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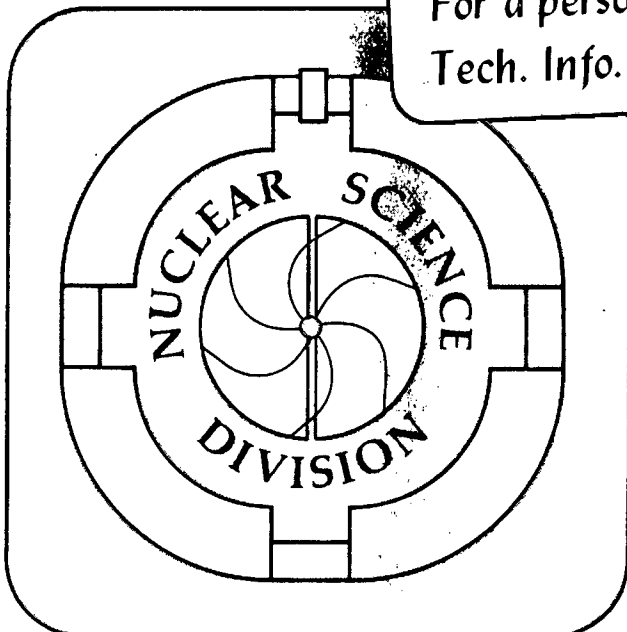
THE  $^{12}\text{C} + ^{12}\text{C}$  REACTION CROSS SECTION BETWEEN 70 AND 290 MeV OBTAINED FROM ELASTIC SCATTERING

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THE  $^{12}\text{C} + ^{12}\text{C}$  REACTION CROSS SECTION BETWEEN 70 AND  
290 MeV OBTAINED FROM ELASTIC SCATTERING\*

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ABSTRACT

Measurements of the elastic scattering of  $^{12}\text{C}$  on  $^{12}\text{C}$  at 10 laboratory energies between 120 and 290 MeV were made to determine the reaction cross section  $\sigma_R$  and the total nuclear cross section  $\sigma_T$ . Analysis of these data and existing data at lower energies show that  $\sigma_R$  reaches a maximum at around 200 MeV in the laboratory whereas  $\sigma_T$  shows little variation with bombarding energy.

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The variation of the nuclear reaction cross section  $\sigma_R(E)$  has been investigated recently by DeVries and collaborators.<sup>1,2</sup> They have focussed attention on the fact that values of  $\sigma_R$  for light-ion projectiles (up to helium) cannot be parameterized by the usual geometric form

$$\sigma_R(E) = \pi(R+\lambda)^2 \left[ 1 - \frac{Z_1 Z_2 e^2}{(R+\lambda) E_{\text{cm}}} \right] \quad (1)$$

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over the entire energy range. For example if  $R$  is adjusted to reproduce  $\sigma_R$  at low energies, Eq. (1) overestimates  $\sigma_R$  at high energies. The difference between this geometric limit and the measured values has been parameterized by multiplying the right-hand side of Eq. (1) by a factor  $(1-T(E))$  where  $T(E)$ , the transparency, reflects a finite mean free path for the interacting ions. The authors of Ref. 1 emphasize that values of  $T$  increase quite rapidly at energies above 10 MeV/A even for strongly absorbed projectiles such as  $\alpha$  particles and that this increase seems to correlate with the known fall-off of the nucleon-nucleon cross section<sup>3</sup> suggesting the dominance of the latter in determining  $\sigma_R$ .

Calculations of the energy variation of  $\sigma_R$ <sup>1,2</sup> and  $\sigma_T$ , the total nuclear cross section,<sup>4</sup> based on the Glauber model give quite a good account of the available data and in this sense support the above conclusion. In particular the calculations predict that for  $^{12}\text{C} + ^{12}\text{C}$  scattering  $\sigma_R$  and  $\sigma_T$  reach a maximum at  $E_{\text{cm}} \sim 100$  MeV.

