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Berkeley, California

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We have measured the reaction cross section σ_R for 40 MeV alpha particles, and we compare it with the prediction σ_I of the Igo potential.[1,2] The ratio σ_R/σ_I plotted against $A^{2/3}$ (A, the atomic number) deviates from unity in a systematic fashion. A straight line with a slope of 5.5×10^{-3} fits the data in figure 1. Superimposed on this trend, σ_R/σ_I dips by 18% near A = 28 protons as was also noted in the 10 MeV proton measurements.[3]

The experimental apparatus used in the reaction cross section measurements (See Fig. 2) has been described in detail elsewhere[4] and will not be discussed here except where parameters of the experiment have been altered because of the change in the projectile. The raw cross section σ, obtained from the target-in and target-out measurements, is listed in Table I. Three principle corrections must be made to σ. A "dummy" foil is placed ahead of the counters when the target is out so that the energy incident on the stopping counter will be the same in the target-in and target-out measurements. The alpha particle energy in counter 3 is therefore different for the two configurations. Fortunately the counter 3 scattering-out correction η_3 can be measured quite accurately.[3] A second correction σ_{el} is due those elastic events where scattering occurs outside of the solid angle subtended by counter 5, the stopping counter. The corresponding

plane angle θ_5 (lab) was set at 28.7° for light and intermediate elements. For elements heavier than tin, θ_5 was set at 43.0°. The third correction σ_{in} is comprised from part of the inelastic and reaction events scattered into the solid angle subtended by the stopping counter. In order to facilitate the separation of elastic events from the inelastic and reaction events, a degrader foil is placed between the target and counter 5. The thickness of the degrader foil was adjusted so that 25 MeV alpha particles are stopped by it.

The correction σ_{in} is due to several sources. The first is the correction due to (α,α') direct interaction events.[5-9] (evaporation spectrum alpha particles will stop in the absorber). The correction due to (α,p) events has been obtained using the Nuclear Monte Carlo Evaporation Model (NMCEM).[10] Experimental data,[11-15] fit with this model, was used to fix the parameters of the model. The predictions of the model for (α,p) cross sections then were calculated. Instead of using a parameter for shell corrections fit to each element as was done in reference 10, Cameron's empirical shell correction[16] was used. This gave consistently good fits to the experimental data throughout the periodic table. The (α,d) and (α,t) corrections were also calculated and found to be small (about 5 mb). The (α,He^3) reaction did not contribute because of the large Q-value associated with this reaction. The NMCEM does not treat the direct interaction (α,p) events properly. To compensate for this the NMCEM calculations were adjusted to fit the average of the peaked forward, direct interaction distributions[17] determined experimentally. It is therefore possible that we have underestimated the contribution of the direct interaction (α,p) events especially in the light elements where σ_R/σ_I is < 1 (see Fig. 1). Unfortunately, no measurements at the extreme

forward angles corresponding to the solid angle intercepted by counter 5 exists to check on this. The values predicted by NMCEM when normalized to the measured σ_R fit the excitation function peaks within 1 MeV, and the absolute magnitude of the excitation function data was usually fit within 20%.

The elastic scattering correction σ_{el} has been estimated from the literature.[7,8,18-20] The elastic scattering data is the sum of shape elastic scattering σ_{SE} and compound elastic scattering σ_{CE}. The latter is not included in the measured quantity in these experiments. The final result $\sigma_R - \sigma_{CE}$, where σ_R is the total reaction cross section, is listed in the last column of Table I. The results for $(\sigma_R-\sigma_{CE})/\sigma_I$ are also shown in Figure 1 where the deviation from unity can be seen. The most prominent features are the agreement with unity for $A^{2/3} \geq 16$, the dip near 28 proton nuclei, and a 10% deviation for light elements. It has been emphasized above that some of this deviation could be due to an underestimate of the (α,p) direct interaction cross sections. The data can be fit by a straight line with slope of 5.5×10^{-3} on this plot <u>versus</u> $A^{2/3}$ if the dip near 28-proton nuclei is neglected. It also should be noticed that we plot $(\sigma_R - \sigma_{CE})/\sigma_I$ <u>versus</u> $A^{2/3}$. However, at 40 MeV, σ_{CE} is expected to be small, and we do not believe that the dip is due to a resonance in σ_{CE}. Instead it probably reflects the decrease in the cross sectional area of nuclei in this region. The same effect was seen in $\sigma_R - \sigma_{CE}$ for 10 MeV protons,[3,4] but not seen in the 22.4 MeV deuteron reaction cross section data.[21] With the completion of these alpha particle σ_R measurements it is possible to obtain the mean free path of alpha particles in nuclear matter λ_{NE}. The attenuation of 18 MeV flux of alpha particles[22] in Ar (arrows in Figure 3) for the region where the Igo potential[1] is well defined has been used. The amount of nuclear material traversed for a 1/e attenuation can be obtained by

