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THE ENERGY VARIATION OF MULTINUCLEON TRANSFER REACTIONS WITH HEAVY-IONS*

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ABSTRACT

The reaction $^{12}C(^{12}C, {}^{9}Be)^{15}O$ was studied at incident energies of 78, 104 and 187 MeV. Combined with the apparent high selectivity of the reaction in exciting simple ^{3}He cluster states, the systematic energy variation of the cross section is used to select cluster states of progressively higher angular momentum.

The discovery of oscillatory angular distributions in one and two-nucleon transfer reactions with heavy-ions has led to their widespread application in supplementing our knowledge of nuclear structure derived from conventional light-ion reactions.[1] For multinucleon transfer reactions, however, the differential cross sections are often featureless and serve as poor signatures of the J-value of a state.[2,3,4] Such structureless distributions are not peculiar to heavy-ion induced transfer, since in recent studies of the (α, p) reaction at high energy[5,6], J-values had to be assigned from the theoretical prediction of the magnitude rather than the shape of the differential cross section. Potentially, however, these multinucleon transfers can uniquely give us information on new types of correlation in nuclear motion in areas inaccessible in general with conventional light-ion reactions. The nature of these states is currently the subject of much study in heavy-ion research.[7] Of particular interest is the comparison of theoretical predictions of cluster structure based on the shell-model[2] or on the recent folding potential model which has been used to generate cluster rotational bands for three and four nucleons outside ^{12}C and ^{16}O cores.[8,9] This latter approach appears highly successful for light nuclei and, extended to other regions of the periodic table, introduces an interesting area for spectroscopy with heavy-ions. In this letter we describe a method of combining the high selectivity of the reactions with a study of the variation of the cross sections over a wide range of energy[10] to select states of progressively higher spin in the rotational band.

To initiate this work we chose the reactions $^{12}C(^{12}C, ^{10}Be)^{14}O$ and $^{12}C(^{12}C, ^{9}Be)^{15}O$; the latter reaction was known to be favorable for spatially symmetric ^{3}He transfer.[11] The reactions were studied using the Berkeley 88" Cyclotron, and the QSD spectrometer to detect the reaction products. The three-nucleon transfer was done at three bombarding energies of 78, 104 and 187 MeV. The spectrum, taken at 187 MeV, in Fig. 1, illustrates the pronounced excitation of states at 15.08 and 12.87 MeV, which have been assigned $J^{\pi} = 13/2^{+}$ and $11/2^{-}$ on the basis of reaction systematics and theoretical predictions.[2,9] In the cluster model these states correspond to ^{3}He orbitals with L = 6 and 5, and are the upper members of rotational bands with 2N + L = 6 and 5, where N is the number of nodes in the wave function of the cluster.[9] As the incident energy is decreased, states of lower spin become strongly excited. This effect is illustrated in Fig. 2, which shows that at the lowest energy of 78 MeV, representative states of $J^{\pi} = 1/2^{-}$, $5/2^{+}$ and $13/2^{+}$ are excited with comparable intensity, whereas at 187 MeV there is a factor of 10^{3} between the cross sections for the $1/2^{-}$ and the proposed $13/2^{+}$ state. This variation, if accounted for by reaction dynamics, can be used to infer J^{π} values.

We describe the reaction by a semiclassical theory[2,12] which gives the transition probability (P) from an initial cluster state in the projectile with orbital and magnetic quantum numbers $(\ell_1 \lambda_1)$ and spectroscopic amplitude S_1, to a final state $(\ell_2 \lambda_2)$ of amplitude S_2. The orbit of the projectile is assumed to follow a straight line. Then

$$P \propto S_1^2 S_2^2 \, | Y_{\ell_1}^{\lambda_1} (\tfrac{\pi}{2}, 0) |^2 | Y_{\ell_2}^{\lambda_2} (\tfrac{\pi}{2}, 0) |^2 \exp \left[- \left(\frac{R \Delta k}{\pi} \right)^2 - \left(\frac{(\Delta L)}{\sqrt{\gamma R}} \right)^2 \right] \quad (1)$$

