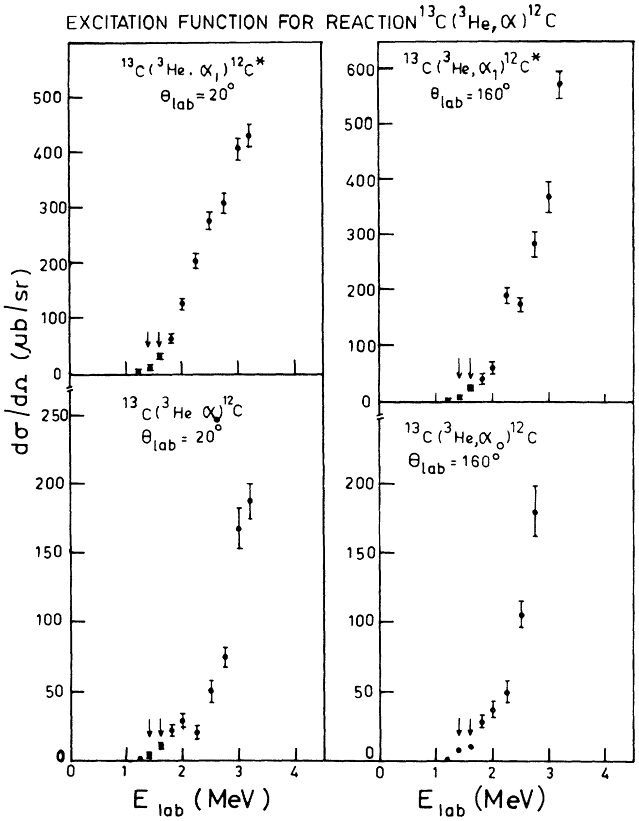

FIG. 2. Excitation functions of the reaction $^{13}C(^3He,\alpha_0)^{12}C_{g.s.}$ and $^{13}C(^3He,\alpha_1)^{12}C^*_{2^+}$ at $\theta_{lab}=20°$ and 160°, respectively. The arrows indicate the two energies at which angular distribution measurements were made.

The excitation function measurements for the reactions $^{13}C(^3He,^4He)^{12}C_{g.s.}$ and $^{13}C(^3He,^4He)^{12}C^*$ (4.44 MeV, 2^+) recorded in the bombarding energy range of 1–3 MeV in steps of 200 keV, at laboratory angles of 20° and 160°, are shown in Fig. 2. With a view to study the reaction mechanism at low energies, angular distribution of alpha particles from this reaction were measured over the range of 10°–170° to the beam with angular acceptance of $\pm 2°$ at bombarding energies of 1.40 and 1.60 MeV. After allowing for the energy loss for half the target thickness, the energies at which angular distributions have been measured correspond to mean center of mass energies of $E_{c.m.}=1.05$ and 1.20 MeV, respectively. The data recorded at the bombarding energies corresponding to mean $E_{c.m.}=1.05$ and 1.20 MeV are shown in Figs. 3(a) and 3(b), respectively, for both the reactions $^{13}C(^3He,^4He)^{12}C_{g.s.}$ and $^{13}C(^3He,^4He)^{12}C^*$ (4.44 MeV, 2^+).

III. ANALYSIS OF DATA

A. Compound nuclear reaction calculations

The angular distribution data shown in Fig. 3 are all asymmetric about 90° (c.m.) and also the anisotropies are large and particularly the anisotropies are more than an order of magnitude in the case of $^{13}C(^3He,^4He)^{12}C_{g.s.}$.

In the case of a reaction mechanism involving compound nucleus either forming an isolated level of definite parity or the reaction going through the overlapping compound nuclear levels satisfying the Hauser-Feshbach[5] statistical model, should give rise to angular distributions symmetric with respect to 90° in the center of mass system. In these cases magnitude of anisotropies will be dependent on the magnitude of the angular momenta involved in the reaction. If compound nuclear levels of same spin but opposite parities interfere, the resulting angular distribution will be asymmetric with respect to 90°.

Alternatively, if the reaction is dominated by direct reaction mechanism, the angular distribution will be asymmetric with respect to 90° in the center of mass system with the magnitude of the anisotropy dependent on the specific reaction mode or modes contributing to the reaction.[6]

In the present reaction $^{13}C(^3He,^4He)$ in the region near $E_{c.m.}=1.20$ MeV if the reaction proceeds through compound nucleus ^{16}O, it will be in the region of excitation around 24 MeV. For this closed shell light mass nucleus, at the excitation of 24 MeV level densities are not so high[7] as to assume that the Hauser-Feshbach statistical model will be valid. Further, at these low bombarding energies the partial waves of l values less than 3 or 4 are contributing to the reaction, as can be inferred from the transmission coefficients calculated from the optical model potential for the entrance channel. However, for a comparison with what is measured in the present experiment, we decide to calculate the angular distributions for the reactions $^{13}C(^3He,^4He)^{12}C_{g.s.}$ and $^{13}C(^3He,^4He)^{12}C^*$ (4.44 MeV, 2^+) at $E_{c.m.}=1.20$ and 1.05 MeV as expected from the Hauser-Feshbach statistical model.

