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We have measured σ_R , the total reaction cross section, for 150 MeV O^{16} ions and 114 MeV C^{12} ions on the elements Be, C, Al, Fe, Ni, Cu, Ag, Sn, Ta, and Au. The energy dependence of σ_R for O^{16} on Al and Ag and C^{12} on Al has also been investigated.

A beam attenuation technique utilizing millimicrosecond electronics was used to make these measurements. Figure 1 shows a schematic diagram of the experimental set-up. A beam particle was accepted by the electronics if it passed, within the resolving time of a coincidence circuit, through two thin plastic scintillators (counter 1 and 3 in figure 1). In order to produce a well defined beam at the target position, two plastic scintillator collimator counters, labeled 2 and 4 in figure 1, were placed in anti-coincidence with counters 1 and 3. Thus the total beam I_0 was determined by measuring the number of $1\,\bar{2}\,3\,\bar{4}$ events where the bar signifies a counter placed in anti-coincidence.

The beam attenuation caused by the target was measured by placing counter 5, the stopping counter, in anti-coincidence with I_0 ie $I_0 - I = 1\,\bar{2}\,3\,\bar{4}\,\bar{5}$ where I refers to the attenuated beam. The measurement was then repeated with the target removed to obtain i_0 and $i_0 - i$. The quantity σ_R is obtained from the following relationship:

$$\frac{I_0 - I}{n \times I_0} - \frac{i_0 - i}{n \times i_0} = \sigma_R + \sigma_{corr}$$

where n is the target density and x the target thickness. The quantity σ_{corr} is composed of inelastic and elastic correction terms which are defined more precisely later.

In the case of heavy ions, which have a relatively short range in matter, the target must be quite thin in order to preserve energy resolution. The target in/target out ratio will be quite small unless some method is devised to reduce the attenuation of the beam which occurs in the stopping counter. A solution to this problem was arrived at by construction of a "dual" stopping counter shown in figure 2. Counter 5, a stopping plastic scintillator with rise and decay time characteristic necessary for high count rates, was placed to intercept the unscattered and multiple Coulomb scattered beam. This counter was used as the anti-coincidence counter 5 in the measurement of $I_0 - I$.

The remaining counter in the dual configuration catches large angle elastic scattering and reaction events. A surface barrier detector was chosen because it provided good energy resolution (3%) and exhibited little saturation for particles of different charge, an important criterion for the efficient detection of transfer reactions. This detector was gated on only by $1\,\bar{2}\,3\,\bar{4}\,\bar{5}$ events. The angles θ' and θ'' shown in figure 2 were adjusted so that the correction for elastically scattered particles outside of θ' and the inelastically scattered particles within θ'' be small.

The power of this method rests on the fact that the attenuation of the beam in counter 5 can be ignored because it is used only as a "yes-no" counter. Had this counter been used to catch the reaction events, energy resolution would be needed and the attenuation could not be neglected. The target in/target out ratio in a case such as this would be about 10/9. With the dual counter configuration this ratio becomes ~ 25. With appropriate modifications a configuration similar to this should enable one to measure proton total reaction cross sections down to about 3 MeV.

The major corrections which must be applied to the raw data are for the elastic scattering of particles outside of the angle θ', inelastic events between θ' and θ'' which proceed through the first few low lying levels which the surface barrier detector cannot resolve and inelastic events within θ'' which strike counter 5 and cancel out the event. Thus the correction term is defined:

$$\sigma_{\text{correction}} \equiv \int_{\theta'}^{\pi} \left(\frac{d\sigma}{d\Omega}\right)_{el} d\Omega - \int_{\theta'}^{\theta''} \sum_{1}^{N} \left(\frac{d\sigma}{d\Omega}\right)_{in} d\Omega - \int_{0}^{\theta''} \sum_{1}^{\infty} \left(\frac{d\sigma}{d\Omega}\right)_{in} d\Omega$$

where N is determined by the resolution of the surface barrier counter, A rough determination of the first and last terms was made by measuring the ratio $I_0 - I/I_0$ as a function of θ' and θ''. The angles could then be set at an optimum value. The contribution to the unresolved levels was assumed to be small. However, this could be in error which would result in too small a value for σ_R.