where $R = R_1 + R_2$; γ is related to an average of the binding energies ε of the initial and final states, according to $\gamma^2 = \frac{2m\varepsilon}{\hbar^2}$, where m is the transferred mass. The quantities ΔL and Δk are defined by:

$$\Delta L = \lambda_2 - \lambda_1 + \frac{1}{2} k_o (R_1 - R_2) + Q_{eff}/\hbar v \quad (2)$$

$$\Delta k = k_o - \lambda_1/R_1 - \lambda_2/R_2 \quad (3)$$

Here v is the relative velocity of the cores in the region of transfer, $k_o = mv/\hbar$ and $Q_{eff} = Q - (Z_1^f Z_2^f - Z_1^i Z_2^i) e^2 /R$. The semiclassical transition probability (Eq. 1) has a structure which parallels that given by the full finite-range DWBA amplitude in the limit of small binding energy. In that case Nagarajan[13] has shown that the six dimensional integral of the DWBA separates into a product of two three-dimensional integrals whose arguments are of the same form as the terms in Eq. 1. The transfer probability is large only if $\Delta k, \Delta L \approx 0$, corresponding approximately to conservation of linear momentum along the incident direction, and to conservation of angular momentum of the transferred particle. The conditions (2) and (3) relate the energy dependence to the J-value of the state. Total transition probabilities between states $(j_1 \ell_1)$ and $(j_2 \ell_2)$ were calculated by summing over the final λ_2 and averaging over λ_1, weighted by coupling coefficients for the particle spin and angular momentum. Details of the bound state wave functions are ignored, apart from the spherical harmonics in Eq. 1 (which enter with fixed arguments because the reaction is confined to the reaction plane in the region between the nuclei) and the parameter $\sqrt{\gamma R}$ for which we used an average value of 2.5.

The results of the calculations for the $1/2^-$, $5/2^+$ and $13/2^+$ states are shown in Fig. 2. One overall normalization was applied in comparing theory and experiment, and equal spectroscopic factors were assumed for all states. The general trend of the data is accounted for by the model, in particular the strong enhancement of the 15.08 MeV state over the ground state ($J^\pi = 1/2^-$) at the incident energy of 187 MeV. This observation is consistent with a high spin assignment ($13/2^+$) to the 15.08 MeV state. It appears, in fact, that there is a systematic variation in the maximum of the cross section which moves progressively to higher energies the higher the J-value of the state.

The enhancement of the $13/2^+$ state may also be due to a larger cluster spectroscopic factor. Indeed both the strongly excited states at 15.08 and 12.87 MeV may be examples of threshold cluster or molecular states,[14, 15] since they lie just above the threshold of 12.07 MeV for the decay $^{15}O \rightarrow {}^{12}C + {}^{3}He$. Intuitively the cluster model is expected to give a good description when the clusters are well separated but when they overlap so that antisymmetrization becomes important, the cluster shell model pictures become equivalent.[16]

The next member of the 2N+L band is predicted by the folding model[9] at approximately 10.9 MeV ($J^\pi = 9/2^+$) in the analog nucleus ^{15}N. Recently[17], a three particle four-hole state of $J^\pi = 9/2^+$ was indeed discovered in ^{15}N at 10.693 MeV, coinciding, within experimental errors, with the state selectively excited at 10.78, 10.73 MeV and 10.704 in three nucleon transfer reactions on ^{12}C induced by ^{10}B [18], ^{6}Li [3] and α particles[5] respectively. The first two reactions also identify the analog excitation in ^{15}O at 10.47 and 10.50 MeV, in good agreement with the excitation we observe at 10.42 MeV (see Fig. 1). This state we therefore associate with the above 3p-4h configuration, and it probably corresponds to the $9/2^+$, L=4 cluster state, since the overlap of the shell model and the folding potential model is expected to be large for this configuration [9].