The Hauser-Feshbach statistical model formula for differential cross section is[8]

$$\frac{d\sigma}{d\Omega}\alpha\alpha'=\sum_L \frac{\lambda^2}{4}\sum_J \frac{1}{(2I+1)(2i+1)}\,\frac{\sum_{Sl} T_l(\alpha)\sum_{S'l'} T_{l'}(\alpha')}{\sum_{\alpha''S''l''} T_{l''}(\alpha'')}\,Z(lJlJ;SL)Z(l'Jl'J;S'L)(-)^{S-S'}P_L(\cos\theta)\,, \qquad (1)$$

where all quantum numbers that specify the colliding nuclei and the two nuclei in the exit channel are denoted by α and α', respectively. Similarly $\mathbf{l}+\mathbf{S}=\mathbf{J}=\mathbf{l}'+\mathbf{S}'$, $\mathbf{S}=\mathbf{I}+\mathbf{i}$, and $\mathbf{S}'=\mathbf{I}'+\mathbf{i}'$ denote the angular momentum coupling for orbital angular momentum l, channel spin $\mathbf{S}$, and intrinsic angular momenta $\mathbf{I}$ and $\mathbf{i}$. T_l denotes the optical model transmission coefficient and Z is angular momentum coupling coefficient and P_L is the Legendre polynomial of order L.

T_l values were computed with a computer program SCATTER with the optical model parameters from the literature,[9,11] for the channels $^{13}C+^{3}He$, $^{15}N+p$, $^{15}O+n$, $^{14}N+d$, $^{12}C+^{4}He$, and $^{8}Be+^{8}Be$. Since the bombarding energy is low in the present work, the information on the discreet states in various residual nuclei in different channels, available in the literature compilation,[10] is sufficient and we did not have to use the level density formulas for any channel. For the entrance channel $^{13}C+^{3}He$ the optical model parameters are taken from Weller *et al.*,[11] who have determined these parameters by fitting elastic scattering angular distributions at 6 MeV. In our present work the angular distributions are done at the sub-Coulomb energies $E_{c.m.}=1.20$ or 1.05 MeV, and the optical model parameters at these low energies are not available and hence we have used the parameters available for the lowest energy in the literature. The absolute cross section calculated by the Hauser-Feshbach statistical model calculations sensitively depends on the T_l values for the entrance channel at the sub-Coulomb energies. The angular distributions of cross sections as calculated by the Hauser-Feshbach statistical model calculations by a program HAFEST (Ref. 12) are shown for $E_{c.m.}=1.05$ and 1.20 MeV in Figs. 3(a) and 3(b). The absolute cross sections calculated with the statistical model are higher than the measured values, and these are divided by a factor of 2 and shown by dashed curves in this figure. It is also seen from Figs. 3(a) and 3(b) that the statistical model anisotropies for the reactions leading to both ground state and first excited state of ^{12}C are much less than the measured values. As pointed out earlier the partial waves of l values less than 4 are contributing to the reaction at these low energies and the anisotropies from the compound nucleus statistical model calculations are not large.

Hence from the above comparison of the anisotropies in the measured angular distributions with those of statistical model calculations, it is clear that the compound nuclear reaction mechanism leading to overlapping levels cannot explain the observed angular distributions.

