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DISCLAIMER

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Fusion Cross Sections for ^{12}C + ^{128}Te and the Deduction of Absolute Average Angular Momenta

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Abstract

Fusion cross sections have been measured for $^{12}C + {}^{128}Te$ *from* $E_{c.m.} = 40.4$ *to 56.6 MeV by direct detection and identification of evaporation residues using a time-of-flight technique. Average angular momenta for fusion are deduced from a sharp cutoff approximation at energies above the Coulomb barrier. These values of* $< \ell >$ *and those already obtained from isomer ratio measurements are in very good agreement in the energy region where both methods should be valid.*

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I. MOTIVATION

The first observation[1,2] of a finite and energy-independent lower limit for the average angular momentum,[3] $< \ell >$, was made recently for the fusion of ^{12}C + ^{128}Te, ^{7}Li + ^{133}Cs, and ^{3}He +^{136}Ba. In these studies we obtained the first moment of the angular momentum distribution in the entrance channel by observing the delayed x-rays and gamma-rays emitted from the decay of the ground ($J^{\pi} = 3/2^{+}, t_{1/2} =$ 9.0 h) and isomeric ($11/2^{-}$, 34.4 h) states in ^{137}Ce populated through the reaction ^{128}Te(^{12}C,3n)^{137}Ce. The relationship between the measured isomer ratio and the angular momentum distribution in the compound nucleus was established through a statistical decay calculation and checked by comparing measurements using different entrance channels. Because of the absence of delayed photon emission from the stable even mass residues adjacent to the isomer ^{137}Ce, we were able to measure only the 3n cross sections. Consequently, we relied on statistical model calculations for the 2n, 3n, and 4n channels to deduce the total fusion cross sections. To determine the zero-th moment of the angular momentum distribution independent of a statistical model branching ratio, one has to measure an absolute value for the total fusion cross section. In this article, we report results of an experiment to measure the fusion cross sections for ^{12}C + ^{128}Te at center-of-mass bombarding energies spanning the range between 40.4 and 56.6 MeV.

II. THE EXPERIMENT

Experiments were carried out with the use of ^{12}C beams provided by the 88-Inch Cyclotron at the Lawrence Berkeley Laboratory. Figure 1 is a schematic drawing of the experimental setup. Targets were made by the evaporation of metallic tellurium (100 μg/cm^2, 98.7 % ^{128}Te) onto carbon foils (20 μg/cm^2) and were mounted perpendicular to the beam direction with the carbon backing facing the beam. Evaporation residues were detected in two multiwire proportional counters (MWPC, or Breskin counters).[4-6] These dual-stage gas-filled counters provided timing and position information over a large area, 16×16 cm^2. Isobutane was used at a pressure of 2 Torr. Both counters were centered at 0°; the first one was positioned at a distance of 18.6 cm from the target and the second counter was placed at a distance of 14.5 cm behind the first one. A circular tantalum disk (diameter = 11 mm, thickness = 2 mm) was mounted in front of the first detector at a distance of 14 cm from the target in order to stop the beam. This beam stopper had a narrow (2 mm) supporting leg and covered the angular range from 0° to 2.4°. An aluminum mask with a circular aperture placed before the first counter defined the maximum angular acceptance at 9°. This angular range, $2.5^{\circ} \leq \theta \leq 9^{\circ}$, is sufficient to catch typically 85 % of the evaporation residues. The beam was collimated by two slits located approximately 30 and 60 cm from the target and having circular apertures with variable and fixed diameters, respectively. Two silicon surface-barrier detectors were mounted at ± 15° to the beam and at a distance of 12.5 cm from the target for monitoring the elastic scattering of ^{12}C by the tellurium target nuclei. Since the cross section for elastic scattering is given by the Rutherford formula at this angle and the solid angles of the monitor detectors were known ($\Delta\Omega = 2.05$ msr), it was possible to obtain an absolute measurement of the cross section independent of the target thickness and the integrated beam current. The beam intensity was kept at typically less than 0.5 pnA in order to keep the counting rate of the gas counters below 10,000 counts/s, thereby avoiding detector sparking problems and reducing electronic deadtime.

