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INELASTIC SCATTERING OF ^{12}C FROM ^{208}Pb TO THE SECOND 0^+ STATE OF ^{12}C

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Abstract

A theoretical and experimental investigation of the inelastic scattering of ^{12}C from ^{208}Pb target exciting the second 0^+ state of ^{12}C has been carried out at incident energies of 132 MeV, 187 MeV and 230 MeV. Experimental data were obtained at the 88" cyclotron at Berkeley. The theoretical analysis has been carried out in the framework of a microscopic folding model and the DWBA. The real parts of the optical potentials in the initial and final channels as well as the real part of the transition form factor have been calculated by double folding the M3Y effective interaction with the respective densities. The results indicate the necessity of reducing the strength of the calculated real potentials in the final channel.

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In this paper we describe the results of an experimental and theoretical investigation of the excitation of the second 0^+ state of ^{12}C by inelastic scattering of this nucleus from ^{208}Pb target. This 0^+ state in ^{12}C is known to have well developed α-cluster structure[1,2] which is evident from the large value (= 0.74) of the ^{8}Be-α reduced width for this state. The theoretical analysis of this excitation process by double folding model is interesting because of the following reasons: (a) previous studies of the heavy ion elastic scattering for weakly bound projectiles employing the M3Y type of effective interaction[3,4] have indicated that the strengths of the calculated potentials must be reduced by a factor of approximately 2 in order to get a fit to the experimental data. The ^{12}C nucleus in the excited 0^+ state is expected to behave like a very loosely bound system. So it is of interest to determine whether a similar reduction is necessary to explain the inelastic scattering data as well; (b) transition form factor obtained by folding the M3Y interaction with transition densities is one of the factors which govern the strength of the inelastic cross-section. It is of interest to see if the calculated form factor is consistent with the data; (c) the $0_1^+ \rightarrow 0_2^+$ transition is particularly suited for studying the central part of the effective interaction since the spin-isospin dependent parts do not contribute for this case.

The experiment was performed using the ^{12}C beams produced by the Lawrence Berkeley Laboratory 88-inch cyclotron. For those inelastic scattering reactions where the scattered ^{12}C nucleus is excited to states above 7.37 MeV, but below 15.96 MeV, the only particle emission channel open is $^{12}C^* \rightarrow {}^{8}Be + \alpha$. These channel fragments will be confined to a cone of an angular width that is determined by the kinetic energy of the recoiling $^{12}C^*$ nucleus and the centre of mass energy of the $^{8}Be,\alpha$ fragments. Maximum efficiency for the detection of the $^{12}C^*$ breakup fragments was achieved by constructing two ΔE × E telescopes in close vertical geometry, with one telescope above and the other below the reaction plane. These telescopes consisted of pairs of ΔE (200 μ) and E (5 mm) detectors manufactured on the same silicon wafer such that the vertical angular acceptance of the telescopes was 1.5° to 10°, and an acceptance of 3° in the horizontal reaction plane. Reject detectors placed behind the E detectors were employed to veto high energy events.

A summed energy spectrum for coincident events in the two telescopes, where at least one telescope records an α-particle, is shown in fig.1a[5] for an incident ^{12}C energy of 187 MeV and for the counters placed at 19° to the beam direction. From kinematic arguments the peak at 178 MeV is determined to arise from the quasielastic breakup of ^{12}C into the α and ^{8}Be channel. The particle identification spectrum in the second telescope, corresponding to this peak, shows a single grouping near the ^{7}Li position, as expected if two α-particles of approximately the same energy simultaneously entered this telescope. An actual α + ^{7}Li coincidence is ruled out by Q-value considerations. Most of the yield of this quasielastic peak is due to the breakup from the 0^+ 7.65 MeV state. This may be seen from fig.1b[5] which shows the ^{8}Be projected energy spectra, arising from the quasielastic peak. The different peaks of this spectra arise from the contribution of different excited states of ^{12}C. Thus the 0^+, 7.65 MeV state of ^{12}C, which has a C of M breakup energy of 0.288 MeV results in a broad peak at 120 MeV, while the 9.64 MeV state results in two narrow peaks. The structure of these peaks is determined by the relative energy of the break-breakup fragments as well as the geometry of the telescope collimators.