As Fig. 1 shows, we also observe a selectively excited state at 11.66 MeV in ^{15}O, the intensity of which was found to increase relative to the 10.42 MeV, $9/2^+$ state between 104 and 187 MeV incident energy, implying a higher orbital than L=4 for this state. (At the incident energy of approximately 10 MeV/nucleon of the reactions induced by ^{10}B and ^{6}Li, this state was only weakly excited.) Tentatively, therefore, we assign this excitation to the $9/2^-$, L=5 configuration predicted by strong and weak coupling SU_3 models [2] at 11.7 and 11.3 MeV respectively. A $9/2^-$ state in ^{15}N at 11.95 MeV has also been inferred from a study of the systematics of the $^{13}C(\alpha,d)^{15}N$ reaction [19], and from a DWBA analysis of the $^{12}C(\alpha,p)^{15}N$ reaction.[5] Although the SU_3 models give rise to appreciable clustering in this configuration, no such state is predicted by the folding model at this region of excitation. Instead, cluster states with $J^\pi = 9/2^-$ and $11/2^+$ are predicted to lie at over 20 MeV in excitation [9], since these are the components of the $11/2^-$ and $13/2^+$ states raised to high excitation by the t or ^{3}He spin-orbit potential. A more detailed study of the energy variation of states excited in the region of 10 and 20 MeV could possibly provide a test of these different approaches to clustering phenomena. The experimental identification of states above 20 MeV would call for even higher incident energies than the 15 MeV/nucleon of the present experiment.

The technique of energy variation is particularly useful for distinguishing states of different L-orbitals lying close in excitation. A case is illustrated in Fig. 3, which compares spectra at 114 MeV[2] and 187 MeV for two-proton cluster states, assigned 3^- and 4^+ in Ref. 2 and lying near the threshold of 6.57 MeV for the decay $^{14}O \rightarrow {}^{12}C + 2p$. The relative intensities of these L=3 and 4 orbitals reverse at the higher energy, in agreement with the above assignment.

We have shown that the energy variation of multinucleon transfer reactions can be a useful technique for identifying cluster states. The measurement of the differential cross sections in multinucleon transfer reactions with light or heavy-ions does not appear to be a unique method of assigning J values [2-6] unless supplemented by varying the bombarding energy over a wide range. The location of similar states in other target nuclei and transfers of more massive clusters are potentially interesting extensions of this technique using high energy accelerators of readily variable energy. The approximate formalism of the reaction mechanism described here, whether of semi-classical or DWBA theory, will simplify the task of conducting surveys in order to discover the interesting interesting areas for investigation [20].

