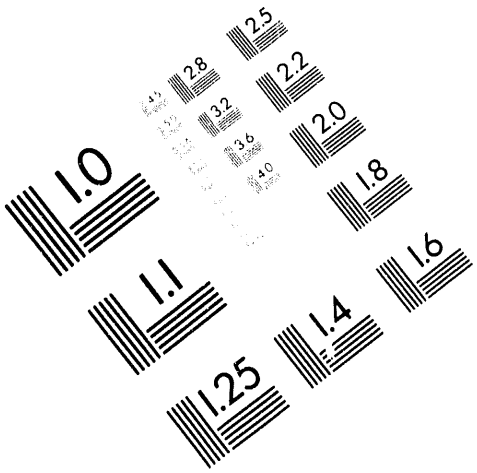

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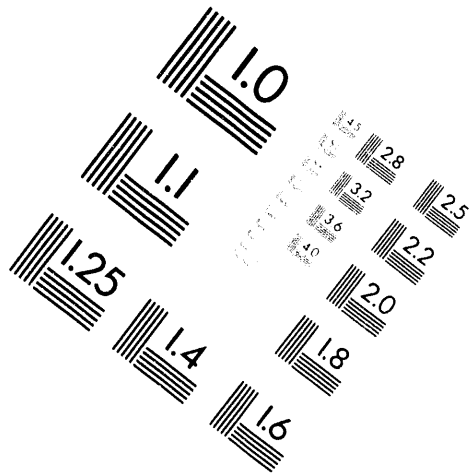

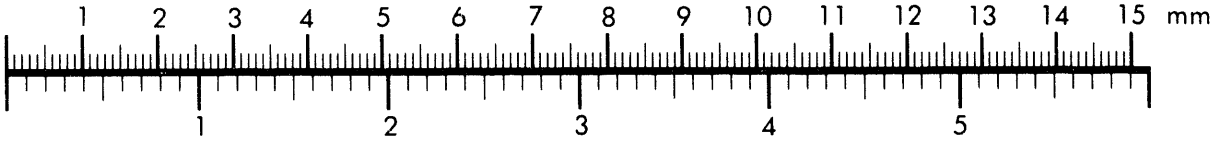

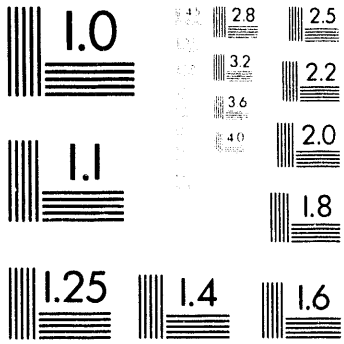

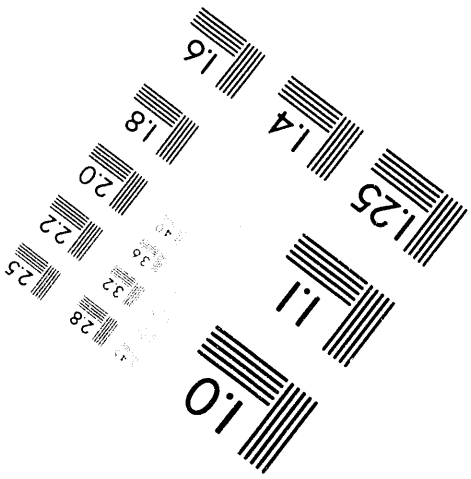

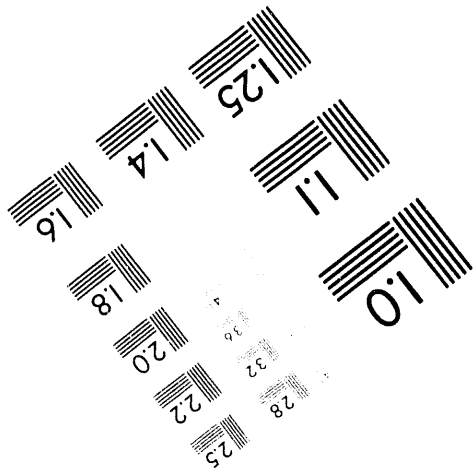

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ANL/PHY/CP--79583

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CONF-930691--1

MANY-PARTICLE DECAYS OF α-CHAIN STRUCTURES IN ^{24}Mg

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Abstract

We have searched for evidence of exotic cluster configurations in ^{24}Mg resembling a linear chain of α particles in various many-particle final states of the ^{12}C+^{12}C system, including ^{12}C(0_2^+)+^{12}C(0_2^+) and ^{8}Be+^{16}O*(4α). Such configurations are predicted to occur by a number of different theoretical models of the structure of ^{24}Mg. An array of highly segmented Double-Sided Silicon Strip Detectors permits detailed, high resolution reconstruction of these many-charged-particle final states.

1. Introduction

Alpha-cluster structures are well established in light nuclei with even $N = Z$. Nuclei which show strong α-cluster character typically display a number of different coexisting shapes based upon the α-particle sub-unit. One such nucleus is ^{24}Mg. A number of theoretical calculations for the structure of ^{24}Mg which display the underlying cluster degrees of freedom have been performed. The theoretical frameworks employed include the Cranked Cluster Model (CCM)[1], and the Nilsson-Strutinsky[2] and Hartree-Fock[3] formalisms.

One very interesting prediction of many of these theoretical results is that there should occur in these light α-particle nuclei configurations that resemble linear chains of α particles[4, 5]. These configurations were suggested to exist as early as 1956, by Morinaga[6]. Experimental evidence for such chain structures in the ^{16}O has been reported by Chevallier, *et al.*[7] who identified a number of strong resonances in the ^{12}C(α,^{8}Be)^{8}Be reaction. The spin sequence of these resonances, as well as the fact that they possessed large decay branches to the ^{8}Be+^{8}Be final state, suggested this assignment. In addition, Ames[8] noted that these resonances possessed α-decay widths to the first excited 0^+ level in ^{12}C at 7.65 of MeV excitation energy.