A Monte Carlo type program was used to calculate the probability of detecting breakup events in the two telescopes. The basis of this program is to allow both a random selection of the $^{12}C^*$ emission angles and the angles for the emission of the α and ^{8}Be projectiles in the $^{12}C^*$ centre-of-mass frame. A test is then performed to determine if the fragments pass through the collimators. From these calculated probabilities the cross sections may be determined from the experimental coincident rates.

The angular distributions of the quasielastic peak for ^{12}C energies of 132, 187 and 230 MeV are shown in fig.3. The contribution to the quasielastic peak from states other than the excited 0^+ state is of the order of a few percent. The errors shown arise mainly from counting statistics. Systematic errors are estimated to be no more than 25% and are primarily due to possible errors in estimation of total dead time, integrated change, the target thickness and the detection system solid angle.

In the folding model description of the heavy-ion inelastic scattering the transition form factors are obtained by double folding the density distributions of the projectile and the target nuclei with the nucleon-nucleon effective interaction[3]. Thus the form factor may be written as

$$F_{tr}(\vec{r}) = \int \rho_{p(tr)}(\vec{r}_2)\, \rho_{T(tr)}(\vec{r}_1)\; V(\vec{r}_1-\vec{r}_2-\vec{r})\; d\vec{r}_1 d\vec{r}_2 \qquad (1)$$

where $\rho_{p(tr)}$ and $\rho_{T(tr)}$ are the transition densities for the projectile and the target nuclei respectively and V is the nucleon-nucleon effective interaction. If either target or the projectile remains in the ground state during the collision, the corresponding transition density in eq.(1) is replaced by the ground state density distribution. Note that eq.(1) is an extension of the double folding model of the optical potential for the elastic scattering[3]. The form factor calculated by eq.(1) is then used in e.g. DWBA calculations of the inelastic scattering. Some authors have used the macroscopic approach of deforming the ground state density distributions in order to get the transition densities[6,7]. However, there is a large difference in the spatial configuration of the 0_1^+ and 0_2^+ states in ^{12}C and hence the 0_2^+ state in ^{12}C cannot be regarded as a breathing vibration mode based on the ground state[8]. This rules out the applicability of the macroscopic approach in our investigation.

Recently Kamimura[8] has calculated the transition densities between various states of ^{12}C as well as the diagonal densities for various states of this nucleus by using a microscopic 3α resonating group (RGM) wavefunction, which were obtained by solving the relative motion between three α-clusters with the total anti-symmetrization between 12 nucleons taken into account. By using these transition densities the electron scattering form factors for the transition $0_1^+ \rightarrow 0_2^+$ in ^{12}C nucleus was excellently reproduced up to $q^2 = 6.0$ fm^{-2}. This shows the reliability of these transition densities, and we have used these in our investigations. For ^{208}Pb the Hartree-Fock densities of Negele [9] have been used.

The effective interaction V should be complex and hence the F_{tr} is a complex quantity. The form of M3Y interaction used in the present calculation is as follows:

$$V(r) = [\ 7999\,\frac{e^{-4r}}{4r} - 2134\,\frac{e^{-2.5r}}{2.5r}\ ]\ \text{MeV} \qquad (2)$$

This is a real interaction. To make the form factor complex two procedures have been used in the literature[10,11]. (a) The real and imaginary parts of V are supposed to have the same form; which is equivalent to multiplying the form factor by a complex normalization constant. (b) A hybrid model in which the imaginary part of the optical potential having a Woods-Saxon form is deformed to give the imaginary part of the form factors. Of course the second procedure is ruled out in our case. On the other hand, Glendenning[12,13] has argued that as long as the coupling of the intermediate channels on the transition being considered is weak, the imaginary part of the form factor may be ignored. We have performed our calculations for inelastic scattering using the prescription (a). The single nucleon exchange contribution to the effective interaction has been included as described in Ref.[3].