The identification of the evaporation residues was made by their time of flight as measured between the cyclotron RF and the first MWPC (T_{RF-1}), and between the two MWPCs (T_{1-2}). Representative two-dimensional spectra for the bombardment of ^{12}C on ^{128}Te target at $E_{c.m.} = 48.4$ MeV are shown in Fig. 2. Figures 2(a) and 2(b) are scatter-plots for T_{1-2} versus the pulse height on Anode 2, and T_{1-2} versus T_{RF-1}, respectively. Also shown are the gates used to separate the evaporation residues (Fig. 2(c)) from beam particles scattered by the target, collimators, and/or beam stopper directly in front of the detector. In separate measurements made with recoiling ^{128}Te nuclei (to determine the efficiency of the detection system) we were able to see that elastically scattered target nuclei were also eliminated by the combination of gates show in Fig. 2. The experimental evaporation residue angular distributions were obtained from the position information given by the MWPCs by gating on the evaporation residue group as shown in Figs. 2(a) and 2(b). Figure 3 shows the measured angular distribution of the evaporation residues for the reaction ^{12}C + ^{128}Te at a center-of-mass bombarding energy of 48.4 MeV.

To deduce the fusion cross sections several factors needed to be taken into account, namely, i) the efficiency of the detection system, ii) the missing azimuthal coverage due to the supporting stem of the beam stopper, and iii) the yield lost because residues emerging at angles less than 2.5° and greater than 9° were not detected. Fission of the compound nucleus was estimated to be negligible at these energies, and consequently the evaporation residue yields gave the total fusion cross sections.

The extrapolation of the experimental angular distributions to both smaller and larger angles was carried out by performing a Gaussian fit of the angular distribution in the region measured. The full line in Fig. 3 shows the result of such fit. This showed that the detected evaporation residues represent approximately 85 % of the total fusion cross section. To obtain an independent estimate of the fraction of residues emerging at angles between 2.5° and 9°, evaporation residue angular distributions were calculated with the statistical model code PACE.[7] These angular distributions, which were Gaussian in shape, were then folded with a Gaussian distribution in order to simulate multiple scattering in the target.[8] The predicted result is given by the dashed line in Fig. 3. The two methods for determining the total cross section agreed to better than 4 %.

The overall efficiency of the two-detector system as a function of particle energy was determined with the kinematic coincidence technique. Elastically scattered ^{12}C projectiles were detected in a silicon surface-barrier counter and the recoiling ^{128}Te nuclei were detected in the Breskin counters mounted on the opposite side of the beam. The efficiency is given by the ratio of the ^{12}C-^{128}Te coincidence yield and the elastically scattered ^{12}C singles yield. Several measurements were carried out with different angular settings for the solid-state detector and the Breskin counters in order to cover the energy range of the evaporation residues produced in the cross section measurements.

III. RESULTS

The absolute fusion cross sections were obtained by integrating the experimental evaporation residue angular distributions (using a Gaussian whose width was determined by fitting the data), taking into account the corrections mentioned above, the efficiency, and the normalization to Rutherford scattering. The fusion cross sections for ^{12}C + ^{128}Te as a function of the center-of-mass bombarding energy are shown in Fig. 4 (solid circles) and are listed in Table I. Taking into account systematic and random uncertainties, an overall error of 10 % in the fusion cross sections was calculated. This uncertainty was obtained by adding in quadrature the various sources of error which were estimated as follows: absolute Rutherford normalization, 5 %; overall efficiency, 8 %; extrapolation procedure, 4 %; and statistics, 2%.

Figure 4 also displays the experimental cross sections for the fusion reaction ^{128}Te(^{12}C,3n)^{137}Ce as reported in Ref. 2 (crosses). These data agree very well with the total fusion cross sections measured in the present work in the energy region where the 3n channel exhausts more than 90 % of the total fusion cross section.