In the nucleus ^{24}Mg, the CCM predicts that chain-like configurations should occur at excitation energies between 40 and 50 MeV, well above the threshold for decay of ^{24}Mg into six α particles, at E_X=28.48 MeV. Thus, any attempt to study such phenomena must contend with the rather difficult experimental problem of reconstructing a complicated six-α-particle final state. In ^{24}Mg, one possible simplification of this situation could be found by considering the excited 0^+ level in ^{12}C at E_X=7.65 MeV. This level has previously been associated with a linear three-α-particle chain structure[4, 9]. If populated, one

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likely decay mode for a highly elongated cluster structure in ^{24}Mg would be by symmetric breakup into two prolate-deformed ^{12}C clusters, corresponding to an exit channel containing two ^{12}C nuclei in their excited 0_2^+ states. A possible signature for the existence of such chain-like configurations in ^{24}Mg could then be the observation of resonance-like behavior in the excitation function for the inelastic scattering channel $^{12}C+^{12}C \rightarrow ^{12}C(0_2^+)+^{12}C(0_2^+)$.

Further information about these chain structures in ^{24}Mg could be obtained by considering other reaction channels in the $^{12}C+^{12}C$ system. One reaction of interest is that leading to $^{8}Be+^{16}O$, where the ^{16}O subsequently decays to α-unbound final states. The $\alpha+^{12}C$ scattering measurements of Chevallier *et al.*, and Ames identified levels in ^{16}O which might be structurally related to those we seek to study in ^{24}Mg. If we are able to populate α-chain configurations in ^{24}Mg through $^{12}C+^{12}C$ scattering, these structures should also possess non-symmetric decay branches to the $^{8}Be+^{16}O^*(4\alpha)$ final state, leaving ^{16}O in one of these levels having a four-α chain character. Of course, since these states in ^{16}O are also unbound with respect to decay into four α particles, these reactions also present the experimental challenge of reconstructing two-body reaction kinematics from a six-charged-particle final state.

2. Experiment

In order to study reactions of this type, we have constructed an array of Double-Sided Silicon Strip Detectors (DSSDs)[10 – 12]. These detectors are fabricated from 5×5 cm^2 silicon wafers effectively segmented into 256 quasi-pixel regions. We have performed measurements using a number of configurations of this array. For our studies of $^{12}C+^{12}C$ inelastic scattering, two DSSDs were used, placed at distances of 14 to 17 cm from the target, centered at angles from 12° to 35° in the laboratory. In order to search for four-α decaying levels in ^{16}O populated by α transfer, we used two additional DSSDs, yielding an array with a total solid angle of 430 msr, divided into 1024 quasi-pixels. For the case of $^{12}C+^{12}C$ scattering to six-α-particle final states, this array permits us to detect and identify as many as all six α particles, and measure each of their angles and energies with quite high precision ($\Delta E \approx 30$ keV FWHM, $\Delta\theta_{lab} \approx 1°$). A time-of-flight measurement relative to the pulsed beam was made for each detected particle for particle identification purposes, although in practice, for events with more than four detected particles, energy and multiplicity were sufficient to identify six-α-particle final states.

For all of our experiments, ^{12}C beams from the ATLAS accelerator at Argonne National Laboratory bombarded 50μg/cm^2 ^{12}C targets at energies between E_{lab}= 52 to 80 MeV. These energies correspond to excitation energies in the composite nucleus ^{24}Mg ranging from ≈40 to 54 MeV, excitation energies at which the CCM predicts the occurrence of elongated α-particle structures in ^{24}Mg. Our excitation-function measurements were made in steps of ΔE_{lab}= 2 MeV, and angular distribution data were obtained in long runs at several selected energies between E_{lab}= 52 and 80 MeV. Data for the $^{8}Be+^{16}O$ α-transfer reaction were taken at five energies in the same range.

3. $^{12}C+^{12}C$ Inelastic Scattering Results

To analyse the $^{12}C+^{12}C$ inelastic scattering data, we considered events in which at

least three α particles were detected in one DSSD. By measuring the angles and energies of these three α particles, assuming that they result from the decay of an excited ^{12}C nucleus, we can reconstruct the kinetic energy, scattering angle and excitation energy of the decaying ^{12}C fragment. The Q value of the two-body inelastic scattering reaction is then determined from the kinematic relationship between kinetic energy and scattering angle of the decaying recoil nucleus[12]

An example of this reconstruction appears in Fig. 1, which shows a spectrum of the reconstructed excitation energy for a decaying ^{12}C , calculated for events in which three α particles hit one DSSD. The $^{12}C(0_2^+)$ level at 7.65 MeV is clearly identified, and is reconstructed with a resolution of approximately 65 to 70 keV FWHM. Figure 2 shows a Q-value spectrum for $^{12}C+^{12}C$ inelastic scattering, determined from the scattering angle and kinetic energy of a ^{12}C fragment which was identified as having been in its 0_2^+ excited state. Several peaks are apparent, and the reaction channel of interest, $^{12}C(0_2^+)+^{12}C(0_2^+)$, is clearly seen at Q=-15.30 MeV.