Specifically the angular distributions are done in the

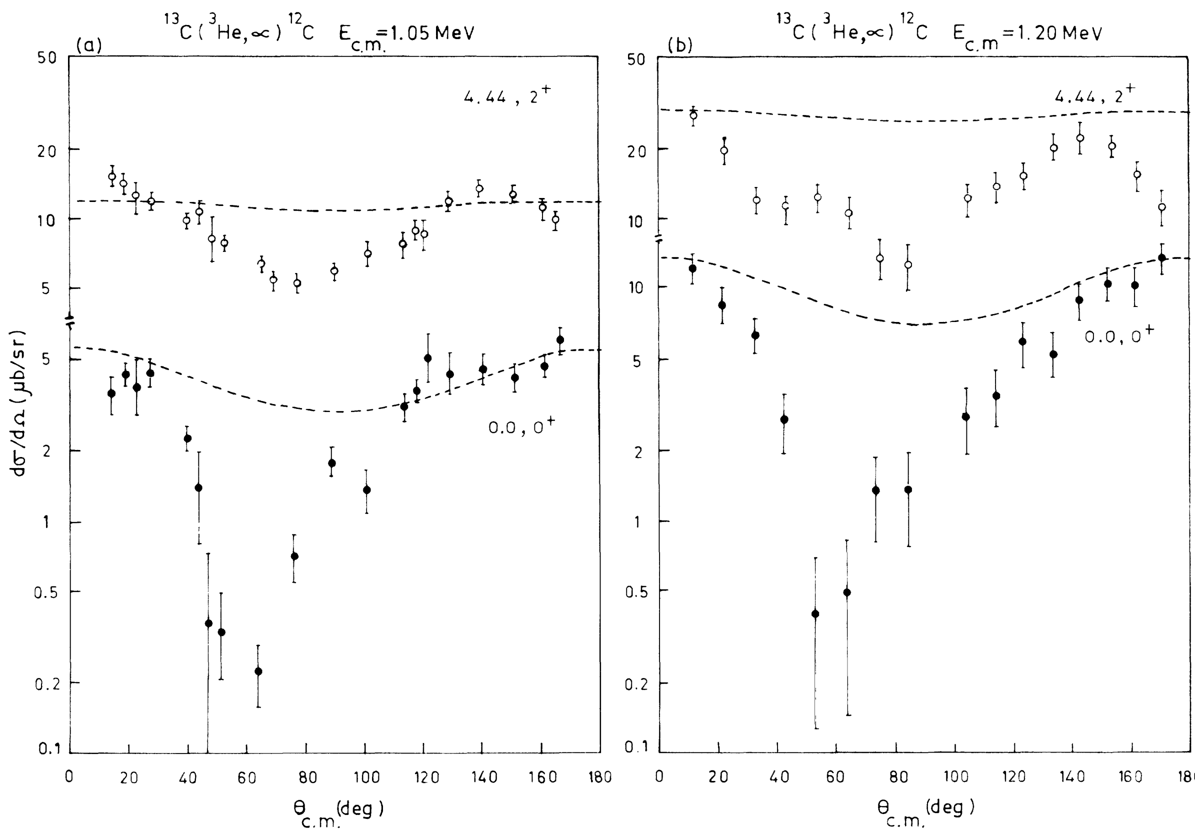

FIG. 3. Alpha particle angular distributions of the reactions $^{13}C(^{3}He,^{4}He)^{12}C_{g.s.}$ and $^{13}C(^{3}He,^{4}He)^{12}C^{*}$ (4.44 MeV, 2^{+}) at (a) $E_{c.m.}=1.05$ MeV and (b) $E_{c.m.}=1.20$ MeV. Closed and open circles with statistical error bars are the data points. Dashed lines are the Hauser-Feshbach statistical model calculations divided by a factor of 2.

present work at $E_{c.m.}=1.05$ corresponding to excitation energy in the compound nucleus (^{16}O) of $E_x=23.84\pm0.11$ and at $E_{c.m.}=1.20$ MeV corresponding to $E_x=23.99\pm0.11$ MeV. The resonances in ^{16}O are well studied as reported in the literature[7] in the region of interest in the present work. There is a sharp resonance of width 26 keV at $E_x=23.876$ in ^{16}O and it is assigned $J^\pi=6^+$ and is observed[9] in the reaction ^{12}C(^{4}He,^{8}Be)^{8}Be. Such a higher spin resonance cannot be excited significantly at low energies in the reaction ^{13}C(^{3}He,^{4}He)^{12}C in the present work. There is a resonance at $E_x=24.07$ MeV which is assigned $J^\pi=1^-$ with isospin $T=1$ since it is observed to decay by electric dipole gamma ray.[7] This level cannot decay through ^{4}He+^{12}C channel since its isospin $T=1$. These two resonances are in the same energy region in the compound nucleus corresponding to bombarding energies at which the angular distributions have been done in the present work.

In the energy range from 23 to 25 MeV in ^{16}O a close examination of known resonances[7] reveals that there are no known alpha emitting resonances of same spin and opposite parities which can interfere to give rise to asymmetric angular distributions as observed in the present work. Hence we conclude that the compound nuclear reaction mechanism cannot explain the observed angular distributions in the reaction ^{13}C(^{3}He,^{4}He)^{12}C$_{g.s.}$ and ^{13}C(^{3}He,^{4}He)^{12}C* (4.44 MeV, 2^+) where asymmetric angular distributions are observed with large anisotropies at sub-Coulomb bombarding energies.

B. Direct transfer reaction calculations

Alternatively, we consider the direct reaction mechanism, where a nucleon or a cluster of nucleons may be transferred between the two colliding nuclei. To investigate the possibility of direct transfer modes playing a significant role in the present sub-Coulomb reactions, exact finite range distorted wave Born approximation (EFRDWBA) calculations were made assuming one step direct transfer of a neutron from target ^{13}C to projectile ^{3}He. These direct neutron pickup calculations showed that it can only give rise to the forward peak in the angular distribution and not the backward peak. However, ^{13}C stripping into ^{9}Be+^{4}He and incoming ^{3}He combining with ^{9}Be can also lead to the reaction ^{13}C(^{3}He,^{12}C)^{4}He. Hence direct one step transfer of ^{9}Be cluster from target ^{13}C to projectile ^{3}He was included as second mode in the direct reaction calculations with EFRDWBA.