IV. DISCUSSION

The calculation of the fusion cross section excitation function was performed with the simplified coupled-channels code CCFUS[9] as described in our previous publication.[2] The predicted total fusion cross sections (solid line) and those for the 3n channel alone (dashed line) are shown in Fig. 4. These predictions describe the experimental data very well at bombarding energies above and below the Coulomb barrier.

The purpose of the present measurements was to make an independent determination of the absolute angular momentum in the ^{12}C + ^{128}Te reaction by deducing it from the measured absolute total fusion cross section at energies well above the Coulomb barrier (V_b = 39.4 MeV). It is well established that the angular momentum distribution has a triangular shape in this energy region. Thus, by using the sharp cutoff approximation one can determine an absolute value for the angular momentum by measuring the absolute fusion cross section. The values of $< \ell >$ thus obtained are shown in Fig. 5 (solid and open circles) for the six bombarding energies measured in the present work. Note that, since the sharp cutoff approximation breaks down near the barrier, the deduced values of $< \ell >$ for $E_{c.m.}$ = 40.4 and 41.9 MeV (open circles) are lower than the true average values. The average angular momentum determined from the isomer ratio measurements[2] are displayed as crosses. The values of $< \ell >$ deduced from the fusion cross sections reported in Refs. 1 and 2 (inferred from the statistical model calculations and the measured 3n cross sections), are presented as open squares. Note the very good agreement between the different sets of data in the energy region where they overlap. The solid line in Fig. 5 represents the average angular momentum for fusion calculated with CCFUS. We observe that the energy dependence for $< \ell >$ is also well reproduced by this barrier penetration calculation. Recently, Gil et al.[10] have shown for the system ^{28}Si + ^{154}Sm that the energy dependence of $< \ell >$ and the measured cross sections are also reproduced by the same type of theoretical calculation.[3]

V. CONCLUSIONS

We have measured the fusion cross sections for ^{12}C + ^{128}Te at $E_{c.m.}$= 40.4 - 56.6 MeV by direct detection and identification of evaporation residues using a time-of-flight technique. By measuring the absolute cross section well above the Coulomb barrier we deduced the absolute angular momentum using the sharp cutoff approximation and, therefore, obtained an independent check of the isomer ratio method for determining the absolute value for the average angular momentum. The present measurements, along with those reported in Refs. 1 and 2, also confirm that the energy dependence for both σ_{fus} (E) and absolute values for $< \ell >$ are self-consistent and well described by theoretical calculations.

VI. ACKNOWLEDGMENTS

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TABLE I. Fusion Cross Sections for ^{12}C + ^{128}Te.

$E_{c.m.}$ (MeV)	σ_{fus} (mb)
56.6	1050±105
53.0	910±91
48.4	763±76
45.4	545±55
41.9	220±22
40.4	132±13