Figure 3 shows the experimental results for 114 MeV C^{12} ions. The term $\sigma_R - \sigma_{CE}$ (where σ_{CE} refers to the compound elastic cross section) is the actual quantity measured in this experiment because of the inability to separate σ_{CE} from shape elastic scattering. However, σ_{CE} for heavy ions is expected to be negligibly small. The dashed curve is the theoretical total reaction cross section calculated by Thomas[1] using a square well nuclear potential model with $r_0 = 1.5f$. The agreement is fairly good. It appears that there may be a minimum in the measured quantity $\sigma_R - \sigma_{CE}$ in the vicinity of Ni. This is consistant with the proton and alpha particle reaction cross sections measured earlier by us.[2,3]

The total reaction cross section results for 150 MeV O^{16} ions are shown in figure 4. The dashed curve is the theoretical prediction for σ_R using the square well model with $r_0 = 1.5f$. The minimum near Ni is again present.

The energy dependence of σ_R for C^{12} and O^{16} on Al is given in figure 5. The square well predictions of σ_R for these two systems are also shown. In the parabolic model the real port of the optical model potential proposed by Igo[4] to fit alpha particle data was used:

$$V = \frac{Z_1 Z_2 e^2}{r} - V_0 \exp - \left(\frac{r - r_0 (A_1^{1/3} + A_2^{1/3})}{d} \right)$$

where V_0, r_0 and d are the parameters in the real part of the Woods-Saxon optical potential. Hill and Wheeler[5] have shown that the total potential could be represented by a parabola that is matched in position, height and curvature to the potential at its maximum. Figure 5 shows the σ_R predictions of this model for O^{16} on Al using $r_0 = 1.23f$, $V_o = -70$ MeV and $d = .48$ f.

Figure 6 illustrates the energy dependence of σ_R for O^{16} on Ag. The theoretical predictions of σ_R using the two different models are also shown. The value of the parameters used are the same as those listed for figure 5.

It should be noted that the σ_R results for C^{12} and O^{16} on U (1850 ± 90 mb and 1970 ± 75 mb respectively at the appropriate energy) measured by Viola and Sikkeland[6] are in excellent agreement with the trend of the data listed in figures 3 and 4. They have also obtained with the parabolic model excellent fits for the energy dependence of σ_R for these systems using virtually the same set of parameters as listed here.

The total reaction cross sections in conjunction with elastic scattering data should enable one to establish the various parameters more precisely in the phase shift and optical model analyses. Alster and Conzett[7] have carried out a phase shift analysis on the elastic scattering of C^{12} ions from several elements. The σ_R predictions from this analysis are about 20% higher than the measured values. This discrepancy is too large to be explained in terms of the small difference in energy of the incident C^{12} ions used in the elastic scattering and σ_R experiments. It will be interesting to see if the phase shift parameters can be adjusted to fit both sets of experimental data.

An optical model analysis carried out by R. Pehl and B. Wilkins on the elastic scattering of alpha particles indicates that the total reaction cross section places a powerful constraint on the shape of the imaginary potential at the extreme outer surface of the nucleus. It is expected that this same feature will be true for the optical model analysis of heavy ion scattering.

If some insight into the shape of the potential in the surface region of the nucleus is to be gained by the analysis of heavy ion elastic scattering data, it would seem that the total reaction cross sections are very necessary data especially since there appears to be some structure as a function of A for σ_R.

FOOTNOTE AND REFERENCES

*Work was performed under the auspices of the U.S. Atomic Energy Commission.

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Figure 1. A schematic diagram of the experimental setup.

Figure 2. The dual counter configuration used as the stopping counter for this experiment.

