Total Reaction Cross Sections of Several Nuclei for 61-Mev Protons*

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The total reaction cross sections of C, A, Fe, and Sn for 61-Mev protons have been measured by a beam attenuation technique. This technique is described, and the results are presented and compared with total reaction cross sections for neutrons and with optical model calculation.

TO the present time, attempts to find unique sets of the parameters characterizing the optical model of the nucleus have been unsuccessful.[1] This is at least partially due to the lack of complete experimental data for the three phenomena which the model is capable of predicting. Concerning the proton nucleus interaction, accurate measurements of the angular distribution for elastic scattering have been available for some time, measurements of polarization have recently become available, but in the energy range from several Mev to several hundred Mev essentially no experimental measurements of the total reaction cross section have been available until the set of experiments described in this and a preceding paper were performed. Since the optical model is capable of predicting all of the three phenomena just listed, it is not hard to understand why a lack of experimental data for all of them would make it impossible to obtain an unambiguous determination of the parameters characterizing the model from an analysis of experiment.

In the intermediate energy range it is generally not possible to make an accurate measurement of the total reaction cross section of nuclei for protons by measuring the cross sections for each of the various possible reactions which the protons can produce. There are usually a large number of possible reactions, some of which are difficult to detect. Furthermore, it would seem difficult to measure the total reaction cross section by a beam attenuation technique because protons lose energy by ionization in passing through an attenuator. If good energy resolution is required, the attenuator must be thin compared to the range of the proton and, as a consequence, the attenuation is so small that it would be extremely difficult to measure with good statistical accuracy. It is for these reasons that total reaction cross sections of nuclei for protons are difficult to measure in the intermediate energy range.

However, a technique has been developed recently at the University of Minnesota which overcomes the problems of the very small attenuations which are

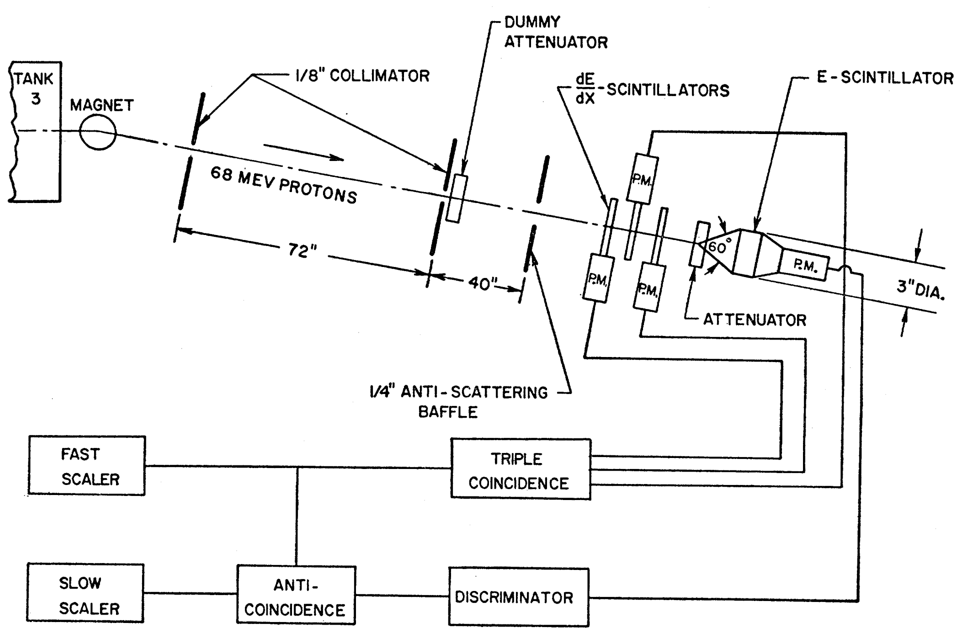

FIG. 1. Schematic of experimental equipment.

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[1] *Proceedings of the International Conference on the Nuclear Optical Model, Florida State University Studies, No. 32* (The Florida State University, Florida, 1959).

TABLE I. Total reaction cross sections for 61 ± 4.5 Mev protons.

Element	Uncorrected value (mb)	Elastic scatt. corrections (mb)	Inelastic scatt. correction (mb)	σ_R final result (mb)
Carbon	208 ± 10	32 ± 6	24 ± 6	200 ± 13
Aluminum	414 ± 21	40 ± 10	18 ± 10	392 ± 25
Iron	644 ± 33	52 ± 20	25 ± 10	617 ± 40
Tin	1030 ± 66	60 ± 20	25 ± 10	995 ± 70
Lead	1490 ± 71	60 ± 20	60 ± 20	1490 ± 77

encountered in applying the beam attenuation technique.[2] Measurements of the total reaction cross section of C, A, Fe, Sn, and Pb for 34-Mev protons, using this technique, were recently reported in another journal.[3]

In this paper we report similar measurements of the total reaction cross sections of the same elements for 61-Mev protons.