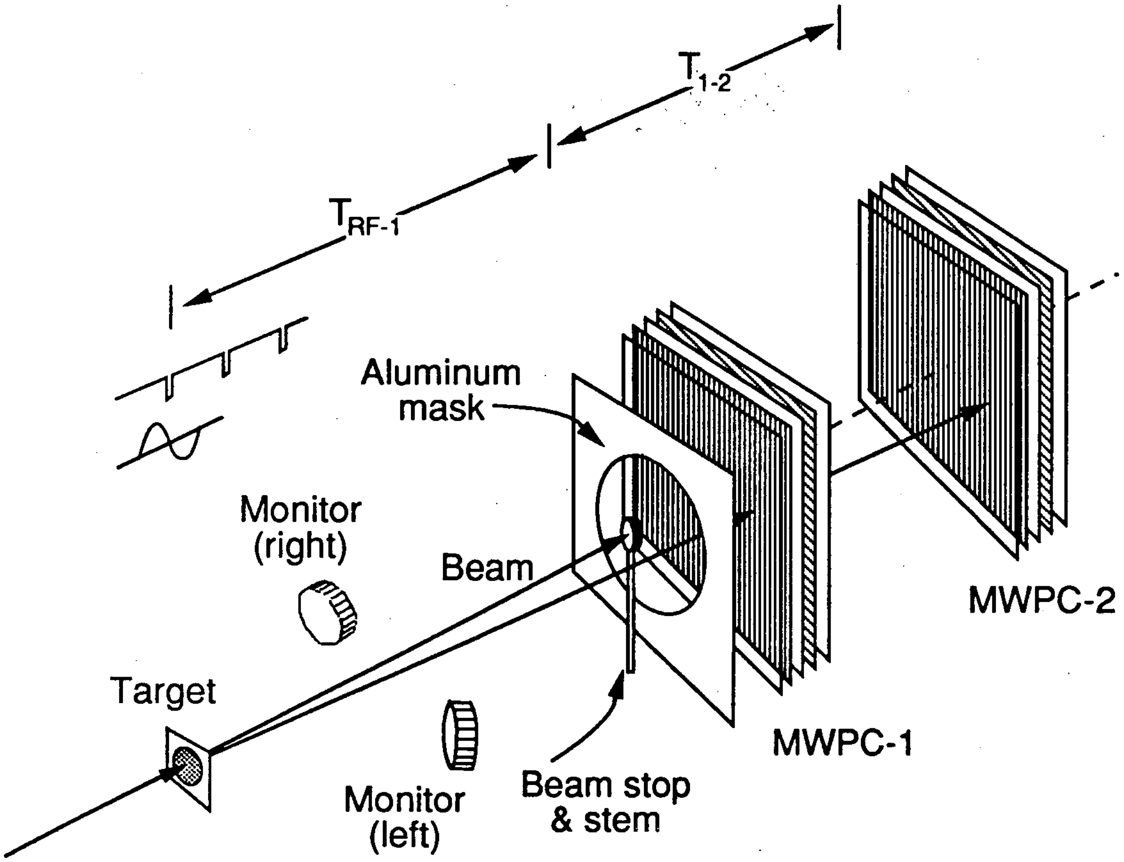
FIG. 1. Schematic drawing of the experimental setup.

FIG. 2. Two-dimensional spectra for the reaction ^{12}C + ^{128}Te at $E_{c.m.} = 48.4$ MeV. (a) T_{1-2} versus Anode 2 pulse height, (b) T_{1-2} versus T_{RF-1}. Gates on the evaporation residue group are shown. (c) represents T_{1-2} versus T_{RF-1} with the gating conditions displayed in (a) and (b) applied.

FIG. 3. The experimental angular distribution of the evaporation residues for the reaction ^{12}C + ^{128}Te at $E_{c.m.} = 48.4$ MeV. The full line represents a Gaussian fit of the measured angular distribution for data points between 2.5° and 9°. The dashed line represents a calculated angular distribution using PACE[7] and then folded with a Gaussian distribution in order to simulate multiple scattering in the target.[6,8]

FIG. 4. The experimental total fusion cross sections (solid circles) and the 3n cross sections (crosses) for the reaction ^{12}C + ^{128}Te as a function of the center-of-mass bombarding energy. The solid line is a calculation of the total fusion cross section as described in the text with input parameters taken from Ref. 2. The dashed line shows the prediction for the 3n cross section, obtained from the predicted total cross section and a statistical decay calculation of the x-n distributions made with the code PACE.

FIG. 5. Average angular momentum as a function of bombarding energy for the fusion of ^{12}C + ^{128}Te deduced from: the present evaporation residue measurements and the sharp cutoff approximation (solid and open circles), the isomer ratio measurements (crosses), and the fusion cross sections inferred from the statistical decay expectations and the 3n cross sections measured in Refs. 1 and 2 (open squares). Note that two low energy points (open circles) are low because the sharp cutoff approximation is not valid. The solid line represents the values of $< \ell >$ predicted by CCFUS.