Nojiri et al[14] have investigated the inelastic scattering of 65 MeV protons from ^{12}C leading to the 0_2^+, 2_1^+, 2_2^+ and 3_1^- states of ^{12}C, by using the transition densities of Kamimura. In these investigations it was found that the effects of 2_1^+ as well as 2_2^+ states on $0_1^+ \rightarrow 0_2^+$ transition in ^{12}C nucleus were negligible. We have, therefore, neglected the effects of 2_1^+ and 2_2^+ states of ^{12}C on the $0_1^+ \rightarrow 0_2^+$ transition and have used the DWBA to perform our calculations.

The real parts of the initial and final channel optical potentials to be used in the DWBA calculations of the inelastic scattering have been obtained by double folding the effective interaction[3] with the corresponding diagonal densities for ^{12}C given by Kamimura[7] and the ground state density of ^{208}Pb. For the imaginary parts the phenomenological Woods-Saxon type of potentials were used. As a check to our calculational procedure, we recalculated the elastic scattering of ^{12}C on ^{208}Pb at 96 MeV and 116.4 MeV with the renormalization constant N (= 1.25) given by Satchler and Love[3]. With this renormalization of the real part of the potential and the same parameters of the imaginary part of the optical potential as those given by Satchler and Love, an excellent fit to the elastic scattering data at these energies was obtained which is shown in fig.2. It should be noted that the density of ^{12}C used in our calculation is different from that used in ref.[3]. Since no energy dependence of the parameter N has been reported in the literature, we held the value of this parameter fixed at 1.25 for all the three experimental incident energies in the initial channel. The same renormalization constant (1.25) was also used to renormalize the transition form factors for all the energies. However, for the final channel, a value of 0.6 was necessary in order to get a fit to the experimental data for inelastic scattering for all the three incident energies. In view of the fact that the ^{12}C nucleus in the 0_2^+ state may be considered as a loosely bound system, the necessity of using a value 0.6 as the renormalization constant for the calculated real part of the potential is consistent with similar finding in the case of other loosely bound projectiles like the deuteron, ^{6}Li, ^{7}Li, and ^{9}Be[4,15]. The imaginary potentials for the incident channel were taken to be the same as those obtained by Satchler and Love for the elastic scattering of ^{12}C from ^{208}Pb at 116.4 MeV. This appears to be reasonable because no significant energy dependence of the imaginary potential is known. The elastic scattering cross sections calculated with these parameters are shown in fig.3. However, for the final channel the imaginary potentials were adusted in order to reproduce the magnitude of the experimental cross sections at the peak positions. The parameters of the adjusted potentials are shown in table 1, along with the parameters for the initial channel as well as the angular momentum $L_{1/2}$ for which the transmission coefficient $T_{L_{1/2}} = 0.5$ and the corresponding distance of closest approach, $D_{1/2}$. We see that the imaginary potentials for the final channel are weaker than those for the initial channel. Also apparent from this table is the fact that final channel imaginary potentials show strong energy dependence. This is probably due to the break-up effects in the final channel. Whereas the break-up effects on the real part of the optical potential for weakly bound projectiles have been investigated by several authors[15,16], such an investigation has not been performed for the imaginary potentials. This is due to the difficulty in defining a microscopic reference imaginary potential with respect to which one can measure the effect of break-up. The relatively weaker potentials in the final channel may be due to the fact that coupling of rotational states to 0_1^+ state is much stronger than the coupling of break-up (and other channels) to the 0_2^+ state in ^{12}C[17]. The saturation of break-up cross sections[18] with increasing energy may be the reason behind the similar final channel imaginary potentials needed at energies 187 MeV and 230 MeV.