EXPERIMENTAL TECHNIQUE

Since the details of the experimental technique have been described before, we present here only an outline. Consider Fig. 1. A collimated beam of 68-Mev protons passes through a set of three thin plastic scintillation counters (total thickness = 2.5 Mev) through an attenuator (9 Mev), and into a thick plastic scintillator in which it stops. If a proton is absorbed in the attenuator, a count will be produced by the thin scintillators, which are connected in coincidence, but not by the thick scintillator. This will cause an anticoincidence count to be recorded. In the experiment one measures the number of anticoincidence counts ΔI, and the number of coincidence counts I which is equal to the number of protons entering the apparatus. These two numbers are related to a cross-section σ by the equation

$$\Delta I/I = Nx\sigma, \tag{1}$$

where Nx is the number of nuclei per cm^2 in the attenuator. Equation (1) is only valid if $Nx\sigma \ll 1$, but this is always satisfied in these experiments as $Nx\sigma \sim 10^{-3}$.

Several corrections must be made before the cross-section σ can be equated to the total reaction cross section. The most important arises from the fact that anticoincidences are recorded even if the attenuator is removed. This is primarily due to events in which the proton undergoes a nuclear reaction before stopping in the thick scintillator, thereby producing a pulse of reduced height which actuates the anticoincidence circuit. This is corrected for by measuring, for the same number of coincidence counts, both ΔI, the anticoincidences with the attenuator in place, and $\Delta I'$, the anticoincidences with the attenuator removed, and then making a subtraction. When the attenuator is out, a dummy attenuator must be inserted in front of the equipment in order to keep the energy of the protons incident on the thick scintillator constant so that the number of spurious anticoincidences will be constant. Thus Eq. (1) must be replaced by the equation

$$(\Delta I - \Delta I')/I = Nx\sigma. \tag{2}$$

Additional corrections must be made because the cross-section σ in Eq. (2) is not the total reaction cross section, but instead, is

$$\sigma = \sigma_R + \int_\theta^\pi (d\sigma/d\Omega)_{el} d\Omega - \int_0^\theta \int_{E_{\max}}^{E_{\max}-\Delta E} (d^2\sigma/d\Omega dE)_{di} d\Omega dE, \tag{3}$$

where σ_R is the total reaction cross section; $(d\sigma/d\Omega)_{el}$ is the cross section for elastic scattering; $(d^2\sigma/d\Omega dE)_{di}$ is the cross section for emitting an inelastic proton, or other charged particle, into solid angle $d\Omega$ and energy interval dE; θ is the half opening angle of the cone subtended by the thick scintillator as seen at the attenuator; $E_{\max}$ is the maximum proton energy entering the thick scintillator; and $E_{\max} - \Delta E$ is the energy bias on the thick scintillator input of the anticoincidence circuit. The single integral corrects for the fact that an elastic scattering at an angle larger than θ will be measured as an anticoincidence. The double integral corrects for charged particles emitted from reactions at small angles and high energies which produce a count in the thick scintillator and prevent an anticoincidence from being recorded.

RESULTS

A summary of all our results is shown in Table I. The uncorrected values of the cross sections as obtained from Eq. (2) are given in the first column. The indicated errors are purely statistical and correspond to typical values of $I \approx 5\cdot10^5$, $\Delta I = 1.6\cdot10^4$, $\Delta I' = 1.2\cdot10^4$. Nx was obtained by weighing the attenuators. Column 2 gives the corrections due to the first integral in Eq. (3).

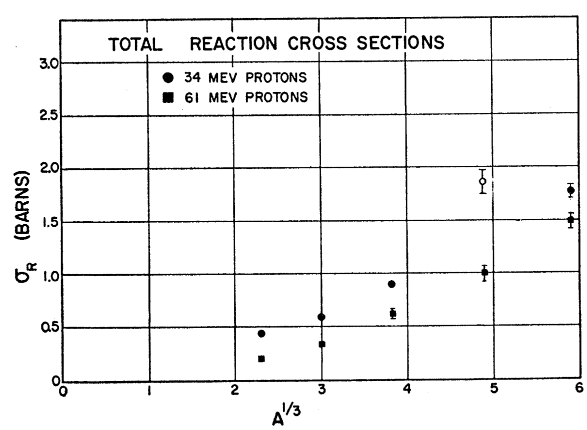

FIG. 2. Total reaction cross sections for 34- and 61-Mev protons.