Although some data for  $^{12}\text{C} + ^{12}\text{C}$  exist at higher<sup>5,6</sup> and lower<sup>7,8</sup> energies there is a serious lack of experimental data on  $\sigma_R$  for heavy ions in this energy region. Thus measurements of the elastic scattering of  $^{12}\text{C} + ^{12}\text{C}$  were undertaken between 120 and 290 MeV. We find that values of  $\sigma_R$  deduced from a parameterized phase shift analysis of the data reach a maximum at  $\sim 200$  MeV (Lab), in qualitative agreement with the calculations of DiGiacomo et. al.<sup>2</sup> and with the  $^{16}\text{O} + ^{12}\text{C}$  data of Brandan and Menchaca-Rocha.<sup>9</sup> Our values of  $\sigma_T$ , however indicate that this cross section is

approximately constant over the energy range studied.

The experiments were carried out using 4+ and 5+ beams of  $^{12}\text{C}$  from the LBL 88-Inch Cyclotron. Measurements were made in  $0.25^\circ$  steps in the forward angle region ( $2^\circ$ - $15^\circ$  lab) which is of critical importance in the determination of  $\sigma_R$  and  $\sigma_T$ . (It can be shown that additional experimental data at angles greater than  $25^\circ$  c.m. have little influence on the deduced values of  $\sigma_R$  and  $\sigma_T$  for the bombarding energies considered here). Since an accurate knowledge of the scattering angle is essential for the accurate determination of  $\sigma_R$  and  $\sigma_T$  two sets of four lithium-drifted silicon detectors of 3mm thickness were located on moveable arms at equal angles to the left and right of the beam direction. The targets were made of natural carbon of thicknesses between 275 and 1000  $\mu\text{g}/\text{cm}^2$  determined to  $\pm 5\%$  by  $\alpha$  energy loss measurements. In addition, two monitor detectors placed at  $\pm 8^\circ$  above and below the scattering plane monitored the vertical position of the beam.

Data were taken at 10 energies between 121.6 MeV and 287.8 MeV. In two cases (121.6 MeV, 161.05 MeV) the angular range of the data was extended beyond  $20^\circ$  lab.

Final differential cross sections were obtained by averaging results from left and right detectors thereby eliminating to first order effects of beam movement and misalignment. The angular error of the data was essentially due to the precision with which the angles of the detectors could be set and was estimated

to be  $0.125^\circ$ . The angular aperture of the detector collimators in the scattering plane was  $0.3^\circ$  which, when combined with the spot size and angular divergence of the beam, yielded a total "smoothing" angle of approximately  $0.5^\circ$  (Lab). An additional measurement at 289 MeV was carried out using two position sensitive detectors and a strip target. The angular accuracy in this case was  $\pm 0.07^\circ$ .

The reaction cross section and the total nuclear cross section for identical particle scattering are given in terms of the S matrix elements obtained from a partial wave expansion of the differential cross section as:

$$\sigma_R = \frac{2\pi}{k^2} \sum_{\substack{\ell=0 \\ \text{(even)}}}^{\ell_{\text{max}}} (2\ell+1) (1 - |S_\ell|^2)$$

$$\sigma_T = \frac{4}{k^2} \sum_{\substack{\ell=0 \\ \text{(even)}}}^{\ell_{\text{max}}} (2\ell+1) (1 - \text{Re}S_\ell)$$

In order to fit the data the following parameterization of  $S_\ell$  was chosen

$$\eta_\ell = |S_\ell| = 1 - \frac{1}{1 + \exp\left(\frac{\ell - \ell_\eta}{\Delta}\right)}$$

and

$$\cos 2\delta_\ell = \text{Re}S_\ell / |S_\ell| = 1 - \frac{2}{1 + \exp\left(\frac{\ell - \ell_\delta}{\Delta}\right)}$$

This parameterization was used in a computer program which optimised the parameters using a non-linear least squares fitting procedure. The ability of this parameterization to reproduce known values of  $\sigma_R$  and  $\sigma_T$  was determined by fitting theoretical 'data' between  $5^\circ$  and  $25^\circ$  (cm) generated from an optical model calculation. Values of  $\sigma_R$  and  $\sigma_T$  so deduced agreed to within 1.5% with the optical model values.

When the experimental data were fitted all theoretical angular distributions were smoothed over a total angle of  $1^\circ$  in order to simulate the experimental geometry. Several of the resultant differential cross-sections are shown in Fig. 1. The results are plotted against momentum transfer rather than c.m. angle to emphasize that the positions of the most forward angle minima are almost energy independent and that the depths of the minima evolve smoothly over the energy range investigated. Values of  $\sigma_R$  and  $\sigma_T$  obtained from the analysis are displayed in Fig. 2.