The measured excitation function for the mutual $^{12}C(0_2^+)$ inelastic scattering channel appears in Fig. 3. We observe a strong peak in the excitation function centered at $E_{c.m.}=$ 32.5 MeV. This energy corresponds to an excitation energy of E_X=46.4 MeV in ^{24}Mg, near the energy at which α-chain structures are predicted to occur by the CCM[1]. This structure is quite wide, with $\Gamma_{c.m.}$ $\approx$4.5 MeV, and as such it is unlikely to arise from the population of a single level in the composite system, or to reflect the influence of a single resonating partial wave.

In order to determine which angular momenta contribute to this inelastic scattering channel, we have obtained detailed angular-distribution data at several energies across this excitation function peak. Figure 4 shows angular distributions obtained at seven energies between $E_{c.m.}=$ 28.5 and 35.5 MeV. A simple comparison to pure Legendre polynomials squared suggests that the dominant angular momenta in this energy region are near 14-16 $\hbar$, placing the structure near the location of a crossing between a rotational band build upon a cluster configuration with a strong $^{12}C+^{12}C$ character, and one built upon a six-α chain structure.

The angular distribution data we obtain are, however, considerably more complex than those expected for a single dominant angular momentum. In particular, at the maximum of the excitation function $E_{c.m.}$=32.5 MeV, the angular distribution shows a strong peak at center-of-mass angles near 90°. This enhancement requires a coherent superposition of several partial waves at this energy. Rae,*et al.*, have recently shown that such a superposition of angular momenta can come about through the population of nearly degenerate members of a rotational band built upon a highly elongated cluster configuration[13]. A fit to the data obtained at $E_{c.m.}$=32.5 MeV using the formalism described in reference [13] appears in Figure 5. The agreement between theory and experiment is surprisingly good considering the simplicity of the model.

4. $^{12}C(^{12}C,^{8}Be)^{16}O^*(4\alpha)$ Results

To examine the possibility of non-symmetric decays of chain structures in ^{24}Mg, we now turn to our results for the reaction leading to $^{8}Be+^{16}O^*$. We wish to identify levels at high excitation energy in ^{16}O that correspond to the possible four-α chain structures identified

in this nucleus as resonances in $\alpha+^{12}C\rightarrow\ ^{8}Be+^{8}Be$ and $\alpha+^{12}C(0_2^+)$. Such reactions are significantly more difficult to study than the final states in $^{12}C+^{12}C$ inelastic scattering, for their identification requires the detection of at least five α particles, rather than only three for the $^{12}C+^{12}C$ case, and a more careful and detailed analysis.

We first consider events in which either five or six α particles have been detected in our array of four DSSDs. If one α particle is missed, its momentum and energy are reconstructed from the momenta of the other detected particles. Figure 6 shows a total reaction Q-value spectrum for six-α coincidence events. The peak at Q_{tot}=-14.55 MeV represents the energy needed to completely dissociate two ^{12}C nuclei into α particles.

Candidate $^{8}Be+^{16}O^*$ events were those in which two α particles from the decay of a ^{8}Be in its ground state were observed on one side of the beam, and the four additional α particles on the other side. For these events, the two-body Q value of the transfer reaction was calculated from the reconstructed kinetic energy and scattering angle of the identified ^{8}Be. In addition, the excitation energy of the decaying ^{16}O can be calculated from the measured angles and energies of the four remaining α particles. For each candidate event the excitation energy of the ^{16}O nucleus determined from the ^{8}Be kinetic energy and angle was required to match the excitation energy determined from the other four α particles to within one MeV.

Finally, all possible combinations of two and three α particles from the decaying ^{16}O were analysed to identify the ^{16}O decay branch, in order to determine whether the ^{16}O decayed to either two ^{8}Be nuclei, or to $\alpha+^{12}C(0_2^+)$. As an example of this analysis, Fig. 7 contains a diagram which shows the velocities of all α particles in an event identified as $^{12}C+^{12}C\rightarrow^{8}Be+^{16}O^*(^{8}Be)$. The primary ^{8}Be goes to the left of the beam at a scattering angle of 42.9°, with a kinetic energy of 20.6 MeV. The recoil ^{16}O on the right side of the beam then decays to two additional ^{8}Be nuclei, which finally decay into four α particles. The high segmentation and excellent energy resolution of the DSSD makes possible a complete and detailed analysis of the six-body final state for this event.

Figure 8 shows the excitation-energy spectra obtained for various final states in the $^{12}C(^{12}C,^{8}Be)^{16}O^*(4\alpha)$ reaction. Figure 8(a) contains data for all events obtained at E_{lab}= 62,65, and 67 MeV which could be identified as $^{8}Be+^{16}O^*(4\alpha)$. A prominent peak is observed at E_X= 19.4 MeV, and a smaller one near 17.5 MeV. Both structures persist if the ^{16}O decays to $\alpha+^{12}C(0_2^+)$. For the $^{8}Be+^{8}Be$ final state, the statistics are quite poor, however there does appear to be some enhancement near E_X= 17.5 MeV. These excitation energies are quite close to those of levels observed as resonances in $\alpha+^{12}C\rightarrow^{8}Be+^{8}Be$ and $\alpha+^{12}C(0_2^+)$. While angular correlation measurements are still required in order to determine the spins of the levels populated in this reaction, and identify them with the resonances observed in $\alpha+^{12}C$ scattering, it seems unlikely that we would be populating different states with similar structural characteristics in the same region of excitation energy in ^{16}O. Should further measurements bear out the association of these peaks with four-α chain states in ^{16}O , this identification would provide considerable additional evidence for the presence of exotic elongated configurations in ^{24}Mg.