The renormalization factor of 1.25 to renormalize the calculated transition form factors is rather difficult to explain. This is because the real part of the ground state potential needs a renormalization of 1.25 whereas the excited state requires a factor of 0.6. Since, the form factor is a complex quantity[19-21] its renormalization factor is the modulus of a complex factor. Probably a value for this closer to the renormalization of the real part of the ground state potential appears to be reasonable.

The results of our calculations for inelastic cross sections at incident energies of 132 MeV, 187 MeV and 230 MeV are shown in fig.4. The experimental resolution due to the finite acceptance of the detectors should be taken into account in considering the comparison between the calculations and the experimental data. In fig.4 the solid lines represent the results of our calculations where the real parts of the initial channel potentials were normalized by 1.25 and those for the final channel were renormalized by 0.6. The dashed curves on the other hand, represent the results when the real parts of both initial and final channel potentials have the same renormalization of 1.25. It can be seen that normalization constant for the final channel other than 0.6 provides bad fits to the experimental data. Calculations were performed with various other values for this renormalization constant and it was noted particularly that the grazing angles of the experimental data are not reproduced by values other than (0.6 ± 0.02). It was also found that the variation of the other parameters such as the strengths, radius and diffuseness of the imaginary part does not alter this conclusion. It should be noted that these findings are particular to the present case where the final state is a weakly bound state and does not reflect a contradiction to other analyses of inelastic scattering[4,10] where the same real and imaginary potentials were used in the initial and final channels.

In conclusion our investigations confirm that for the loosely bound projectiles the double folding model over-estimates the calculated real part of the potential and a renormalization of nearly 50% is necessary to fit the data for inelastic scattering. It is for the first time that this effect has been demonstrated by an investigation of inelastic scattering. The M3Y interaction with one nucleon exchange taken into account in the zero order appears to provide a good description of the central part of the nucleon-nucleon effective interaction over a range of projectile energies.

The folding model calculations reported in this paper have been performed by using the code DFOLD developed at Daresbury Laboratory. The DWBA calculations were performed by using the code DWUCK4 which has been extended to handle 500 partial waves. We have used 180, 200 and 240 partial waves for incident energies 132 MeV, 187 MeV and 230 MeV respectively. The CRAY-1 Computer of Daresbury Laboratory was used to perform these calculations and we want to thank the computing staff for their excellent support. We also thank Dr. M. Kamimura for providing us with his transition densities and Dr. G.R. Satchler for useful discussions. These investigations were supported by the Director, U.S. Office of Energy Research, Division of the Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract No.W-7405-ENG-100, and U.K. Science and Engineering Research Council.

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Table 1

Parameters of the potential

Energy	Initial Channel						Final Channel			
	N^a	W (MeV)	r_o fm	a_o fm	$L_{1/2}$	$D_{1/2}$	N^a	W	r_o	a_o
116.4	1.25	-14.7	1.30	0.52						
132.0	1.25	-14.7	1.30	0.52	71.6	12.00	0.6	12.0	1.30	0.52
187.0	1.25	-14.7	1.30	0.52	89.9	11.83	0.6	- 6.8	1.20	0.40
230	1.25	-14.7	1.30	0.52	103.6	11.74	0.6	- 6.8	1.20	0.40

a Renormalization factor for the folded real potential

Figure Captions

Fig.1a) The yield of coincident events between the two telescopes from the reaction of 187 MeV ^{12}C on ^{208}Pb with the requirement that one telescope record and α-particle, plotted as a function of the summed energy in the two telescopes.

b) The energy of ^{8}Be nuclei in coincidence with an α-particle for the transition $^{208}Pb(^{12}C, \alpha^{8}Be)^{208}Pb(g.s.)$ at 187 MeV bombarding energy. This projected energy spectrum was taken at $\theta_{LAB} = 19°$ with the detector configuration which has an average vertical angular separation of $\Delta\Phi = 5.9°$.