Figure 3. A plot of σ_R-σ_{CE} versus A for 114 MeV C^{12} ions. The dashed curve is the square well model predictions of σ_R for $r_0 = 1.5f$.

Figure 4. A plot of σ_R-σ_{CE} versus A for 150 MeV O^{16} ions. The dashed curve is the square well model predictions of σ_R for $r_0 = 1.5f$.

Figure 5. The energy dependence of σ_R-σ_{CE} for C^{12} and O^{16} on Al. The curves represent the theoretical prediction of σ_R using the square well model and the parabolic model. The $\overline{\underline{\phi}}$ are the O^{16} + Al experimental points and the $\overline{\underline{\Phi}}$ are the C^{12} + Al experimental points.

Figure 6. The energy dependence of σ_R-σ_{CE} for O^{16} on Ag. The curves represent the theoretical predictions of σ_R using the square well model and the parabolic model. The dots are the experimental points.

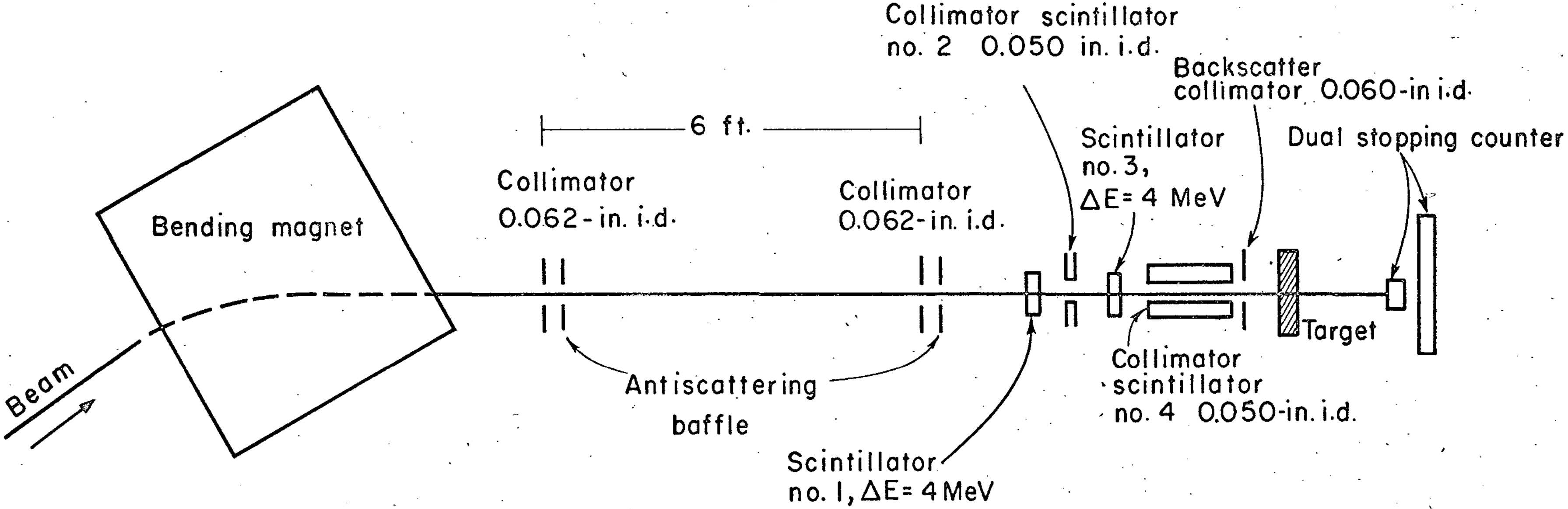

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Fig. 1

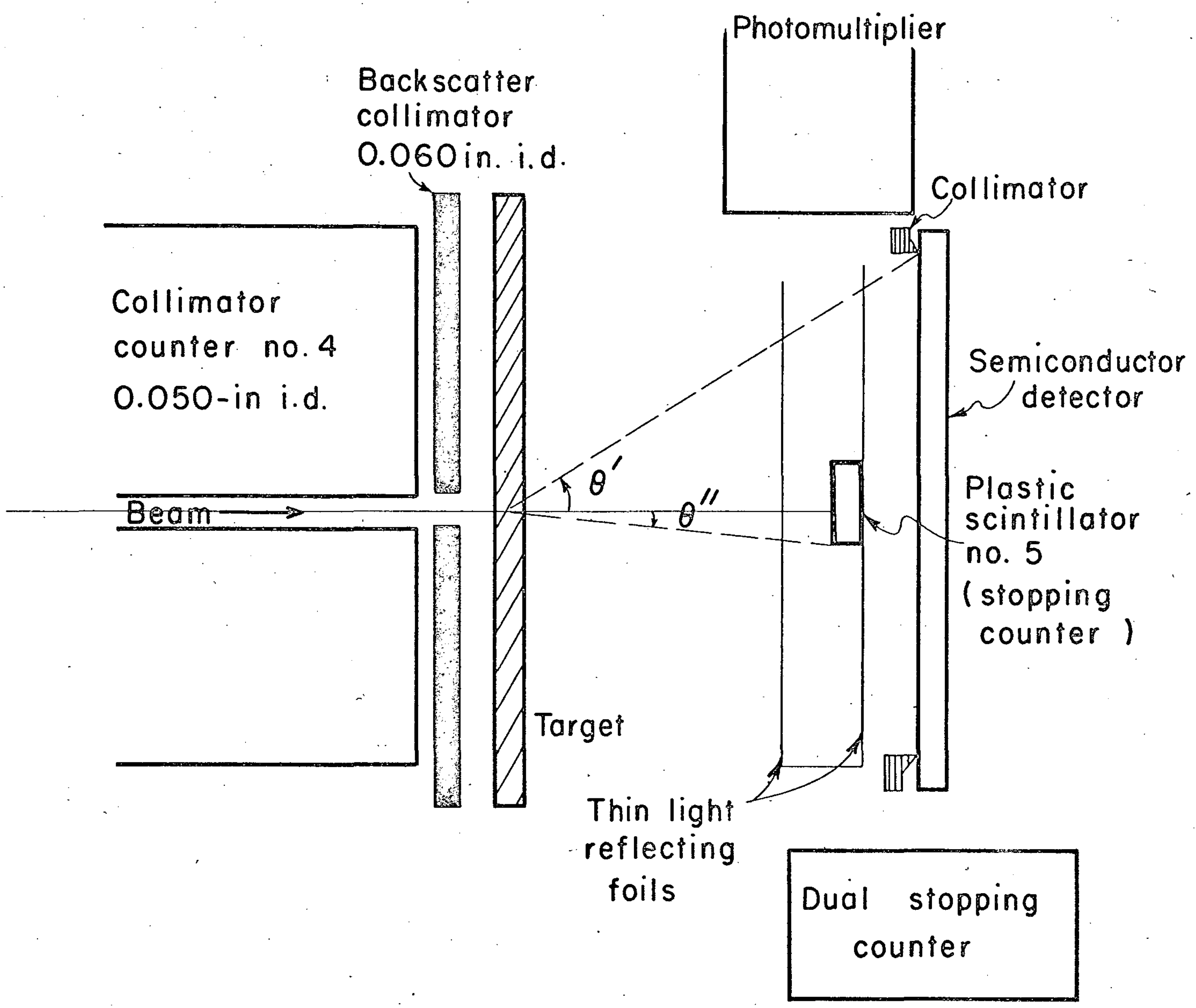

Fig. 2

MU-30014

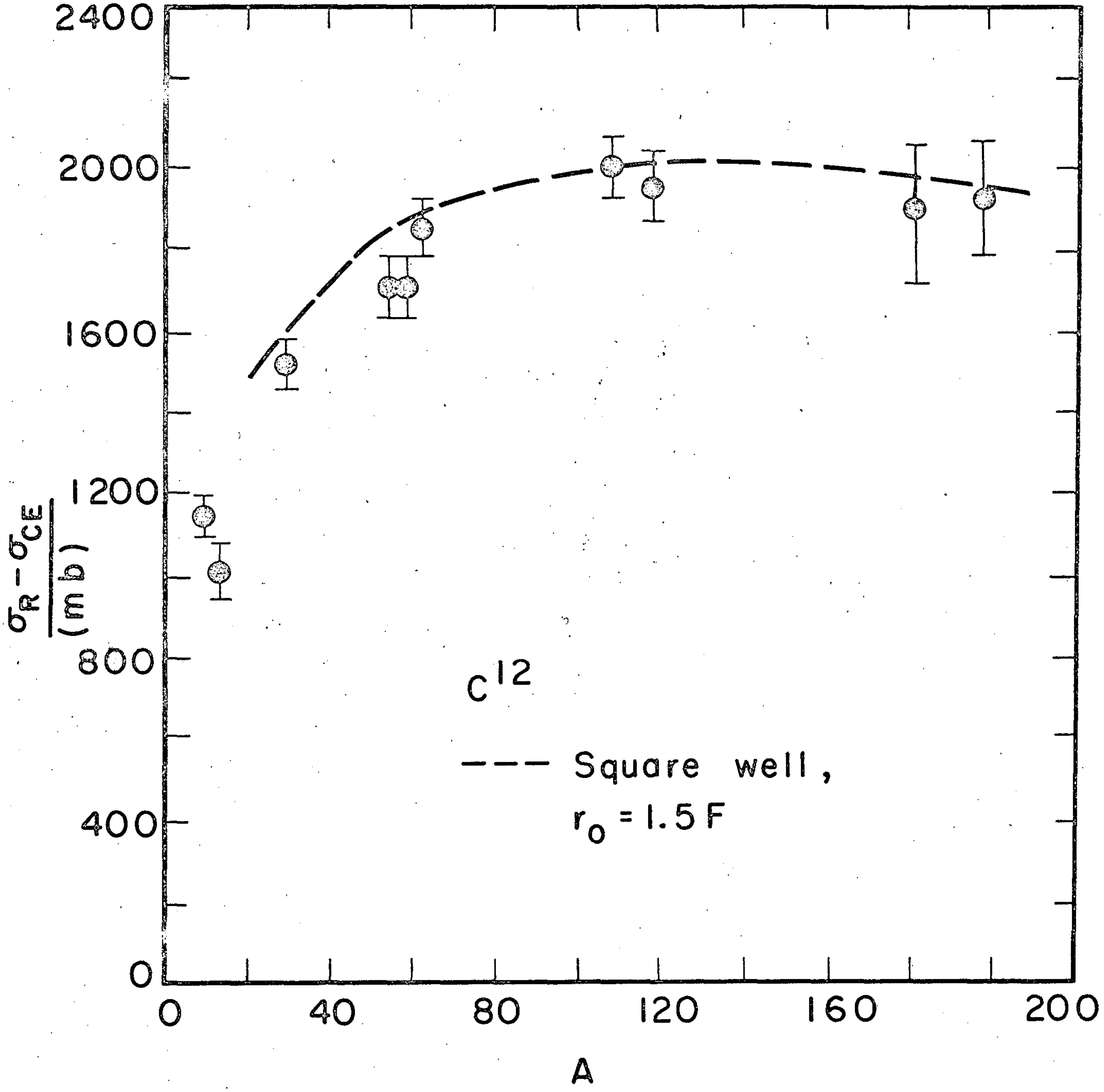