5. Summary and Conclusions

We have used an array of DSSDs to make a detailed study of many-particle final

states in the $^{12}C+^{12}C$ system. A strong peak is observed in the excitation function for $^{12}C(^{12}C,^{12}C(0_2^+))^{12}C(0_2^+)$ inelastic scattering. The energy of the excitation-function peak, as well as the shapes of the angular distribution data are consistent with the possibility that extended α-particle cluster configurations in ^{24}Mg are formed in this system. Furthermore, we observe that through the reaction $^{12}C(^{12}C,^{8}Be)^{16}O$, levels in ^{16}O at high excitation energy which decay to $^{8}Be+^{8}Be$ and $\alpha+^{12}C(0_2^+)$ are populated at the same center-of-mass energies at which we observe the excitation function peak in the $^{12}C(0_2^+)+^{12}C(0_2^+)$ final state. Observation of these states in ^{16}O , which have been suggested to possess a four-α chain structure, could represent non-symmetric decays of similar configurations in ^{24}Mg.

The possibility that we are populating such unusual configurations in ^{24}Mg is an intriguing and compelling one, and suggests a number of avenues for future investigation. An angular correlation measurement for the four-α unbound levels in ^{16}O would make the association of these levels with resonances in α scattering more likely. Also important is a determination the beam-energy dependence of the yield for these final states in ^{16}O. Finally, we hope to pursue reaction calculations for the angular-momentum mismatched $^{12}C(0_2^+)+^{12}C(0_2^+)$ final state. This additional information should help to further clarify the situation for these potentially exotic and interesting reactions.

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Figure Captions

Figure 1. Reconstructed ^{12}C excitation-energy spectrum at E_{lab}= 65 MeV.

Figure 2. Q-value spectrum for $^{12}C+^{12}C$ inelastic scattering at E_{lab}=65 MeV, where one ^{12}C nucleus is left in its 0_2^+ state. The $^{12}C(0_2^+)+^{12}C(0_2^+)$ mutual excitation is at Q=-15.30 MeV. The solid curve represents the three-α detection efficiency as determined from a Monte Carlo simulation of the detector setup. The efficiency scale is given on the right-hand axis.

Figure 3. $^{12}C+^{12}C\rightarrow^{12}C(0_2^+)+^{12}C(0_2^+)$ inelastic scattering excitation function, reproduced from [12].

Figure 4. $^{12}C+^{12}C\rightarrow^{12}C(0_2^+)+^{12}C(0_2^+)$ inelastic scattering angular-distribution data. The numbers to the left indicate the center-of-mass energy in MeV, and the multiplicative factor to be applied to the cross section scale for each energy. The solid(dashed) curves represent pure squared Legendre polynomials of order 16(14).

Figure 5. $^{12}C+^{12}C\rightarrow$ $^{12}C(0_2^+)+^{12}C(0_2^+)$ angular distribution at $E_{c.m.}$=32.5 MeV, with fit from reference [13].

Figure 6. Total reaction Q-value spectrum for $^{12}C+^{12}C \rightarrow 6\alpha$ at E_{lab}= 65 MeV.

Figure 7. Velocity diagram for an event identified as $^{12}C+^{12}C\rightarrow^{8}Be+^{16}O^*(^{8}Be)$. The solid lines represent the magnitude and direction of the velocity of identified α particles, projected onto the X-Z plane. The dashed line represents the velocity of an unobserved alpha particle, and the beam velocity is indicated by the central arrow.

Figure 8. ^{16}O excitation-energy spectra for events where the ^{16}O decays into (a) any combination of four α particles, (b) $\alpha+^{12}C(0_2^+)$, and (c) $^{8}Be+^{8}Be$. The decay thresholds for each channel are indicated by the solid lines.