[2] T. J. Gooding and R. M. Eisberg, Annual Progress Report, University of Minnesota, 1957–58 (unpublished).
[3] T. J. Gooding, Nuclear Phys. (to be published).

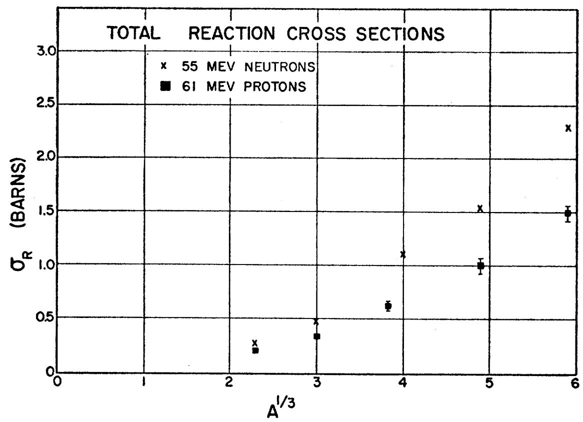

FIG. 3. Total reaction cross sections for 55-Mev neutrons and 61-Mev protons.

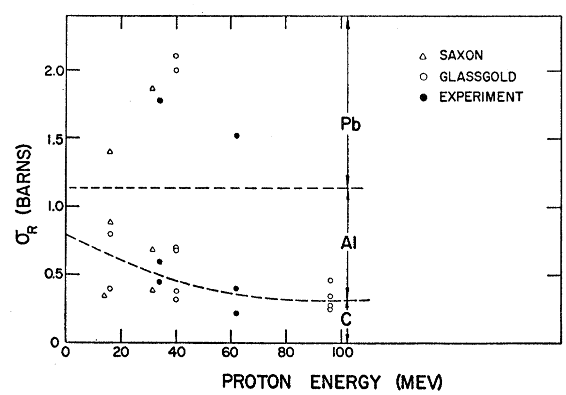

FIG. 4. Comparison of measured total reaction cross sections with optical model calculation.

They were found by integrating elastic scattering angular distributions at 30 Mev,[4] 40 Mev,[5] and 90 Mev,[6] from 30° to 180° and interpolating to 61 Mev. For carbon we could also use preliminary elastic scattering data at 68 Mev.[7]

The second integral of Eq. (3) is represented by Column 3. We used data at 40 Mev[3] and 90 Mev[6] to estimate this correction. The relative errors on both corrections are large but contribute but little to the total error of the cross-section values.

The final corrected numbers for the total reaction cross sections in millibarns are given in Column 4 of Table I. These cross sections were measured at the energy 61±4.5 Mev; the 9 Mev range corresponds to the thickness of the attenuator.

In addition to these measurements we checked Gooding's results on carbon, tin, and lead at 34 Mev with our different experimental equipment. We found very good agreement except for the point on Sn where we got a considerably lower value.

Our results are plotted against $A^{\frac{1}{3}}$ in Fig. 2 together with Gooding's data at 34 Mev. It is evident that the cross sections decrease with energy. The same holds true for a comparison neutron data at 26 Mev[8] and 55 Mev.[9] Figure 3 shows a comparison of our data with neutron cross sections measured at 55 Mev. Again our values are low due to the increased energy. For heavier elements however there seems to be an additional reduction of our values which might be due to a coulomb repulsion effect. Figure 4 shows the experimental values for proton total reaction cross sections at 34 Mev and 61 Mev and theoretical predictions of Saxon[10] and Glassgold.[11] These are calculated from best fits to elastic scattering angular distributions at 17 Mev and 31 Mev (Saxon), 40 Mev and 95 Mev (Glassgold). Comparison of the predictions with experimental values indicates that it would be worthwhile to repeat their work using both the elastic scattering data and the total reaction cross-section data. It is to be hoped that such analyses would lead to a less ambiguous determination of the optical model parameters.

[4] J. Leahy, University of California Radiation Laboratory Report UCRL-3273, February, 1956 (unpublished).
[5] N. M. Hintz, Annual Progress Report, University of Minnesota, 1957 (unpublished).
[6] Gerstein, Niederer, and Strauch, Phys. Rev. **108**, 427 (1957).
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[8] Private Communication from Livermore Cyclotron Group.
[9] R. Voss and R. Wilson, Proc. Roy. Soc. (London) **A236**, 41 (1956).
[10] Melkanoff, Nodvik, and Saxon, Phys. Rev. **106**, 793 (1957).
[11] A. E. Glassgold and P. J. Kellogg, Phys. Rev. **109**, 1291 (1958).