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TOTAL REACTION CROSS SECTIONS FOR HEAVY IONS

Bruce Wilkins and George Igo

April, 1963
TOTAL REACTION CROSS SECTIONS FOR HEAVY IONS
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April, 1965

We have measured \( \sigma_R \), the total reaction cross section, for 150 MeV \(^{16}\text{O}\) ions and 114 MeV \(^{12}\text{C}\) ions on the elements Be, C, Al, Fe, Ni, Cu, Ag, Sn, Ta, and Au. The energy dependence of \( \sigma_R \) for \(^{16}\text{O}\) on Al and Ag and \(^{12}\text{C}\) 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 \( 1 \bar{2} 3 4 5 \) 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 \( I_0 \) i.e. \( I_0 - I = 1 \bar{2} 3 4 5 \) 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 \( \sigma_R \) is obtained from the following relationship:

\[
\frac{I_0 - I}{n \times I_0} - \frac{I_0 - I}{n \times I_0} = \sigma_R + \sigma_{\text{corr}}
\]
where \( n \) is the target density and \( x \) the target thickness. The quantity \( \sigma_{\text{corr}} \) 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 \( 1 \ 2 \ 3 \ 4 \ 5 \) events. The angles \( \theta' \) and \( \theta'' \) shown in figure 2 were adjusted so that the correction for elastically scattered particles outside of \( \theta' \) and the inelastically scattered particles within \( \theta'' \) 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 cut 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 \( \theta' \), inelastic
events between \( \theta' \) and \( \theta'' \) which proceed through the first few low lying
levels which the surface barrier detector cannot resolve and inelastic
events within \( \theta'' \) which strike counter 5 and cancel out the event. Thus
the correction term is defined:

\[
s_{\text{correction}} = \int_{\theta'}^{\pi} \frac{d\sigma}{d\Omega} \, d\Omega - \int_{\theta'}^{\theta''} \frac{d\sigma}{d\Omega} \, d\Omega - \int_{\theta''}^{\theta''} \frac{d\sigma}{d\Omega} \, d\Omega
\]

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 \( I_0 - I/L_0 \) as a function of \( \theta' \) and \( \theta'' \). 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 \( \sigma_R \).

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

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

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

$$V = \frac{Z_1Z_2e^2}{r} - V_0 \exp \left(-\frac{r-r_0(A_1^{1/3} + A_2^{1/3})}{d}\right)$$

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 $\sigma_R$ predictions
of this model for $^16O$ on Al using $r_0 = 1.23\alpha$, $V_0 = -70$ MeV and $d = .40\alpha$.

Figure 6 illustrates the energy dependence of $\sigma_R$ for $^16O$ on Ag.
The theoretical predictions of $\sigma_R$ 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 $\sigma_R$ results for $^{12}C$ and $^{16}O$ on $U$ (1850 ± 90 mb and 1970 ± 75 mb respectively at the appropriate energy) measured by Viola and Silkeland$^6$ 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 $\sigma_R$ 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 $^{12}C$ ions from several elements. The $\sigma_R$ 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 $^{12}C$ ions used in the elastic scattering and $\sigma_R$ 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 $\sigma_R$. 
FOOTNOTE AND REFERENCES

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

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 $\sigma_R - \sigma_{CE}$ versus $A$ for 114 MeV $^{12}$C ions. The dashed curve is the square well model predictions of $\sigma_R$ for $r_0 = 1.5f$.

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

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

Figure 6. The energy dependence of $\sigma_R - \sigma_{CE}$ for $^{16}$O on Ag. The curves represent the theoretical predictions of $\sigma_R$ using the square well model and the parabolic model. The dots are the experimental points.
Fig. 1
Collimator counter no. 4
0.050-in i.d.

Beam

Backscatter collimator
0.060 in. i.d.

Photomultiplier

Collimator

Semiconductor detector

Plastic scintillator
no. 5
(stopping counter)

Target

Thin light reflecting foils

Dual stopping counter

Fig. 2
Square well, \( r_0 = 1.5F \)

![Graph showing \( \sigma_R - \sigma_{CE} \) vs. A for \( ^{12}C \)]
\[
\frac{\sigma_R - \sigma_{CE}}{(\text{mb})}
\]

--- Square well,
\[ r_0 = 1.5 F \]

Fig. 4
Al – O^{16}

- Square well, r_0 = 1.5 F.

- Parabolic well, r_0 = 1.23 F.

\# Experimental points.

Al – C^{12}

- Square well, r_0 = 1.5 F.

\# Experimental points
Square well, \( r_0 = 1.5 \) F

Parabolic well, \( r_0 = 1.23 \) F

Fig. 6