$T_{1\text{-}2}$
$T_{RF\text{-}1}$
Aluminum mask
Monitor (right)
Beam
MWPC-2
Target
MWPC-1
Monitor (left)
Beam stop & stem

Figure 1

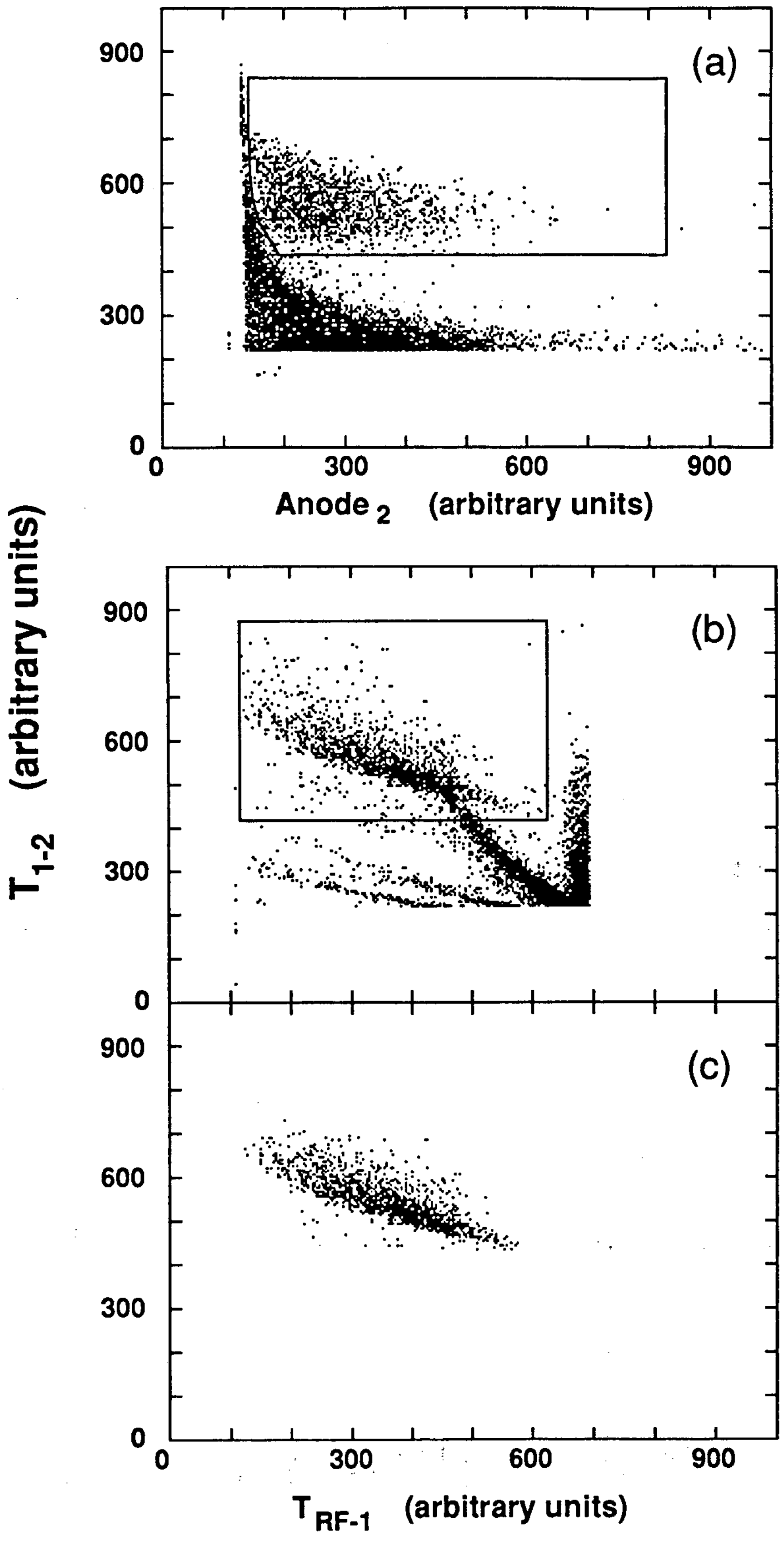

(a)
900
600
300
0
0
300
600
900
Anode 2 (arbitrary units)
T 1-2 (arbitrary units)
(b)
900
600
300
0
(c)
900
600
300
0
0
300
600
900
T RF-1 (arbitrary units)