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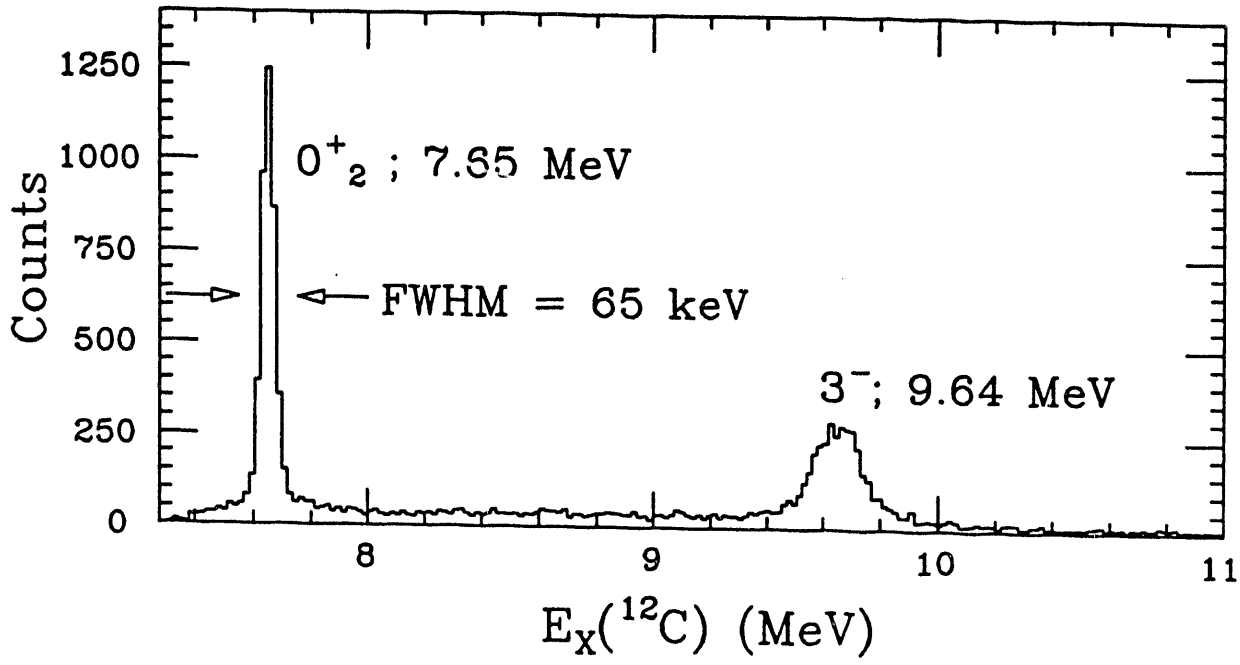
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1000
750
500
250
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FWHM = 65 keV
3^-; 9.64 MeV
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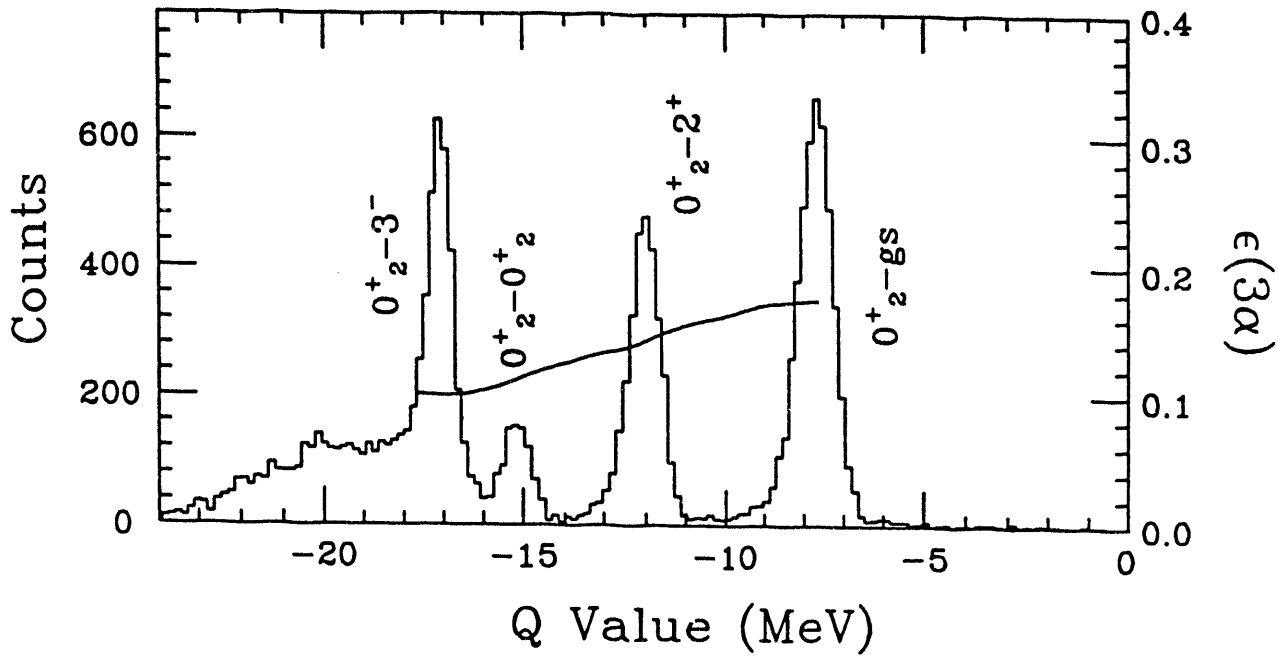
9
10
11
$E_X(^{12}C)$ (MeV)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0+2−gs

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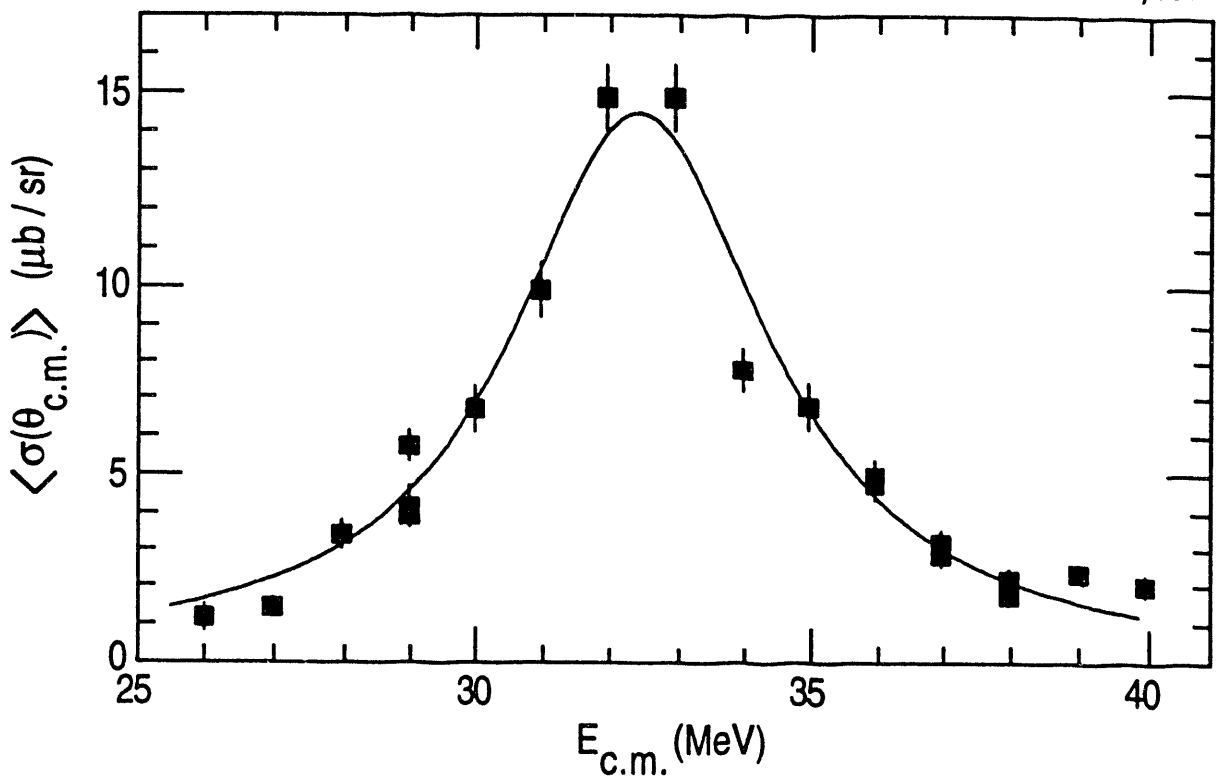