The EFRDWBA calculations were made with program LOLA (Ref. 13) assuming (i) neutron transfer and (ii) ^{9}Be ($J^\pi=\frac{3}{2}^-$) cluster transfer from the target ^{13}C to projectile ^{3}He. The bound state wave functions for ^{12}C+n and ^{12}C$^*_{2^+}$+n in ^{13}C$_{g.s.}$ ($J^\pi=\frac{1}{2}^-$) were calculated with the potential of Woods-Saxon form, used by Franey *et al.*[3] in the analysis of the neutron transfer heavy ion reaction, (^{13}C,^{12}C). The bound state wave function for ^{9}Be+^{4}He in ^{13}C was calculated with a potential of cosh form used by Bradlow *et al.*[14] in the analysis of α-transfer reaction (^{13}C,^{9}Be) on ^{16}O leading to ground and excited states of ^{20}Ne. ^{9}Be+^{3}He bound state wave function in ^{12}C and in ^{12}C$^*_{2^+}$ as well as that of ^{3}He+n in ^{4}He were calculated with Woods-Saxon form of potentials.

The parameters of all the above potentials for the calculation of bound wave functions are given in Table I. The value of N, the number of nodes in the wave function and relative L, the angular momentum are also listed in this table. The depth of the potentials are adjusted for the appropriate separation energies.

The optical model potential parameters for the calculation of distorted waves were taken for the incident channel ^{3}He+^{13}C, from Weller *et al.*,[11] who have deduced the Woods-Saxon form of potential parameters from fitting 6 MeV elastic scattering angular distribution data. These parameters are $V=173.9$ MeV, $R_R=2.185$ fm, $a_R=0.81$ fm, $W=4.55$ MeV, $R_I=5.315$ fm, $a_I=0.65$ fm, and $R_{Coul}=3.298$ fm. For the exit channel ^{12}C+^{4}He the parameters are taken from Carter *et al.*,[15] who have studied the elastic scattering in the energy range 10–19 MeV and deduced the optical model parameters. These parameters are $V=110.0$ MeV, $R_R=4.280$ fm, $a_R=0.50$

TABLE I. Interaction potentials $V(r)$ used to calculate bound state relative motion wave functions. S.E. = separation energy.

Bound state	Form of $V(r)$	Reference
^{13}C$_{g.s.}\rightarrow{}^9$Be+^{4}He	$-V_0(1+\cosh R/a)(\cosh r/a+\cosh R/a)^{-1}+V_{Coul}(r)$ $V_0=146.89$ MeV, $R=1.676$ fm, $a=0.6$ fm, $R_c=3.668$ fm, $(N,L)=(1,2)$ S.E. = 10.662 MeV.	14
^{12}C$_{g.s.}\rightarrow{}^9$Be+^{3}He	$-V_0[1+\exp(r-R)/a]^{-1}+V_{Coul}(r)$ $V_0=75.795$ MeV, $R=3.522$ fm, $a=0.65$ fm, $R_c=3.522$ fm, $(N,L)=(1,1)$ S.E. = 26.287 MeV	
^{12}C$^*_{2^+}\rightarrow{}^9$Be+^{3}He	Woods-Saxon form for all the following cases: $V_0=69.686$ MeV, $R=3.522$ fm, $a=0.65$ fm, $R_c=3.522$ fm, $(N,L)=(1,1)$ S.E. = 21.857 MeV	
^{13}C$_{g.s.}\rightarrow{}^{12}$C+$n$	$V_0=47.897$ MeV, $R=2.747$ fm, $a=0.6$ fm, $(N,L,j)=(0,1,\frac{1}{2})$ $V_{s.o}=6.0$ MeV, S.E. = 4.947 MeV	3
^{13}C$_{g.s.}\rightarrow{}^{12}C^*_{2^+}$+$n$	$V_0=48.044$ MeV, $R=2.747$ fm, $a=0.6$ fm, $(N,L,j)=(0,1,\frac{3}{2})$ $V_{s.o.}=6.0$ MeV, S.E. = 9.385 MeV	3
^{4}He$\rightarrow{}^3$He+n	$V_0=81.24$ MeV, $R=1.587$ fm, $a=0.6$ fm, $(N,L)=(0,0)$, S.E. = 20.568 MeV	

fm, $W_D=4.0$ MeV, $R_I=4.280$ fm, $a_I=0.30$ fm, and $R_{\mathrm{Coul}}=2.791$ fm.