The errors in the deduced values of  $\sigma_R$  and  $\sigma_T$  contain various contributions. Tests showed that changes in absolute normalization of  $\pm 5\%$  produced only  $\pm 0.5\%$  changes in values of  $\sigma_R$  and  $\sigma_T$ . Furthermore the effect of smoothing the theoretical predictions during the fitting procedure produced changes of the same order. However a relatively large change in  $\sigma_R$  and  $\sigma_T$  could be induced by making a small systematic shift in the experimental angles. At 288 MeV a shift of only  $\pm 0.25^\circ$  (cm) produced  $\pm 5\%$  changes in  $\sigma_R$  and  $\sigma_T$ , and this effect was therefore considered to be the



dominant source of experimental error. The total estimated experimental error was obtained by adding in quadrature the errors estimated from all these effects.

The above analysis was also applied to published data<sup>8</sup> between 70 and 127 MeV (Lab) and the results are included in Fig. 2. These values seem to exhibit some structure. However, a considerable improvement in the quality of the data at forward angles would be required to confirm this suggestion.

To investigate the model dependence of the deduced values of  $\sigma_R$  and  $\sigma_T$  our data were also fitted using the standard 6 parameter Optical Model. It should be made clear that in these fits emphasis was placed on obtaining the best description of the forward angle diffraction structure and not on the determination of a smoothly energy dependent optical model parameter set. The deduced values of  $\sigma_R$ , although slightly higher, (see Fig. 2) exhibit the same trend with energy as those obtained from the phase shift model. The values of  $\sigma_T$  are also very similar for the two models except at the lowest energies.

In Fig. 3 our results for  $\sigma_R$  are compared with the calculations of DiGiacomo et. al.<sup>2</sup> and those for  $\sigma_T$  with that of Peng et. al.<sup>4</sup> The calculation for  $\sigma_T$  disagrees somewhat with our data which do not exhibit the sharp rise and fall of the predicted values. In fact our data are consistent with a constant value ( $\sigma_T = 2570$  mb) over the energy range studied. The agreement for  $\sigma_R$  is more satisfactory. In particular it does appear that

the reaction cross section reaches a maximum at  $E_{\text{cm}} \approx 100$  MeV.

Caution is required however in drawing conclusions from these comparisons. Brink and Satchler<sup>10</sup> have noted that a maximum in the reaction cross section may be merely due to the attraction of the real nuclear potential. Over a limited energy range this attraction may produce trajectories with a significant curvature thus pulling flux into the region of strong absorption and lengthening the path over which the two nuclei are in close contact. Although Brink and Satchler concluded from calculations using energy independent optical potentials that this effect could not produce all of the observed fall off in  $\sigma_R$ , it should be stressed that relatively small changes in the real potential produce large effects at low and medium energies ( $E_{\text{cm}} \approx 100$  MeV) as can be seen from the simple semi-classical formula

$$\sigma_R = \pi R^2 \left( 1 - \frac{V_C(R) + V_N(R)}{E_{\text{cm}}} \right) \quad (2)$$

with the radius  $R$  deduced from the high energy  $\sigma_R$  values (Ref. 6 and Fig. 3). Equation (2) is similar to Eq. (1) but does not neglect the nuclear attraction in the vicinity of the Coulomb barrier. This 'trajectory' effect (as well as the effect of the Fermi motion of nucleons) was included in the calculation of  $\sigma_R$  (Ref. 2) but not in the calculation of  $\sigma_T$  (Ref. 4). Unfortunately the strength of the nuclear attraction in the  $^{12}\text{C} + ^{12}\text{C}$  case cannot be deduced with high precision

since present optical models are unable to give a satisfactory account of the elastic scattering data at all angles (Ref. 8).

In conclusion our experiments indicate a maximum in  $\sigma_R(E)$  at  $E_{cm} \approx 100$  MeV as predicted in Refs. 1 and 2. However the role of the energy dependence of the nucleon-nucleon force in producing such a maximum remains uncertain. Accurate measurements of  $\sigma_R$  and  $\sigma_T$  over a wider range of energies will undoubtedly be of use in understanding the respective roles of 'mean field' and 'nucleon-nucleon' aspects of the problem. Further theoretical work in the low and medium energy region near the maximum of  $\sigma_R(E)$  would also be valuable.