Fig.2 Elastic scattering of ^{12}C from ^{208}Pb at 96 and 116.4 MeV. The imaginary part of the optical potential was the same as those given by Satchler and Love[3] and the real part was calculated by double folding with renormalization constant $N = 1.25$.

Fig.3 The elastic scattering of ^{12}C from ^{208}Pb at 132 MeV, 187 MeV and 230 MeV with parameters given in table 1. The renormalization of the calculated real part of the potential was 1.25.

Fig.4 Inelastic cross-section for the excitation of 0_2^+ state in ^{12}C in ^{12}C + ^{208}Pb collision. The solid line represents the results of calculations where the renormalization constant of the calculated initial channel real potential was 1.25 and that of final channel real potential was 0.6. The dashed line represents the results when both the initial and final channel real potentials are renormalized by a factor of 1.25.

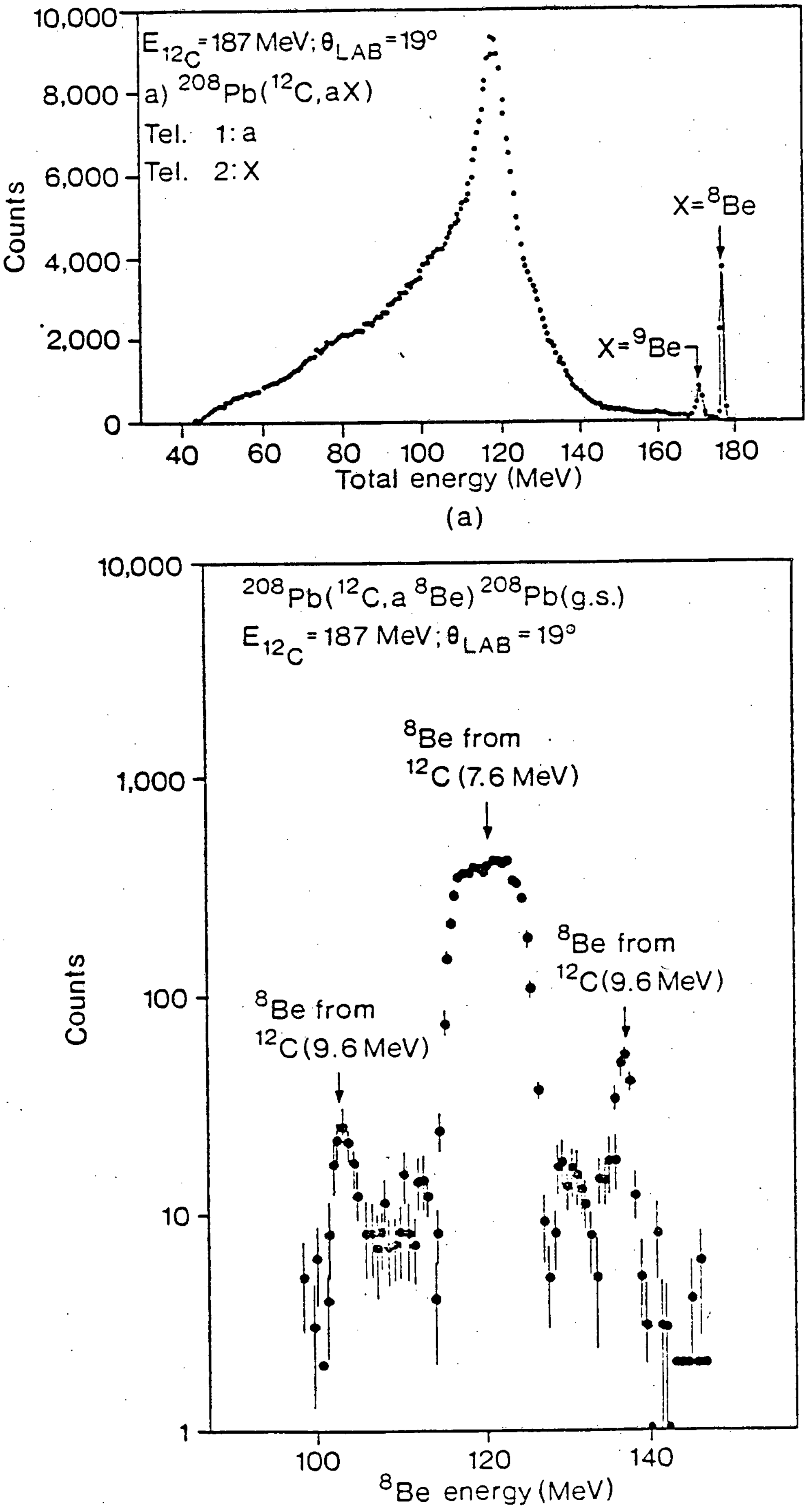
10,000
8,000
6,000
4,000
2,000
0
Counts
$E_{^{12}C}$=187 MeV; θ_{LAB}=19°
a) $^{208}Pb(^{12}C,aX)$
Tel. 1: a
Tel. 2: X
X=^{8}Be
X=^{9}Be
40
60
80
100
120
140
160
180
Total energy (MeV)
(a)
10,000
1,000
100
10
1
Counts
$^{208}Pb(^{12}C,a\,^{8}Be)^{208}Pb$(g.s.)
$E_{^{12}C}$ = 187 MeV; θ_{LAB} = 19°
^{8}Be from ^{12}C (7.6 MeV)
^{8}Be from ^{12}C (9.6 MeV)
^{8}Be from ^{12}C (9.6 MeV)
100
120
140
^{8}Be energy (MeV)
(b)