The single effective interaction used for the calculation of transition amplitude is the potential $V_{^{12}\mathrm{C}-n}$ (Ref. 3) for neutron transfer and $V_{^{9}\mathrm{Be}-\alpha}$ (Ref. 14) for ^{9}Be transfer and these are the potentials, shown in Table I for calculation of bound states $^{12}\mathrm{C}+n\rightarrow{}^{13}\mathrm{C}_{\mathrm{g.s.}}$ and $^{9}\mathrm{Be}+{}^{4}\mathrm{He}\rightarrow{}^{13}\mathrm{C}_{\mathrm{g.s.}}$, respectively. The EFRDWBA calculation with the above optical model and bound state parameters made with the LOLA program with the direct one step transfer mode assumptions of neutron transfer and ^{9}Be cluster transfer are shown, respectively, in Figs. 4(a) and 5(a) for the reaction leading to $^{12}\mathrm{C}_{\mathrm{g.s.}}$ for $E_{\mathrm{c.m.}}=1.20$ and 1.05 MeV, respectively. The l transfer allowed is uniquely equal to 1 for both transfer modes from angular momentum considerations. In these calculations partial waves up to 8 were included and the integrations were made up to 30 fm. Specifically, the EFRDWBA calculations are for the reaction $^{13}\mathrm{C}(^{3}\mathrm{He},{}^{4}\mathrm{He})^{12}\mathrm{C}_{\mathrm{g.s.}}$ (reaction mode 1) and $^{13}\mathrm{C}(^{3}\mathrm{He},{}^{12}\mathrm{C}_{\mathrm{g.s.}})^{4}\mathrm{He}$ (reaction mode 2) and in both cases angular distribution of alphas are shown in Figs. 4(a) and 5(a). The reaction mode 1 (neutron transfer) gives rise to forward peak and the reaction mode 2 (^{9}Be transfer) gives rise to backward peak. When the l transfer is the same in both the direct reaction modes, there can be coherent interference of the two modes.[16] The resultant angular dis-

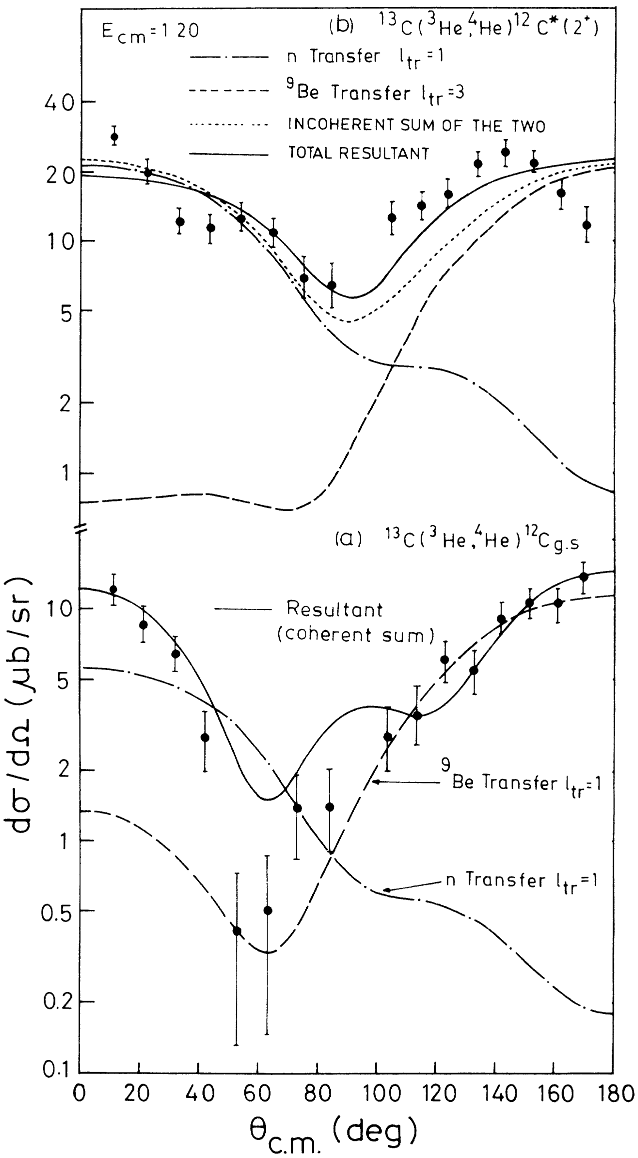

FIG. 4. Alpha particle angular distributions of the reaction (a) $^{13}\mathrm{C}(^{3}\mathrm{He},{}^{4}\mathrm{He})^{12}\mathrm{C}_{\mathrm{g.s.}}$ and (b) $^{13}\mathrm{C}(^{3}\mathrm{He},{}^{4}\mathrm{He})^{12}\mathrm{C}^{*}_{2^+}$ at $E_{\mathrm{c.m.}}=1.20$ MeV. Closed circles with statistical error bars are the data points. Dashed lines and dot-dashed lines show the EFRDWBA calculations for ^{9}Be cluster transfer and neutron transfer, respectively. Solid lines show the calculations of resultant of both the direct transfer modes. For the dotted line in (b) see text.