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FOOTNOTES AND REFERENCES

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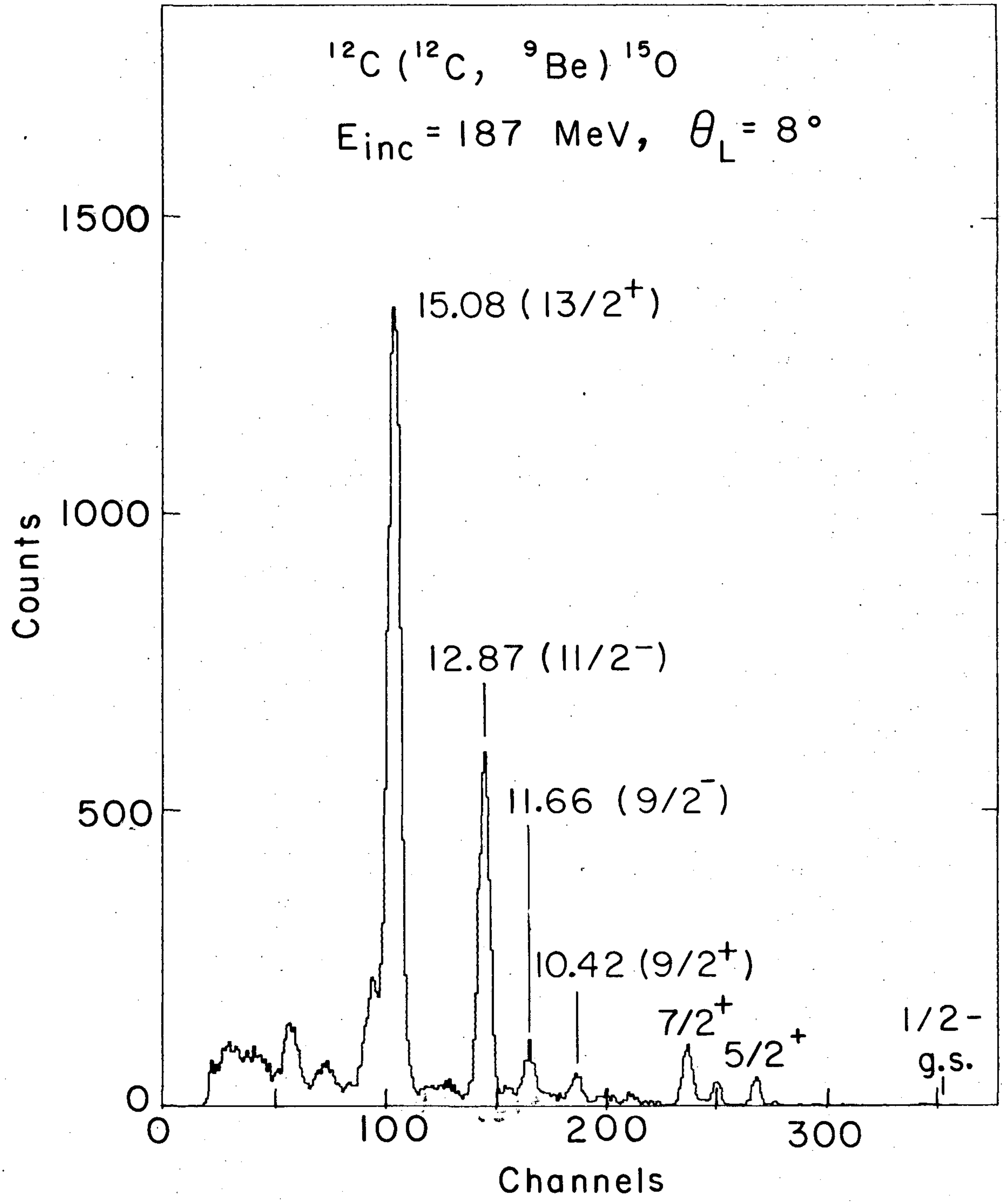
FIGURE CAPTIONS

Fig. 1. Energy spectrum for the reaction $^{12}C(^{12}C, {}^{9}Be)^{15}O$ at $E_L = 187$ MeV and $\theta_L = 8°$.