Fig. 1

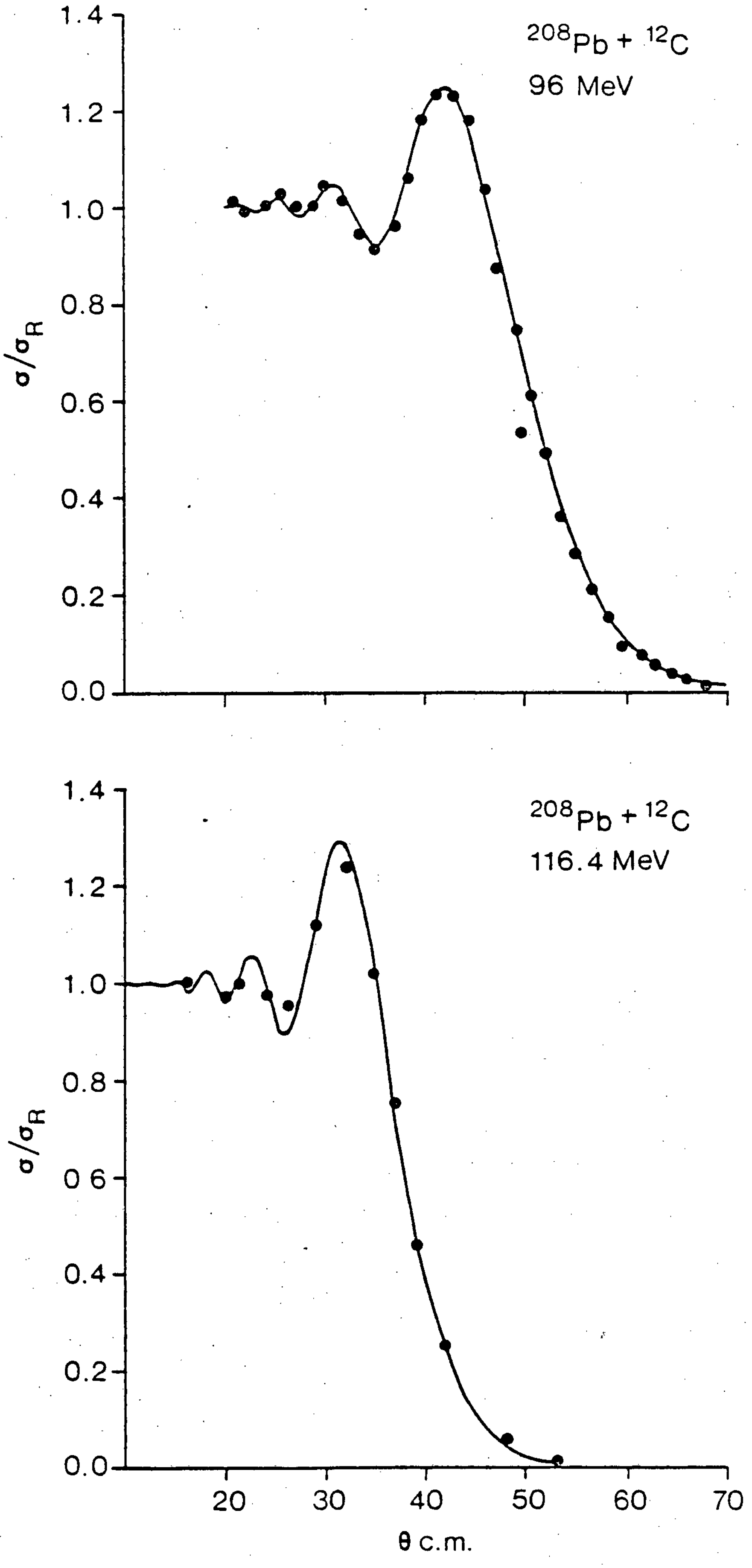
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
σ/σ_R
^{208}Pb + ^{12}C
96 MeV
1.4
1.2
1.0
0.8
0 6
0.4
0.2
0.0
σ/σ_R
^{208}Pb + ^{12}C
116.4 MeV
20
30
40
50
60
70
θ c.m.