Figure 2

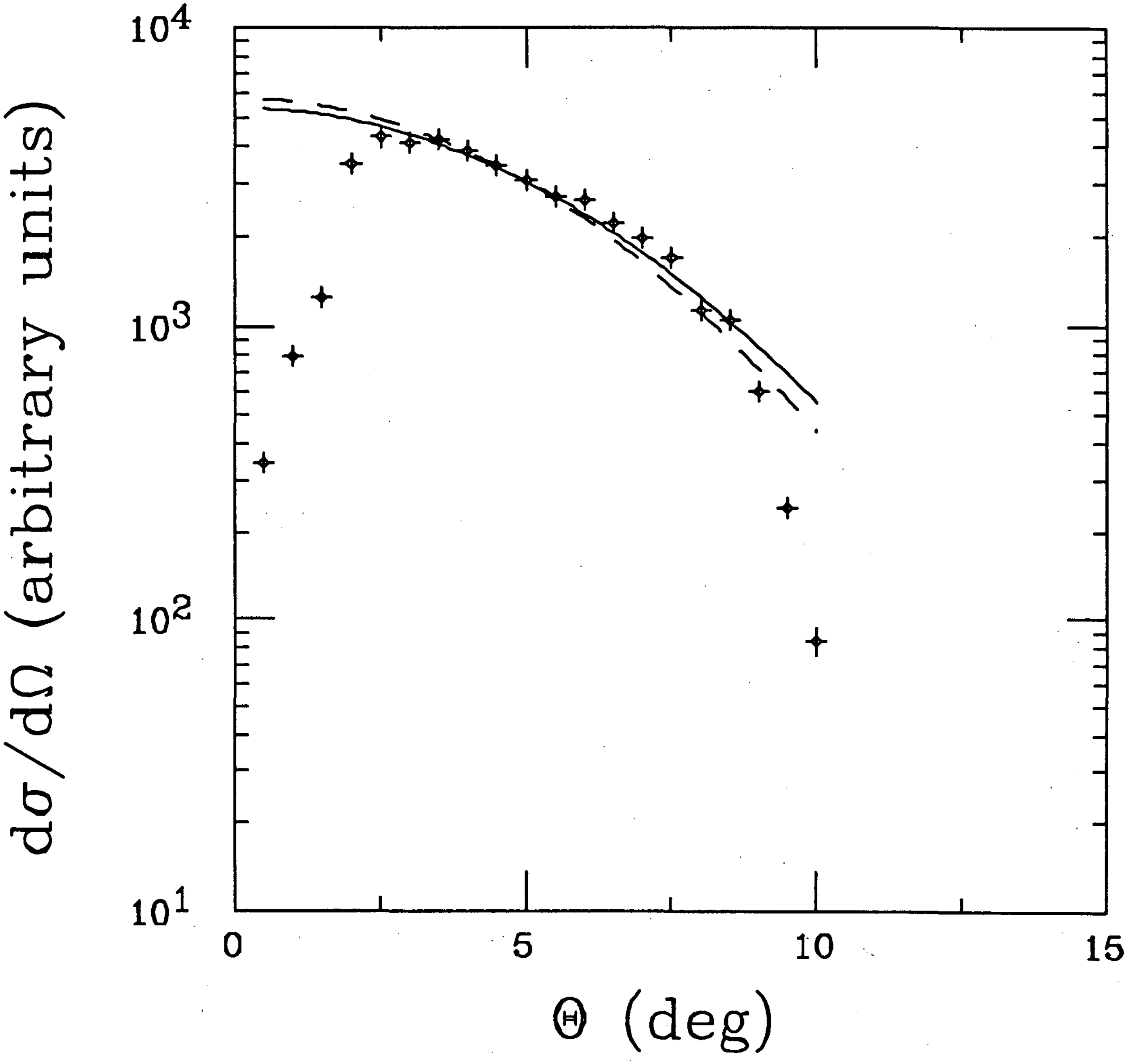