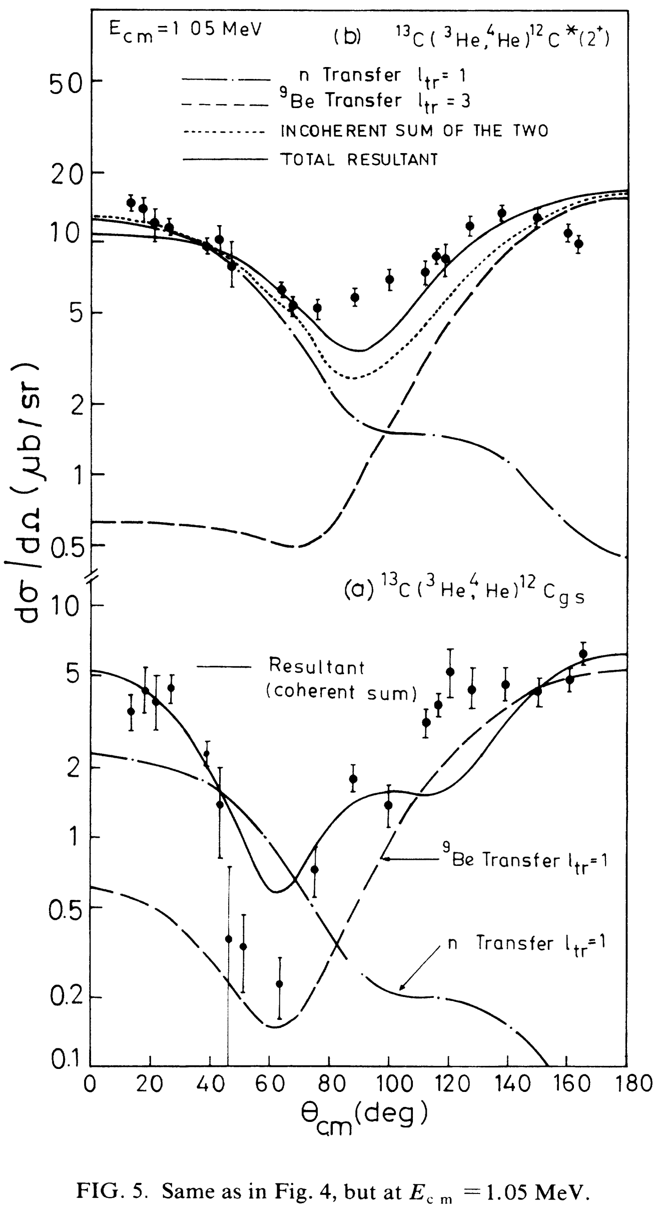

FIG. 5. Same as in Fig. 4, but at $E_{\mathrm{c.m.}}=1.05$ MeV.

tribution from the coherent interference of the two amplitudes was calculated with a computer program for which the transition amplitudes F and G for reaction modes (1) and (2), respectively, obtained from the LOLA program, are the inputs. The resultant amplitude was taken as $F+G$ for this calculation with the phases of the transition amplitude for the reaction mode (1), ^{13}C(^{3}He,^{4}He)^{12}C$_{g.s.}$, and reaction mode (2), ^{13}C(^{3}He,^{12}C$_{g.s.}$)^{4}He, as calculated from the LOLA program. In this calculation for interference of both the transfer modes the product $(S_1S_2)^{1/2}$ of the spectroscopic amplitudes $(S_1)^{1/2}$, for ^{3}He$+n\rightarrow^4$He and $(S_2)^{1/2}$ for ^{12}C$+n\rightarrow^{13}$C$_{g.s.}$, is taken as an adjustable multiplicative factor for the transition amplitude for neutron transfer. Similarly the product $(S_3S_4)^{1/2}$, of the spectroscopic amplitude $(S_3)^{1/2}$ for ^{9}Be$+^4$He$\rightarrow^{13}$C$_{g.s.}$ and $(S_4)^{1/2}$ for ^{9}Be$+^3$He$\rightarrow^{12}$C, is the multiplicative factor for the transition amplitude for ^{9}Be transfer. The result of this interference calculation without any additional arbitrary normalization factor is shown in Figs. 4(a) and 5(a) where it is observed that the angular distributions are well described by this calculation.

In the case of the analysis of the angular distribution to the 4.44 MeV $J^\pi=2^+$, first excited state of ^{12}C the l transfer is 1 for the neutron transfer mode since the configuration of ^{12}C$^*_{2^+}$ is described essentially by pickup of $P_{3/2}$ neutron from ^{13}C$_{g.s.}$.[17] So far as the ^{9}Be transfer is concerned, l transfer of 1, 2, and 3 are allowed by angular momentum considerations. However, calculations with EFRDWBA show that the predominant contribution to the cross section arises from l transfer $=3$ while l transfer $=1$ and 2 contribute very little. For this calculation the bound state of ^{9}Be$+^3$He in first excited state of ^{12}C$^*_{2^+}$ is as given in Table I. The number of nodes $N=1$, and $L=1$. This is the dominant configuration for this state expected from the calculations of Kurath and Millener.[18] The EFRDWBA calculations for neutron transfer and ^{9}Be transfer with the LOLA program for this reaction ^{13}C(^{3}He,^{4}He)^{12}C$^*_{2^+}$ for angular distribution of alphas at $E_{c.m.}=1.20$ and 1.05 MeV are shown in Figs. 4(b) and 5(b), respectively. Since the l transfers are not same, but are 1 and 3, respectively, for neutron transfer and ^{9}Be transfer in this case, the resultant angular distribution is obtained by incoherent addition[16] of the two individual contributions. This resultant is shown by dotted lines in Figs. 4(b) and 5(b) and it is almost close to the observed angular distribution. However, in the ^{9}Be cluster calculations, the l transfer of 1 and 2 with the bound state configuration of ^{9}Be$+^3$He$\rightarrow^{12}$C$^*_{2^+}$ with $(N,L)=(1,1)$ and l transfer of 1 with bound state configuration of $(N,L)=(0,3)$, also contribute a small amount to the cross section. If these contributions are also taken into account with the relative magnitude of these configurations relative to the dominant configuration taken from Ref. 18 the final resultant angular distribution of alphas are slightly modified becoming closer in agreement with the data and this is shown by the solid curve in Figs. 4(b) and 5(b).