#### FOOTNOTES AND REFERENCES

\*This work was supported by the Director, U.S. Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics, and by Nuclear Sciences of the Basic Energy Sciences Program of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

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FIGURE CAPTIONS

Fig. 1. Elastic scattering cross sections as a function of momentum transfer. The smooth lines are the results of calculations using the parameterized phase shift model.

Fig. 2. Deduced values of  $\sigma_R$  and  $\sigma_T$  from parameterized phase shift analysis shown with least squares quadratic fit for  $\sigma_R(E)$  and least squares linear and quadratic fits for  $\sigma_T(E)$ . Results of optical model fits are also given.

Fig. 3. Least squares quadratic fits from Fig. 2 shown with microscopic calculations for  $\sigma_R$  (Ref. 2) and  $\sigma_T$  (Ref. 4). Representative data points from the present work (squares) as well as low energy data taken from Ref. 7 (open circles) and high energy data from Ref. 6 (filled circles) are given in the figure.

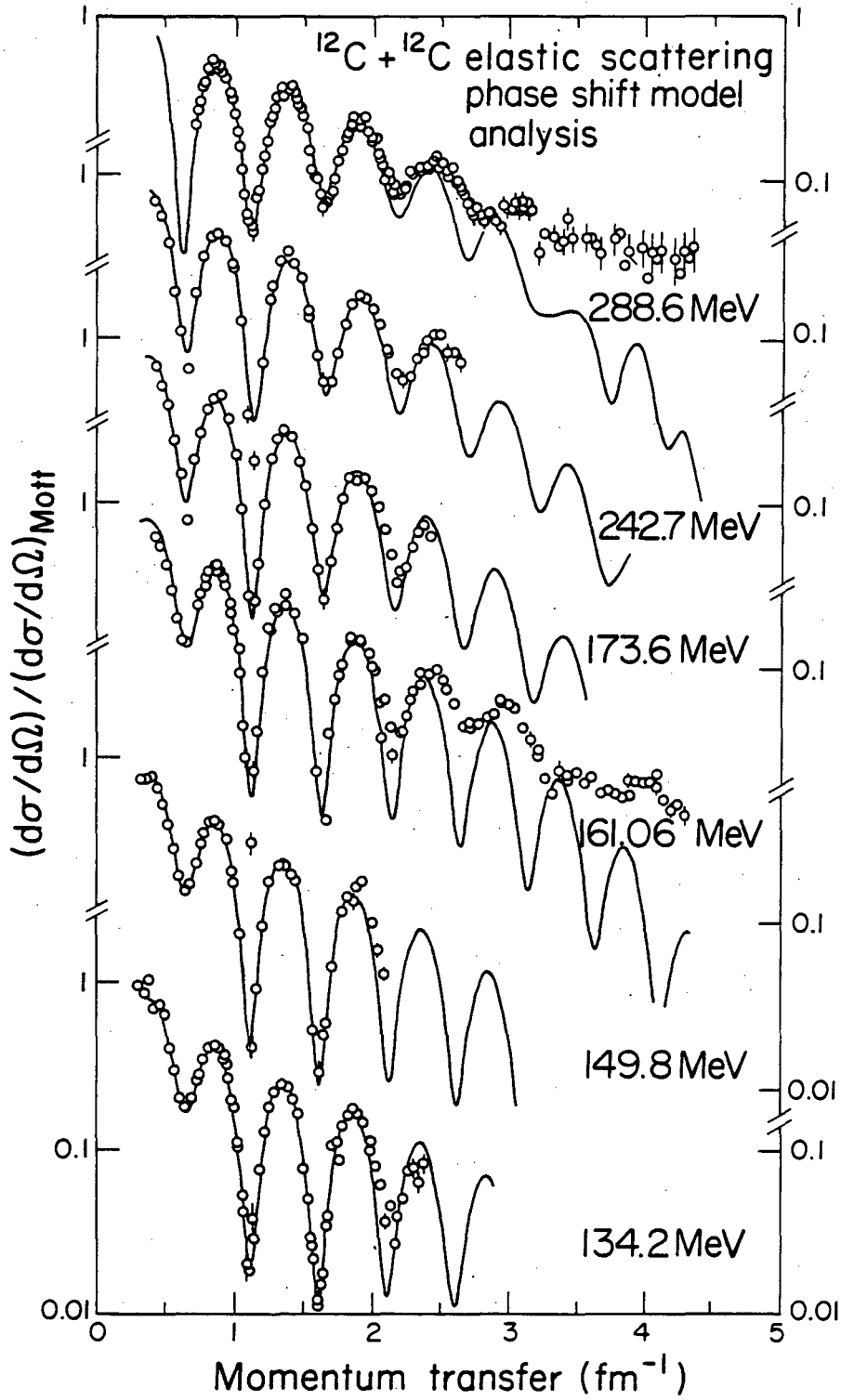
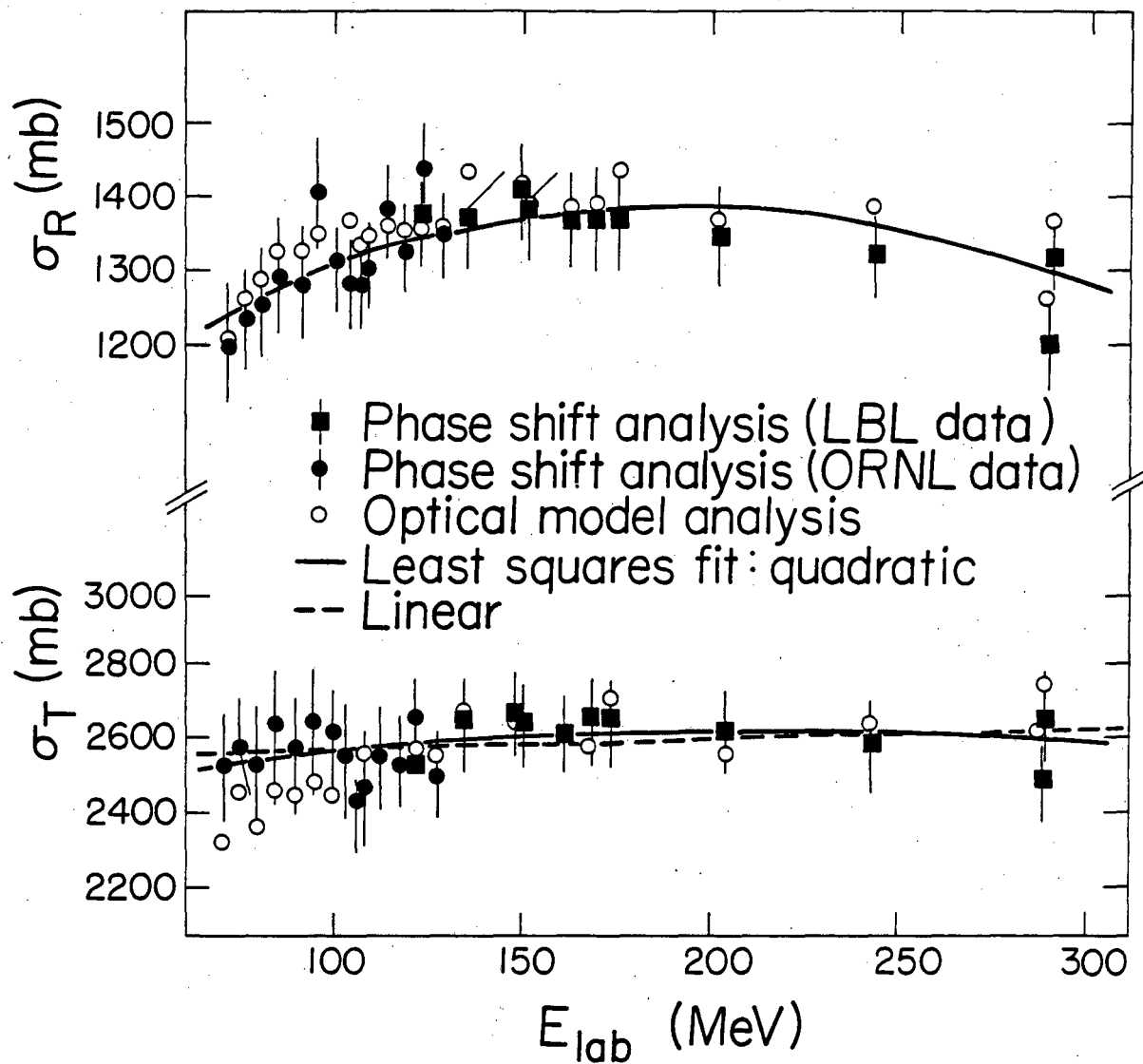