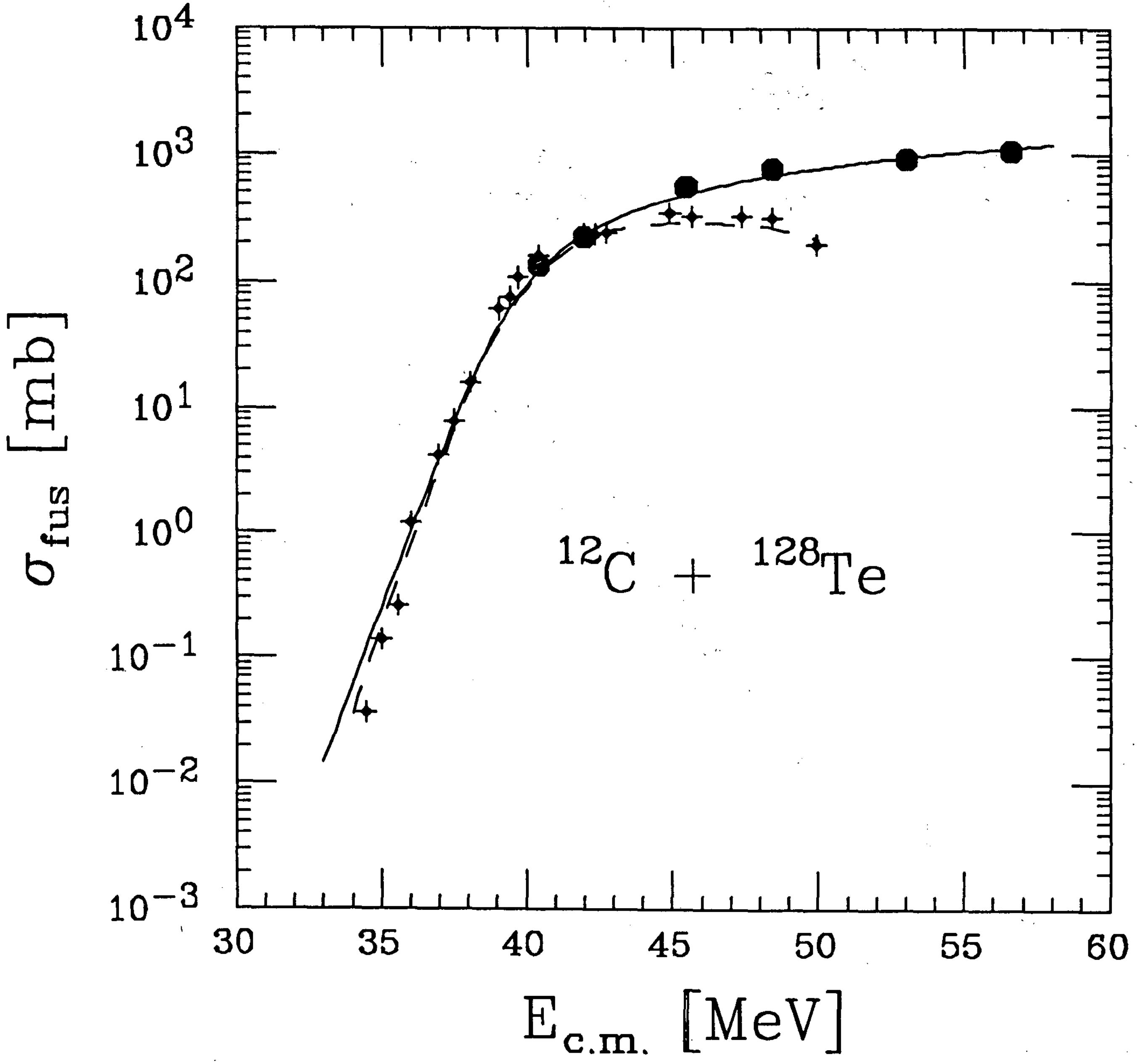