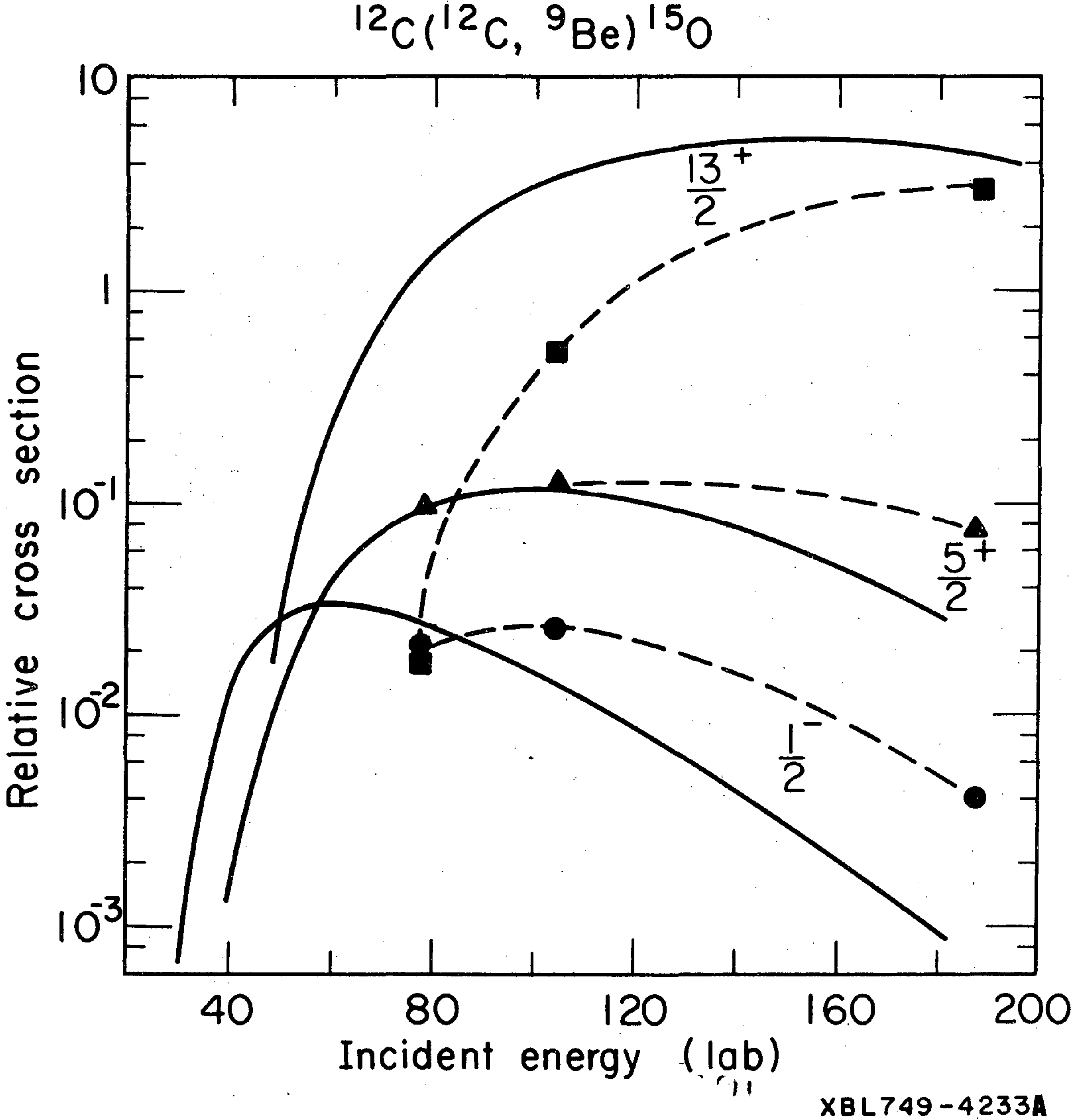
Fig. 2. The energy variation of the relative differential cross sections for states of different J^{π} excited in the reaction $^{12}C(^{12}C, {}^{9}Be)^{15}O$. The dotted lines are to guide the eye through the experimental points, and the solid lines are the theoretical predictions based on Eq. 1.

Fig. 3. Comparison of the energy spectra for states of $J^{\pi} = 3^{-}, 4^{+}$ excited in the reaction $^{12}C(^{12}C, {}^{10}Be)^{14}O$ at 114 MeV (Ref. 2) and 187 MeV.