The values of spectroscopic factors S_1S_2 and S_3S_4 derived by these two mode resultant EFRDWBA fits to the measured angular distributions to the ^{12}C$_{g.s.}$ and first excited 4.44 MeV, 2^+ states of ^{12}C at $E_{c.m.}=1.20$ MeV (Fig. 4) as well as at $E_{c.m.}=1.05$ MeV (Fig. 5) are shown in Table II. The average value of the ratio $S_1S_2(2^+)/S_1S_2$(g.s.) is 3.62 (average of 2.97 and 4.27 from fits at two energies) for the neutron transfer. The average value of the ratio $S_3S_4(2^+)/S_3S_4$(g.s.) is 0.23 (average of 0.19 and 0.27 from fits at the two energies) for the ^{9}Be transfer. The spectroscopic factor $S_4(2^+)$ is for ^{9}Be$+^3$He$\rightarrow^{12}$C$^*_{2^+}$ and S_4(g.s.) is for ^{9}Be$+^3$He$\rightarrow^{12}$C$_{g.s.}$ and the ratio $S_4(2^+)/S_4$(g.s.) from the calculation of three nucleon spectroscopic strengths by Kurath and Millener[18] is $(1.085/2.398)^2=0.2045$. The value of 0.23 for this ratio, derived from the present EFRDWBA fits, is in close agreement with the above theoretical expectation. The value of the ratio $S_2(2^+)/S_2$(g.s.), i.e., ratio of spectroscopic factors of ^{12}C$^*_{2^+}+n\rightarrow^{13}C_{g.s.}$ and ^{12}C$_{g.s.}$ $+n\rightarrow^{13}$C$_{g.s.}$, from the calculation of Cohen and Kurath[17] is 1.8294 while the average of this ratio from the present EFRDWBA fits is 3.62.

The use of single effective interaction in the calculation of transition amplitude in the present EFRDWBA analysis, i.e., $V_{^9\text{Be}-\alpha}$ for ^{9}Be transfer and $V_{^{12}\text{C}-n}$ for neutron transfer, is the approximation employed in the present analysis. Though this may change the absolute cross section calculated for a transition for a specific final state consequently affecting the spectroscopic factor for that particular state, the ratio of the spectroscopic factors of first excited state to ground state of ^{12}C is not likely to be affected significantly by this approximation. However, from ^{9}Be cluster transfer mode analysis the value of the ratio of $S_4(2^+)/S_4$(g.s.) deduced agrees well with that expected from structure calculations while such a ratio $S_2(2^+)/S_2$(g.s.) deduced for neutron transfer is somewhat higher than the value predicted from structure calculations.

TABLE II. Spectroscopic factors from the EFRDWBA analysis.

$E_{c.m}$ (MeV)	State in ^{12}C MeV;J^π	l_{tr} (n transfer)	S_1S_2	$S_1S_2(2^+)/S_1S_2$(g.s.)	l_{tr} (^{9}Be transfer)	S_3S_4	$S_3S_4(2^+)/S_3S_4$(g.s.)
1.20	0;0$^+$	1	0.102	2.97	1	0.336	0.19
1.20	4.44;2$^+$	1	0.303		3	0.063	
1.05	0;0$^+$	1	0.102	4.27	1	0.384	0.27
1.05	4.44;2$^+$	1	0.436		3	0.102	

IV. DISCUSSION

It is observed that the compound nuclear reaction mechanism cannot explain the observed angular distributions in the reaction $^{13}C(^{3}He,^{4}He)^{12}C_{g.s.}$ and $^{13}C(^{3}He,^{4}He)^{12}C^{*}$ (4.44 MeV, 2^{+}) where asymmetric angular distributions are observed with large anisotropies at sub-Coulomb bombarding energies.

From the comparisons of direct transfer calculations with the measured angular distributions it is clear that the direct reaction mechanism assumptions of neutron and ^{9}Be cluster transfer at these sub-Coulomb energies in these reactions $^{13}C(^{3}He,^{4}He)^{12}C_{g.s.}$ and $^{13}C(^{3}He,^{4}He)^{12}C^{*}$ (4.44 MeV, 2^{+}) are quite valid. Notably, the agreements of the angular distributions with the calculations are quite good, and the ratios of spectroscopic strengths of the first excited state to the ground state of ^{12}C for one nucleon and three nucleon transfers are reasonable. The approximation of single effective interaction used in the EFRDWBA calculations may be responsible for some deviation between the expected and deduced values of spectroscopic strength ratio of the first excited state to ground state for neutron transfer.