numerical integration (see Figure 3). In Figure 3 contours for a Woods-Saxon type nuclear distribution[23] consistent with charge density measurements[24] are plotted. The half-value radius is $1.2A^{1/3} \times 10^{-3}$cm; and the diffuseness parameter, 0.6×10^{-13}cm; and A, the atomic weight. However, it should be noted that these measurements are sensitive to $\langle r^2 \rangle$ rather than the shape of the charge distribution tail. The justification for putting credence in this shape for the tail of the distribution is that the potential tail[1,2] has this shape, and Hartree-Fock self-consistent calculations show that the nuclear distribution must therefore have a similar shape. The mean free path obtained in this way from the data up to 50 MeV may be expressed in terms of the mean free path in nuclear matter of uniform density $\rho o/20$ where ρo is the central density. It was decided to express it in terms of a surface density $\rho o/20$ rather than in terms of a central density ρo because the Pauli Principle may have a profound effect on the mean free path at low energies in the central part of the nucleus.

The values of σ_R at 40 MeV obtained in this experiment can be compared with values obtained at higher energies.[25-27] There is a slow change with energy amounting to about 50% in the energy range 4×10^1 MeV to 10^6 MeV. It is therefore reasonable to assume that λ_{NE} is inversely proportional to σ_R. Figure 4 shows a plot of λ_{NE} <u>versus</u> energy thus obtained. A straight line is drawn through the experimental points. The slow overall variation with energy and the small average value (12F) are apparent. These quantitative values for λ_{NE} are of considerable importance in interpreting attenuation effects in nuclear reactions involving alpha particles.[28]

Table I. The raw cross section σ, the counter 3 scattering-out correction η_3, the inelastic and reaction scattering correction σ_{in},[5-17] the elastic scattering correction σ_{el}[7,8,18-20] and the non-elastic cross section $\sigma_R - \sigma_{CE}$.

Element	σ (mb)	η_3 (mb)	σ_{in} (mb)	σ_{el} (mb)	$\sigma_R - \sigma_{CE}$ (mb)
Be	789 ± 7	9 ± 4	36 ± 7	51 ± 3	783 ± 11
C	894 ± 12	12 ± 6	60 ± 9	65 ± 3	901 ± 16
Al	1105 ± 17	23 ± 10	54 ± 8	41 ± 2	1141 ± 21
Ti	1422 ± 30	32 ± 18	77 ± 12	31 ± 5	1500 ± 37
V	1397 ± 32	43 ± 18	80 ± 12	31 ± 5	1480 ± 39
Fe	1363 ± 34	36 ± 20	68 ± 12	31 ± 5	1436 ± 42
Ni	1271 ± 28	40 ± 18	79 ± 15	36 ± 2	1354 ± 37
Cu	1526 ± 36	42 ± 19	128 ± 26	50 ± 3	1646 ± 48
Zn	1511 ± 37	42 ± 19	129 ± 26	48 ± 3	1639 ± 49
Zr	1753 ± 48	45 ± 32	97 ± 23	124 ± 7	1771 ± 63
Nb	1704 ± 52	53 ± 27	105 ± 24	134 ± 7	1728 ± 64
Mo	1792 ± 65	47 ± 34	103 ± 24	160 ± 10	1782 ± 78
Ag	1881 ± 52	61 ± 27	99 ± 25	195 ± 10	1846 ± 64
Sn	1858 ± 65	59 ± 34	97 ± 25	246 ± 13	1768 ± 78
Ta	1846 ± 83	79 ± 44	97 ± 25	136 ± 7	1886 ± 97
Au	1931 ± 63	88 ± 39	100 ± 25	200 ± 10	1919 ± 79
Pb	1953 ± 62	89 ± 42	100 ± 30	250 ± 13	1892 ± 82
Bi	1923 ± 87	100 ± 46	100 ± 30	270 ± 20	1853 ± 105
Th	1973 ± 84	92 ± 51	100 ± 30	404 ± 20	1761 ± 105