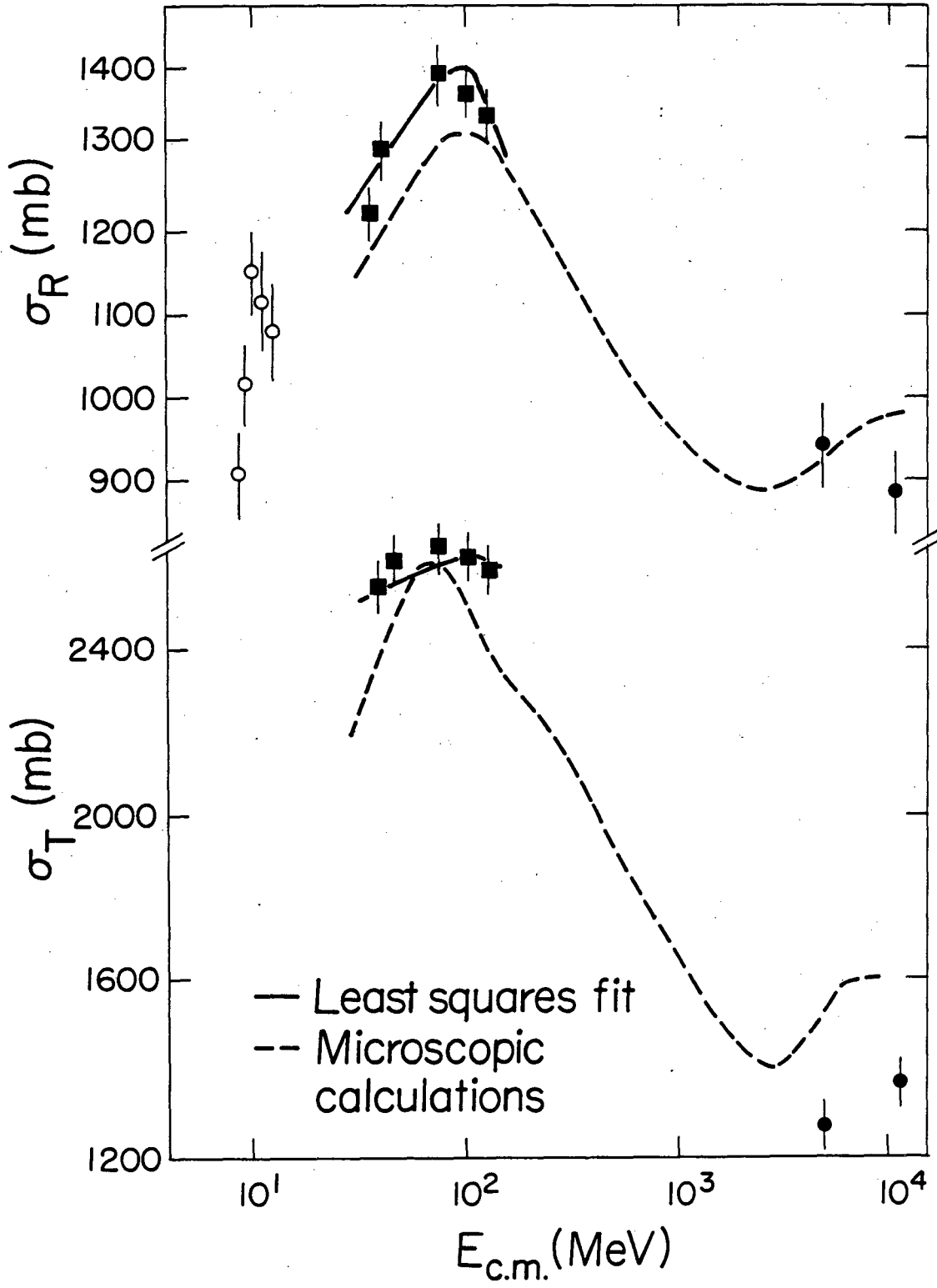
Fig. 1

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Fig. 2



— Least squares fit  
-- Microscopic calculations

Fig. 3

XBL 817-2418

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