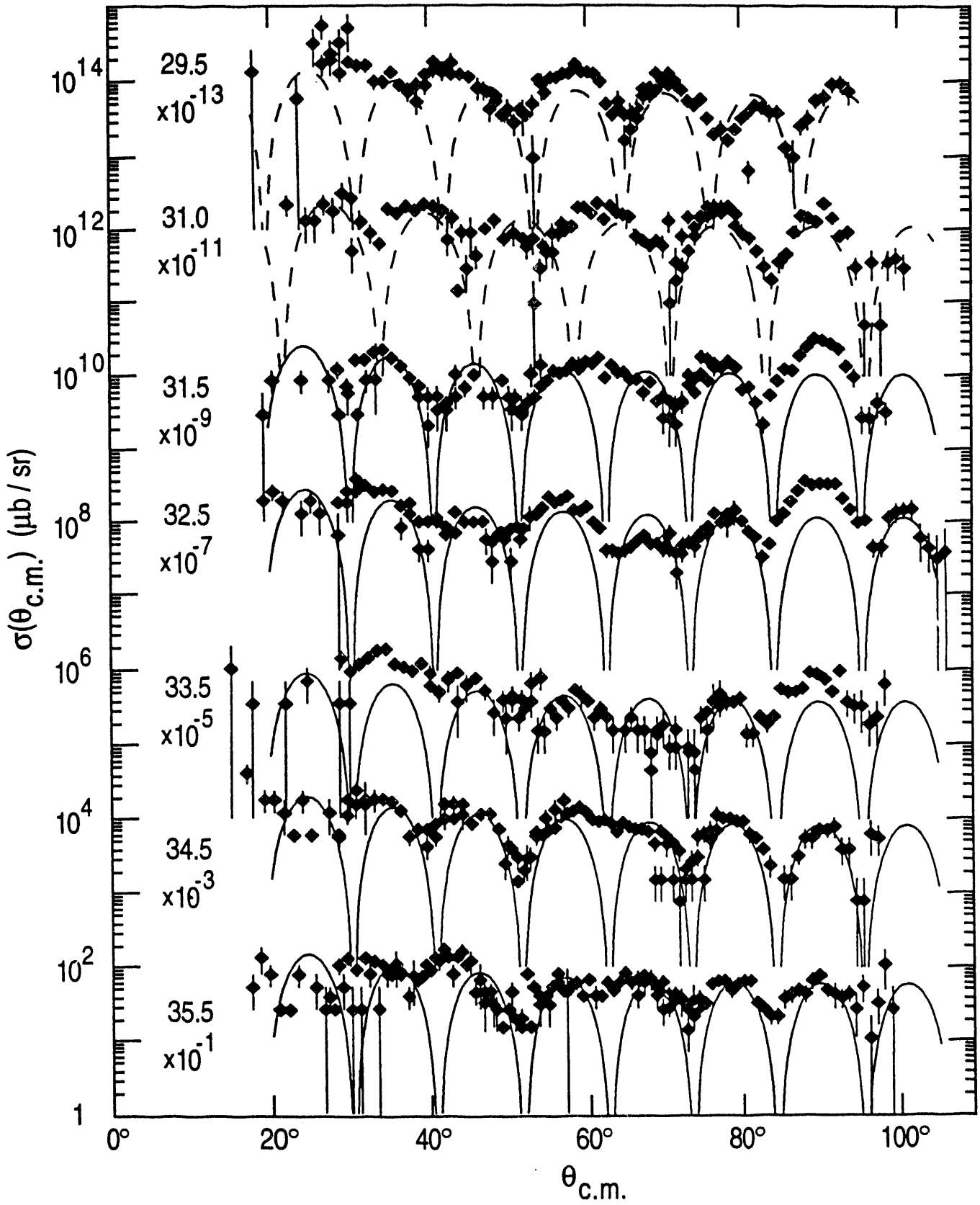
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x10^-11
31.5
x10^-9
32.5
x10^-7
33.5
x10^-5
34.5
x10^-3
35.5
x10^-1
10^14
10^12
10^10
10^8
10^6
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40°
60°
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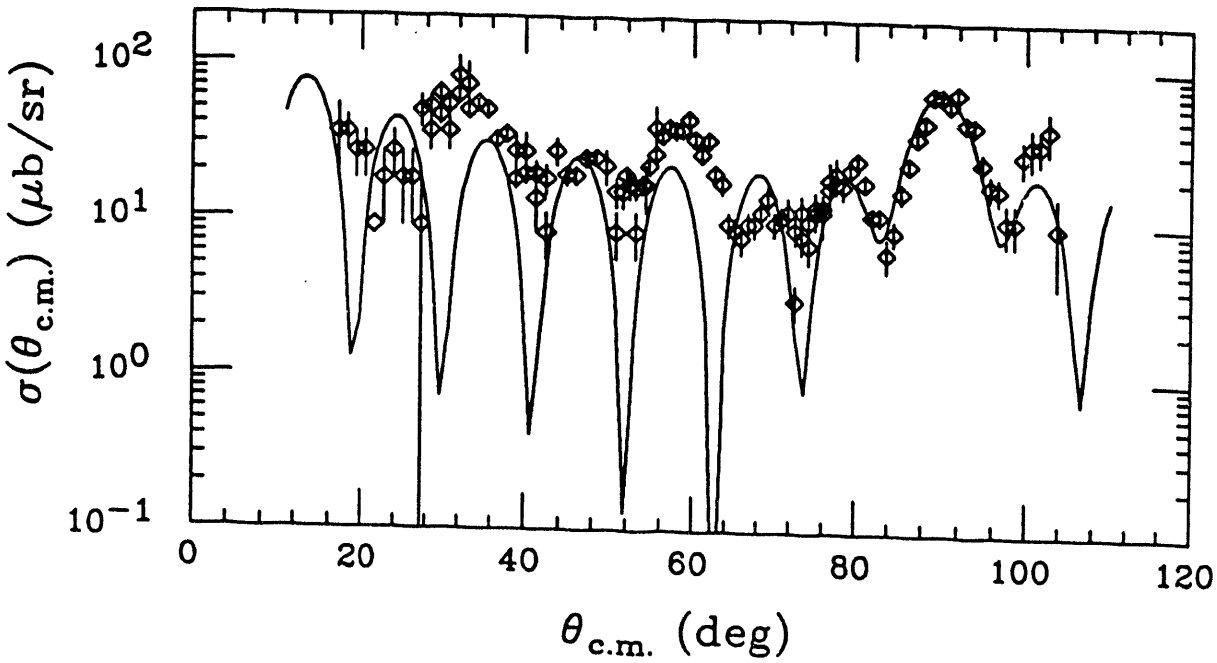
100°
θc.m.