Fig. 2

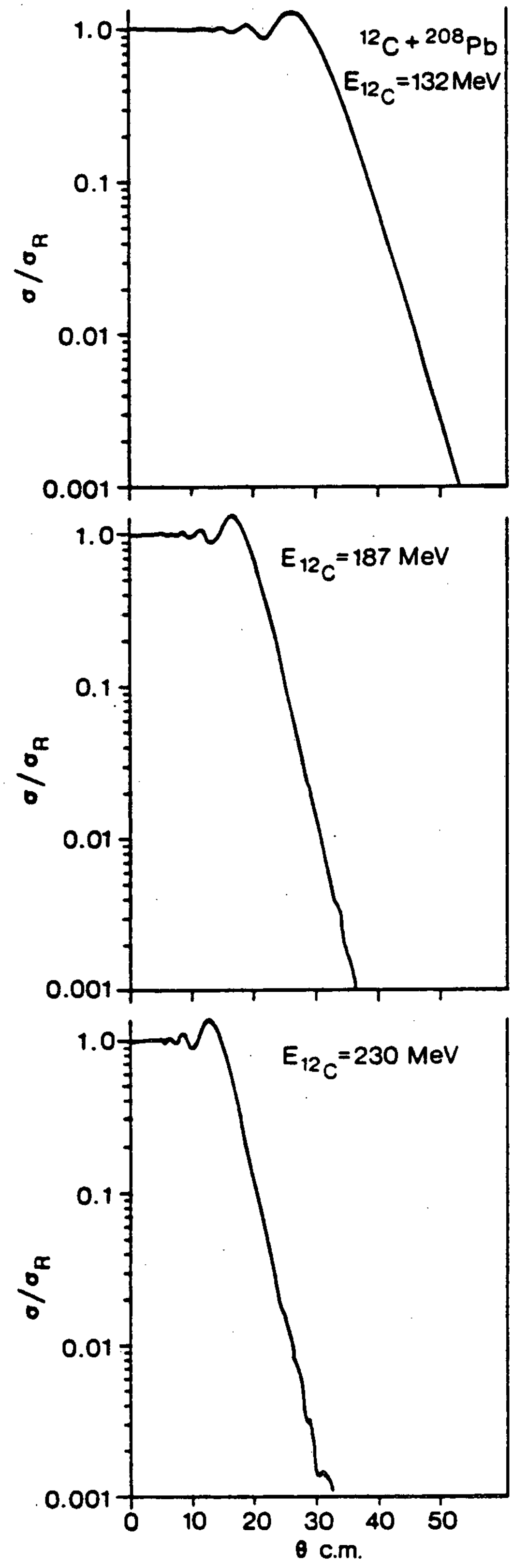
1.0
0.1
0.01
0.001
σ/σ_R
$^{12}C + ^{208}Pb$
$E_{^{12}C}$=132 MeV
$E_{^{12}C}$=187 MeV
$E_{^{12}C}$=230 MeV
0
10
20
30
40
50
θ c.m.