10^4
10^3
10^2
10^1
0
5
10
15
$d\sigma/d\Omega$ (arbitrary units)
Θ (deg)

Figure 3



10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
σ_{fus} [mb]
30
35
40
45
50
55
60
$E_{c.m.}$ [MeV]
$^{12}C + ^{128}Te$

Figure 4

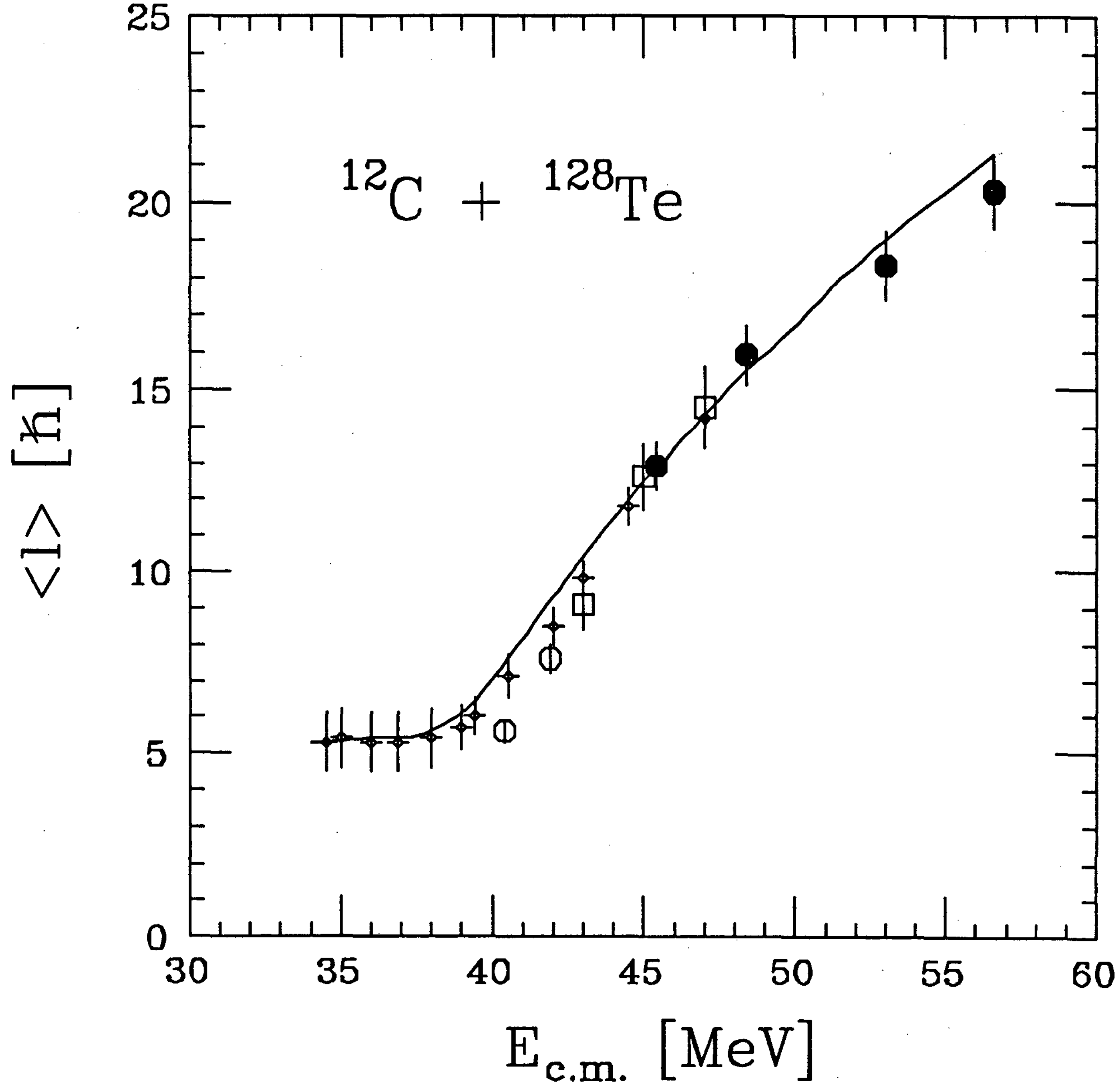

$^{12}C + {}^{128}Te$
$\langle l \rangle$ [ħ]
$E_{c.m.}$ [MeV]
0
5
10
15
20
25
30
35
40
45
50
55
60

Figure 5

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