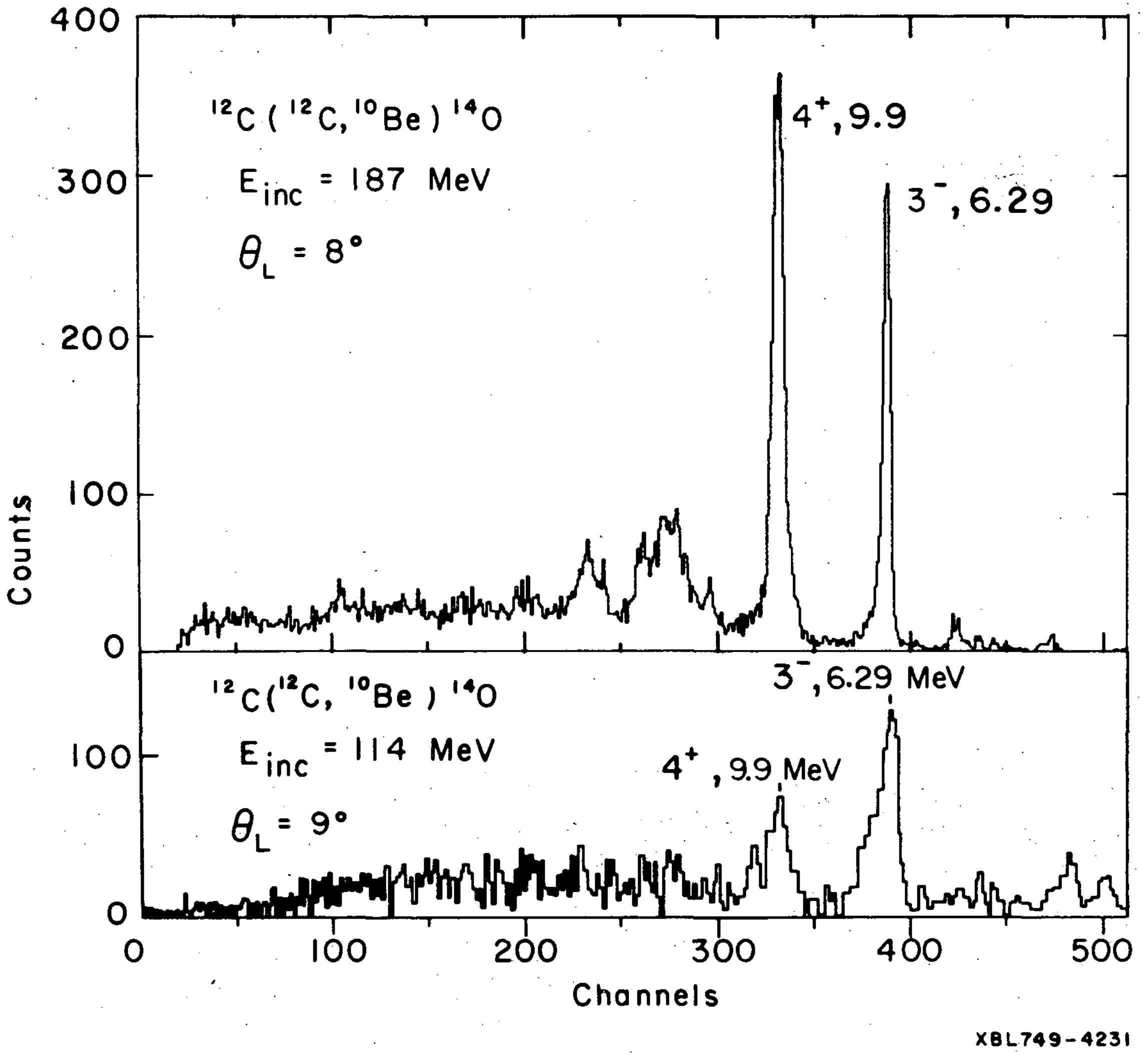
XBL746-3473

Fig. 1



XBL749-4233A

Fig. 2



400
300
200
100
0
Counts
$^{12}C(^{12}C,^{10}Be)^{14}O$
E_{inc} = 187 MeV
θ_L = 8°
4^+, 9.9
3^-, 6.29
$^{12}C(^{12}C,^{10}Be)^{14}O$
E_{inc} = 114 MeV
θ_L = 9°
3^-, 6.29 MeV
4^+, 9.9 MeV
100
0
0
100
200
300
400
500
Channels
XBL749-4231

Fig. 3

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