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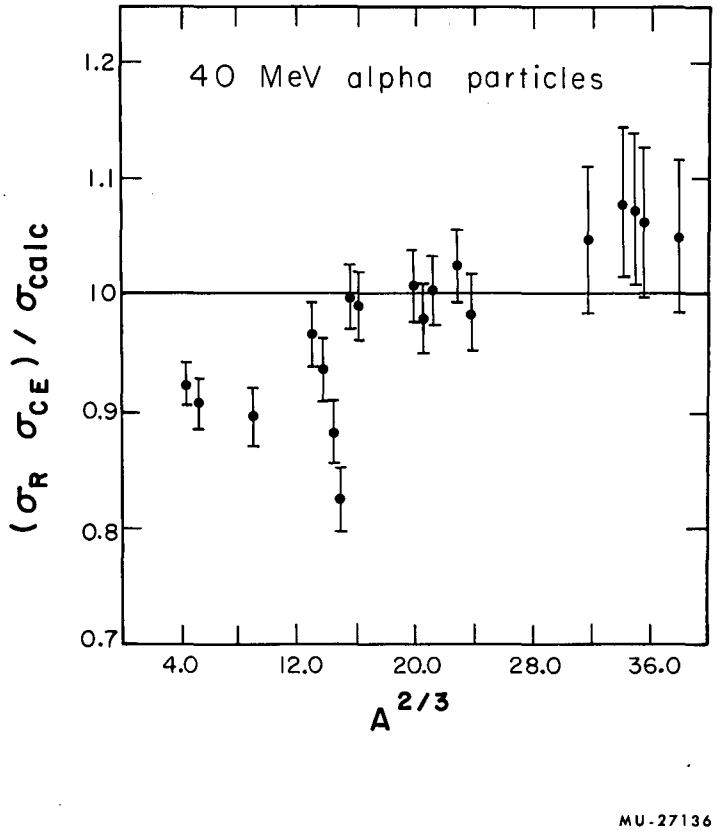

Fig. 1. The ratio of the non-elastic cross section for 40 MeV alpha particles σ_R - σ_{CE} and the corresponding theoretical value σ_I versus the two-thirds power of A.