Fig.3

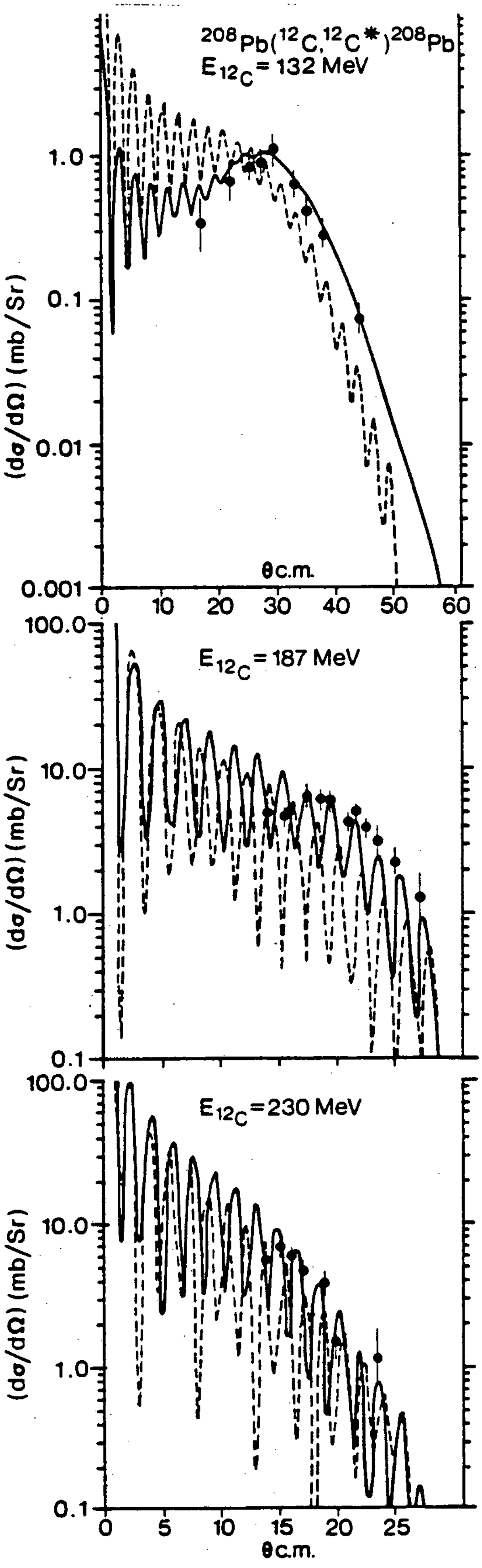
^{208}Pb(^{12}C,^{12}C*)^{208}Pb
$E_{^{12}C}$ = 132 MeV
(dσ/dΩ) (mb/Sr)
1.0
0.1
0.01
0.001
θc.m.
0
10
20
30
40
50
60
$E_{^{12}C}$ = 187 MeV
(dσ/dΩ) (mb/Sr)
100.0
10.0
1.0
0.1
$E_{^{12}C}$ = 230 MeV
(dσ/dΩ) (mb/Sr)
100.0
10.0
1.0
0.1
0
5
10
15
20
25
θc.m.

Fig.4

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