Fig. 3

MU-30011

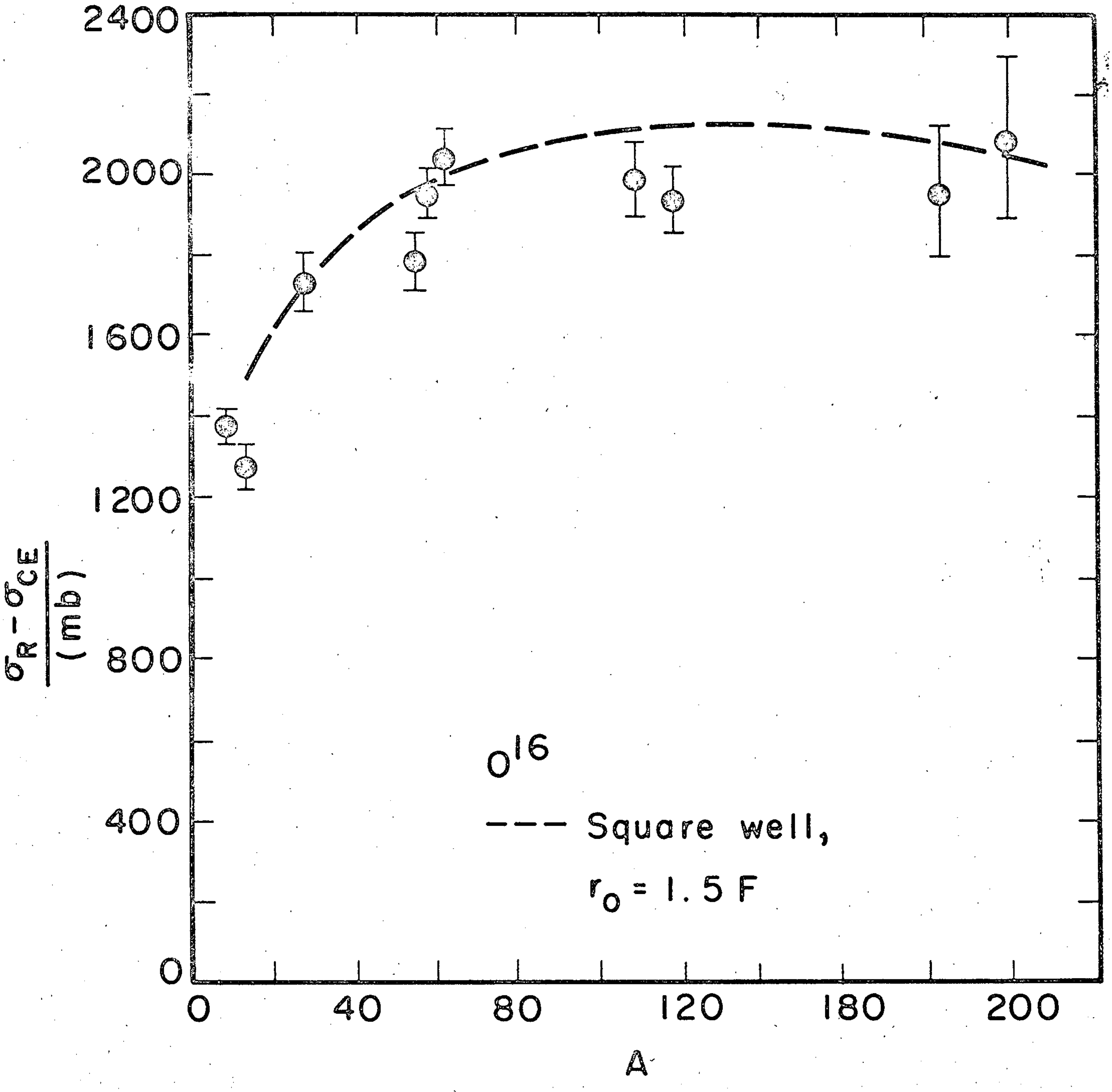

Fig. 4

MU-30012

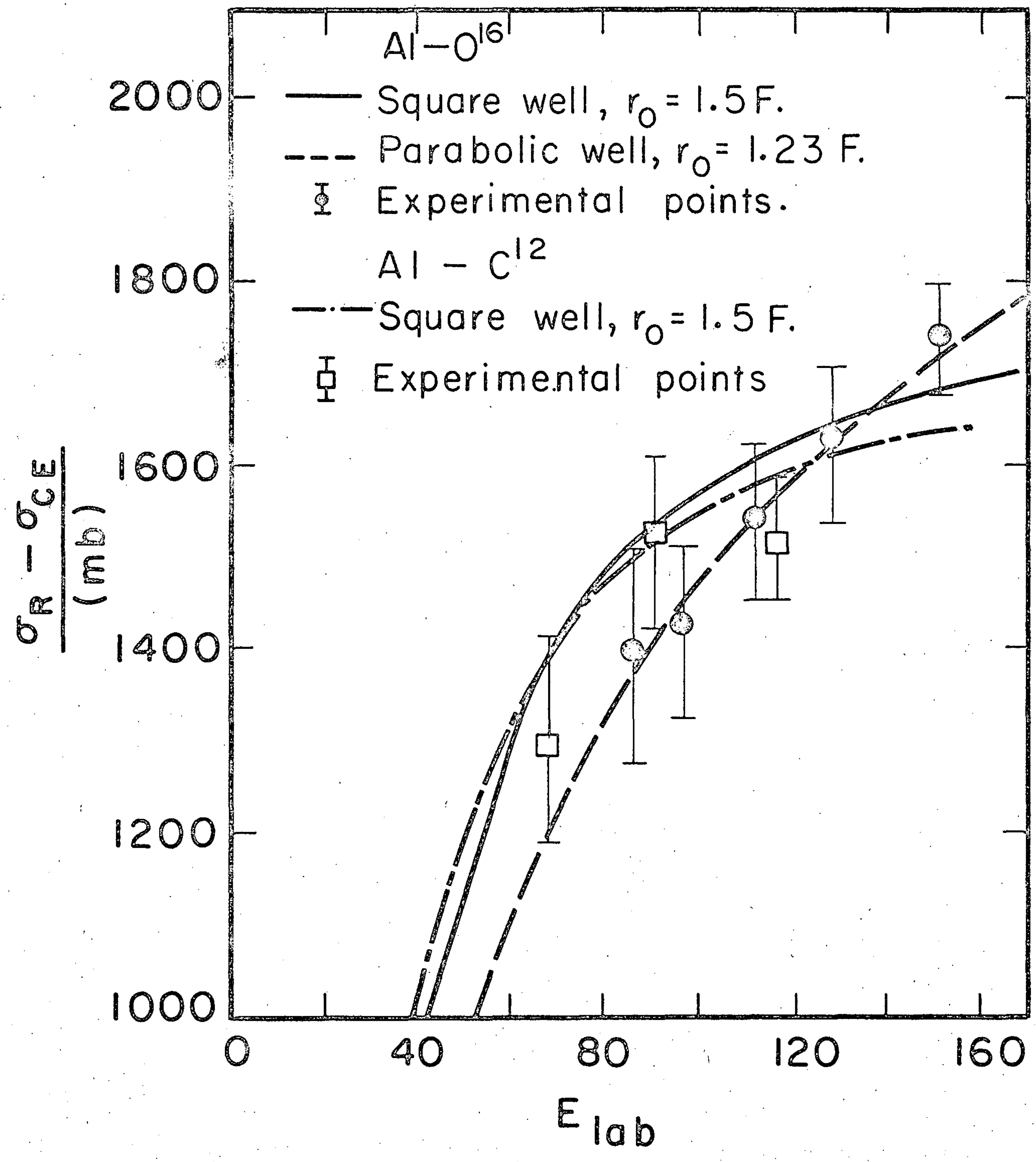

Fig. 5

MU-30013

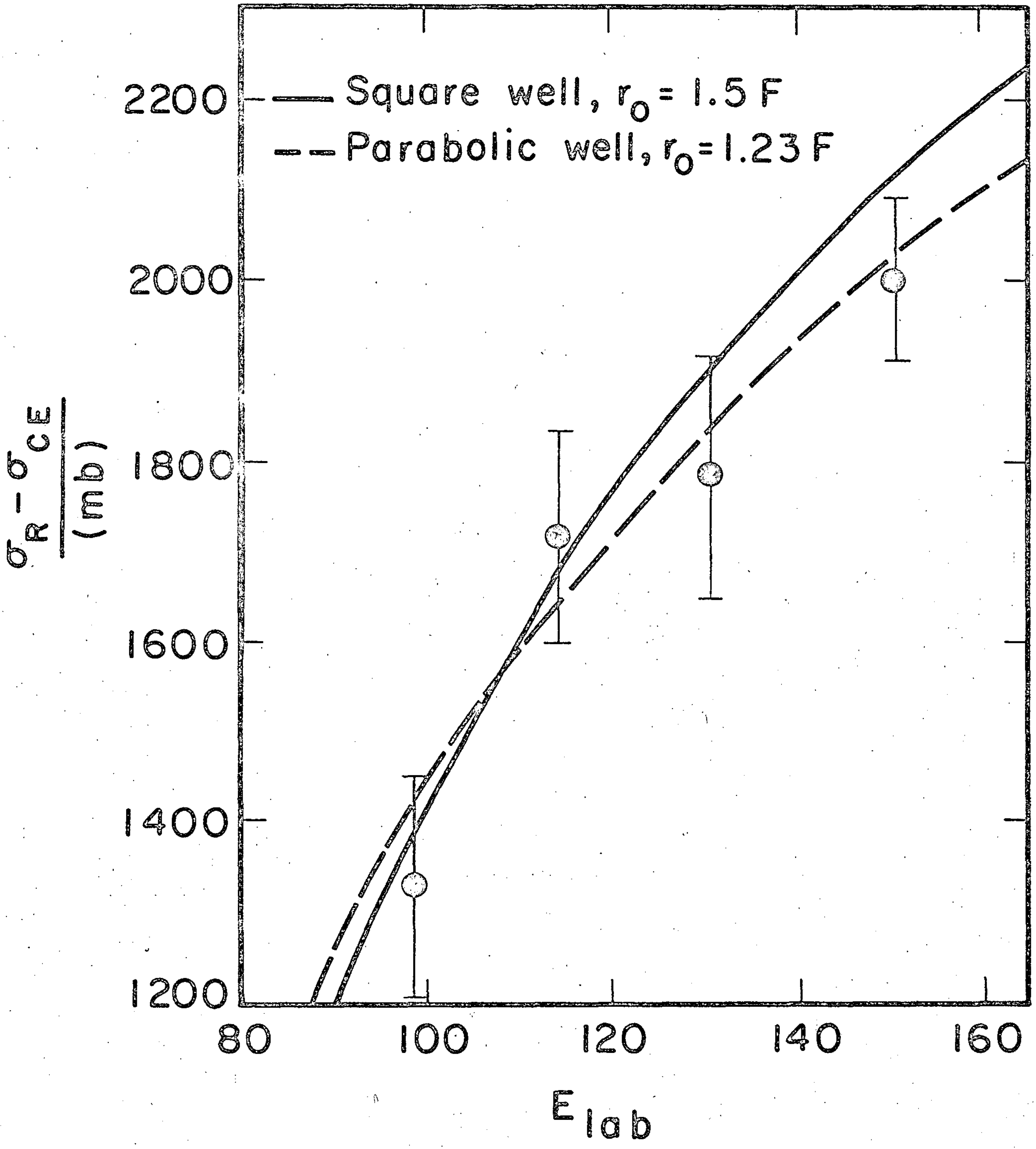

Fig. 6

MU-30010