10^2
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80
100
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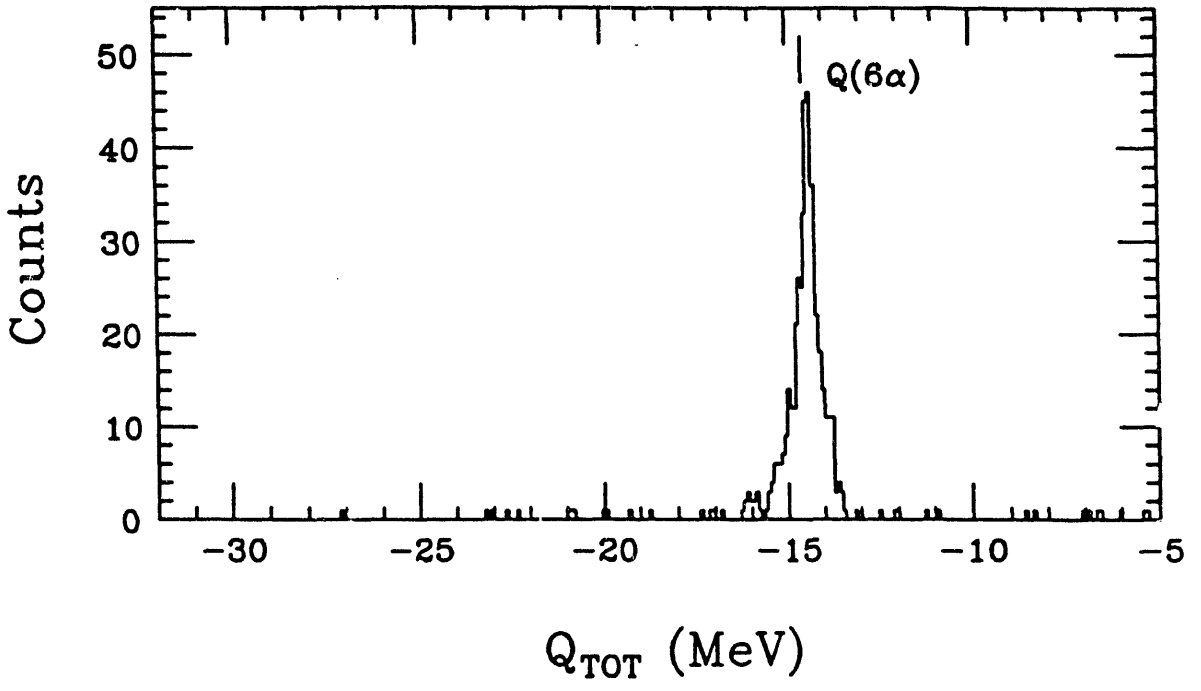
$\theta_{c.m.}$ (deg)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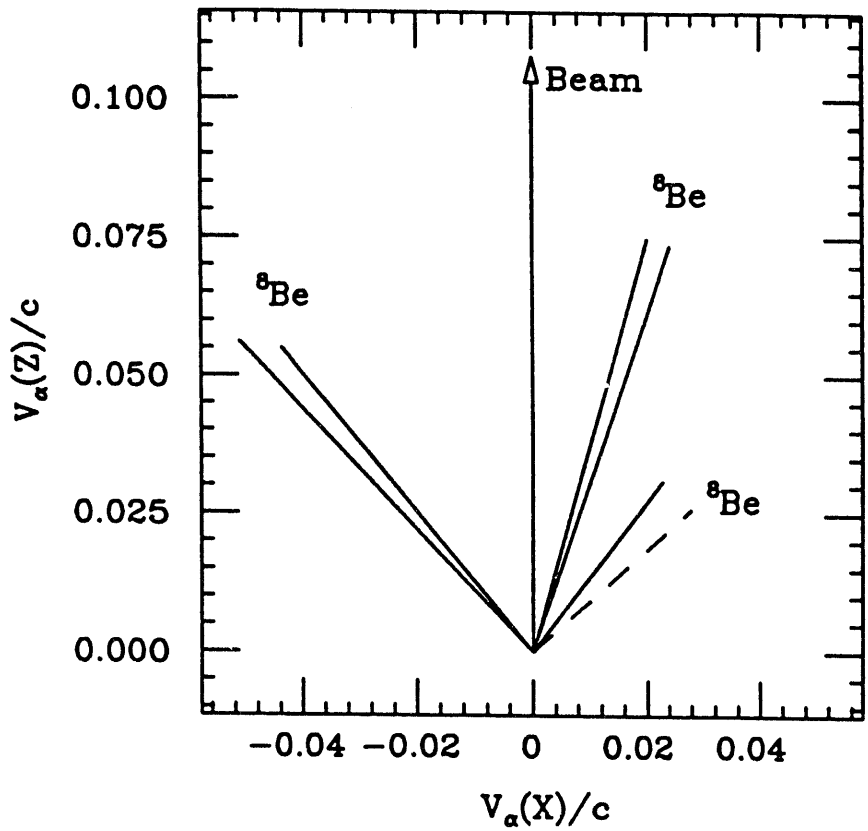
−25
−20
−15
−10
−5