At the sub-Coulomb energies in the bombardment of ^{13}C with ^{3}He the direct transfer of ^{9}Be cluster in addition to neutron transfer, as brought out in the above results, is significant. Heavy particle stripping in the reaction $^{13}C(^{3}He,^{4}He)^{12}C$ was postulated by Owen *et al.*,[19] who analyzed the reaction data at low energies by zero range plane wave analysis employing radial cutoff in the calculations. Due to the approximate nature of these calculations the reaction mechanism involving heavy particle stripping was then not confirmed. In our present work exact finite range distorted wave Born approximation calculations are employed along with appropriate bound state wave functions. The present results at lowest ever sub-Coulomb energies in this reaction confirm the ^{9}Be cluster transfer along with the neutron transfer. Kellogg and Zurmuhle[20] have studied this reaction at higher energies of 12, 15, and 18 MeV and, by zero range DWBA analysis, have fitted the dominant forward peak in the angular distributions by assuming neutron transfer alone. Any possible contributions from the heavy particle stripping are neither included nor brought out in their analysis. At these higher energies the angular distributions are also complex with the presence of several peaks which can arise from both neutron transfer as well as heavy particle stripping, making it difficult to determine the individual contributions. Contrary to this, the present angular distribution measurements at sub-Coulomb energies of the reactions $^{13}C(^{3}He,^{4}He)^{12}C_{g.s.}$ and $^{13}C(^{3}He,^{4}He)^{12}C^{*}_{2^{+}}$ are analyzed by EFRDWBA direct reaction theory with assumptions of neutron transfer as well as one step ^{9}Be cluster transfer. This analysis shows definite evidence for the existence of direct ^{9}Be cluster transfer at these sub-barrier energies and the ratio of three nucleon spectroscopic strength of first excited state of ^{12}C to ground state deduced from this analysis is in close agreement with that of structure calculations.[18]

ACKNOWLEDGMENTS

We acknowledge the technical assistance of N. L. Ragoowansi and H. H. Oza during the experiment. Our thanks are also due to Dr. D. R. Chakrabarty for assistance in some stages of the experiment.

[1] P. J. A. Buttle and L. J. B. Goldfarb, Nucl. Phys. **78**, 409 (1966).
[2] H. J. Korner and J. P. Schiffer, Phys. Rev. Lett. **27**, 1457 (1971).
[3] M. A. Franey, J. S. Lilley, and W. R. Phillips, Nucl. Phys. **A324**, 193 (1979).
[4] M. A. Eswaran, in *Proceedings of the International Seminar on Direct Reactions, Bangalore, India, 1989,* edited by N. G. Puttaswamy (Indian Academy of Sciences, Bangalore, 1990).
[5] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952).
[6] N. Austern, R. M. Drisko, E. C. Halbert, and G. R. Satchler, Phys. Rev. **133**, B3 (1964).
[7] F. Ajzenberg-Selove, Nucl. Phys. **A460**, 1 (1986).
[8] R. G. Stokstad, in *Treatise on Heavy-Ion Science,* edited by D. A. Bromley (Plenum, New York, 1985), Vol. 3, p. 83.
[9] F. Brochard, P. Chevallier, D. Disdier, V. Rauch, G. Rudolf, and F. Scheibling, Phys. Rev. C **13**, 967 (1976); D. Wilmore and P. E. Hodgson, Nucl. Phys. **A55**, 673 (1964); C. M. Perey and F. G. Perey, Phys. Rev. **132**, 755 (1963).
[10] F. Ajzenberg-Selove, Nucl. Phys. **A433**, 43 (1985); **A449**, 1 (1986).
[11] H. R. Weller, N. R. Roberson, and D. R. Tilley, Nucl. Phys. **A122**, 529 (1968).
[12] M. A. Eswaran, Suresh Kumar, E. T. Mirgule, and N. L. Ragoowansi, Phys. Rev. C **39**, 1856 (1989).
[13] R. M. DeVries, Phys. Rev. **8**, 951 (1973).
[14] H. S. Bradlow, W. D. M. Rae, P. S. Fisher, N. S. Godwin, G. Proudfoot, and D. Simelein, Nucl. Phys. **A314**, 171 (1979).
[15] E. B. Carter, G. E. Mitchell, and R. H. Davis, Phys. Rev. **133B**, 1421 (1964).
[16] Steve Edwards, D. Robson, and Thurman L. Talley, Phys. Rev. C **8**, 456 (1973).
[17] S. Cohen and D. Kurath, Nucl. Phys. **A101**, 1 (1967).
[18] D. Kurath and D. J. Millener, Nucl. Phys. **A238**, 269 (1975).
[19] G. E. Owen, L. Madansky, and S. Edwards, Jr., Phys. Rev. **113**, 1575 (1959).
[20] E. M. Kellogg and R. W. Zurmuhle, Phys. Rev. **152**, 890 (1966).