Q_{TOT} (MeV)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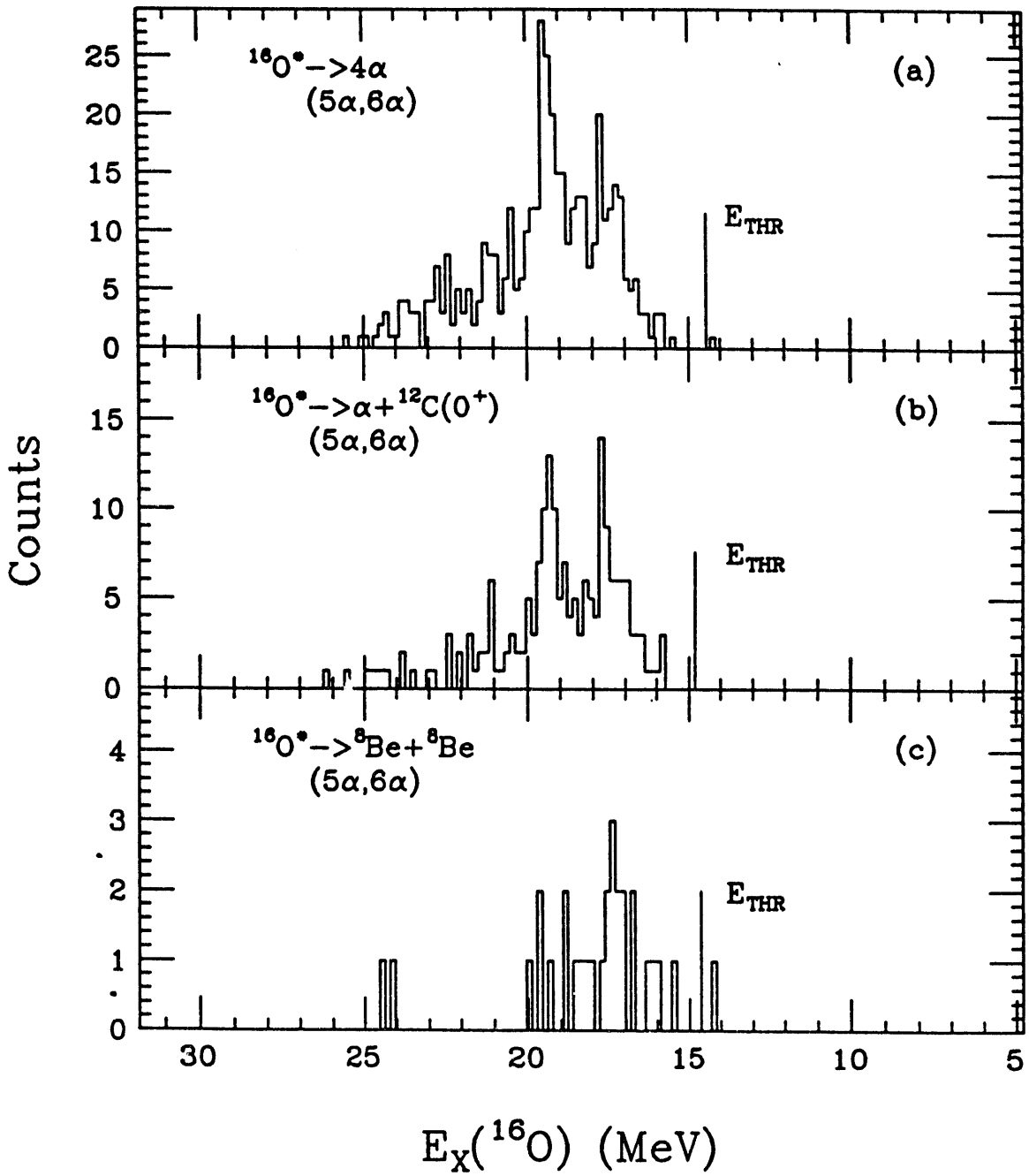
$V_\alpha(X)/c$


$^{16}O^{*}$->4α
(5α,6α)
(a)
E_{THR}
$^{16}O^{*}$->α+$^{12}C(0^{+})$
(5α,6α)
(b)
E_{THR}
$^{16}O^{*}$->^{8}Be+^{8}Be
(5α,6α)
(c)
E_{THR}
Counts
$E_X(^{16}O)$ (MeV)

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