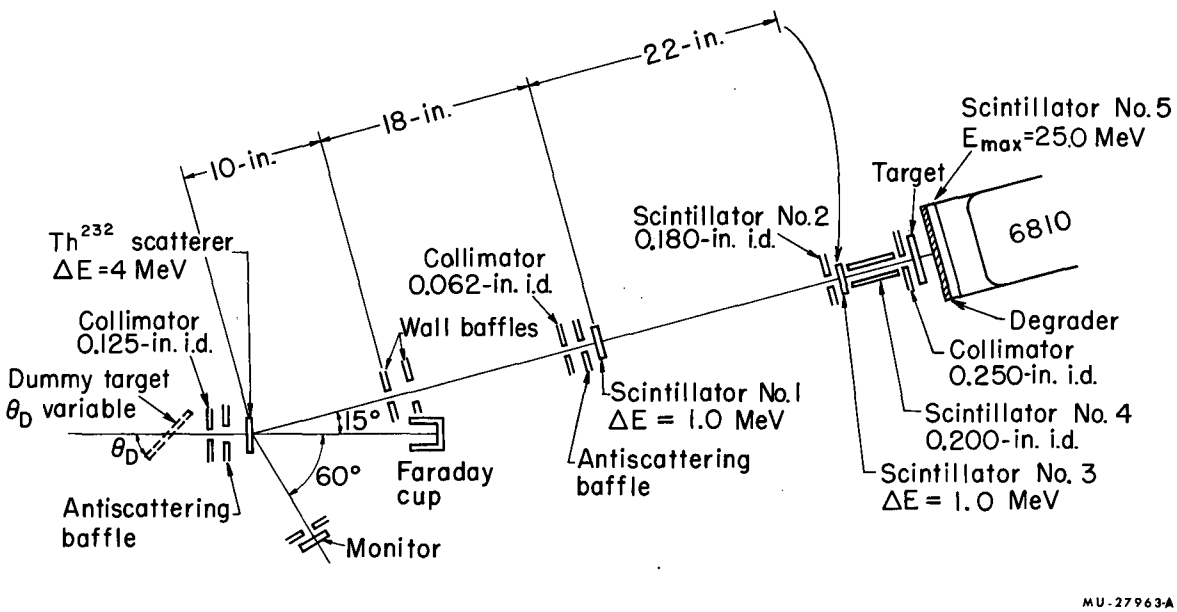

Fig. 2. Schematic diagram of the experimental apparatus.

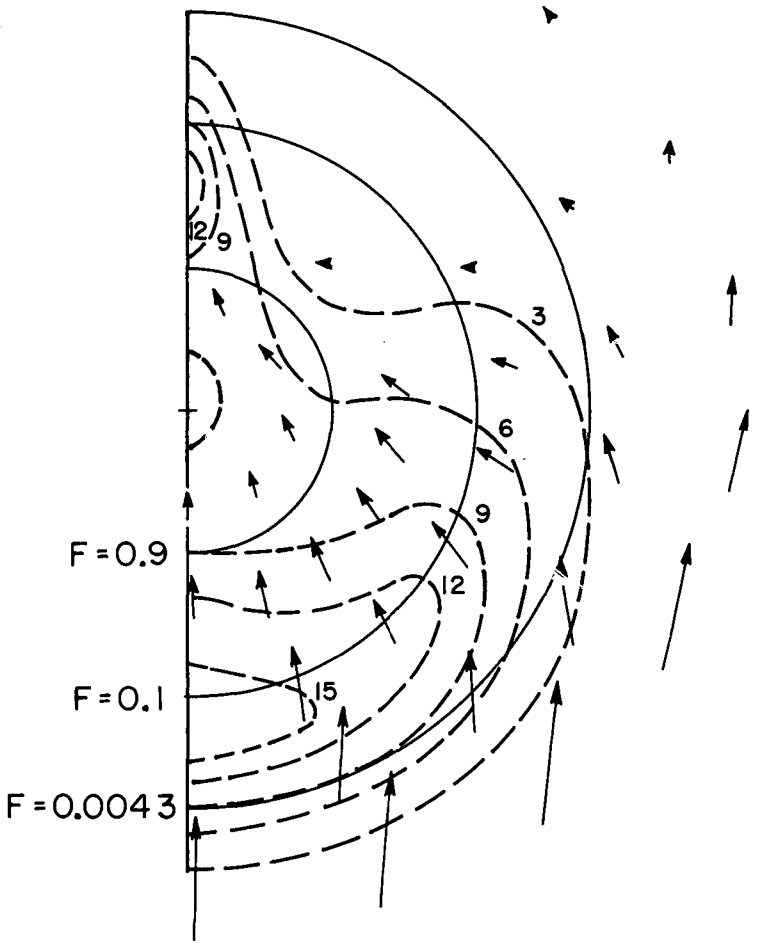

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Fig. 3. The flux of 18 MeV alpha particles in Ar[1,2,22] (arrows), the flux absorption (dashed lines), and the nuclear matter contours (solid lines).[16]

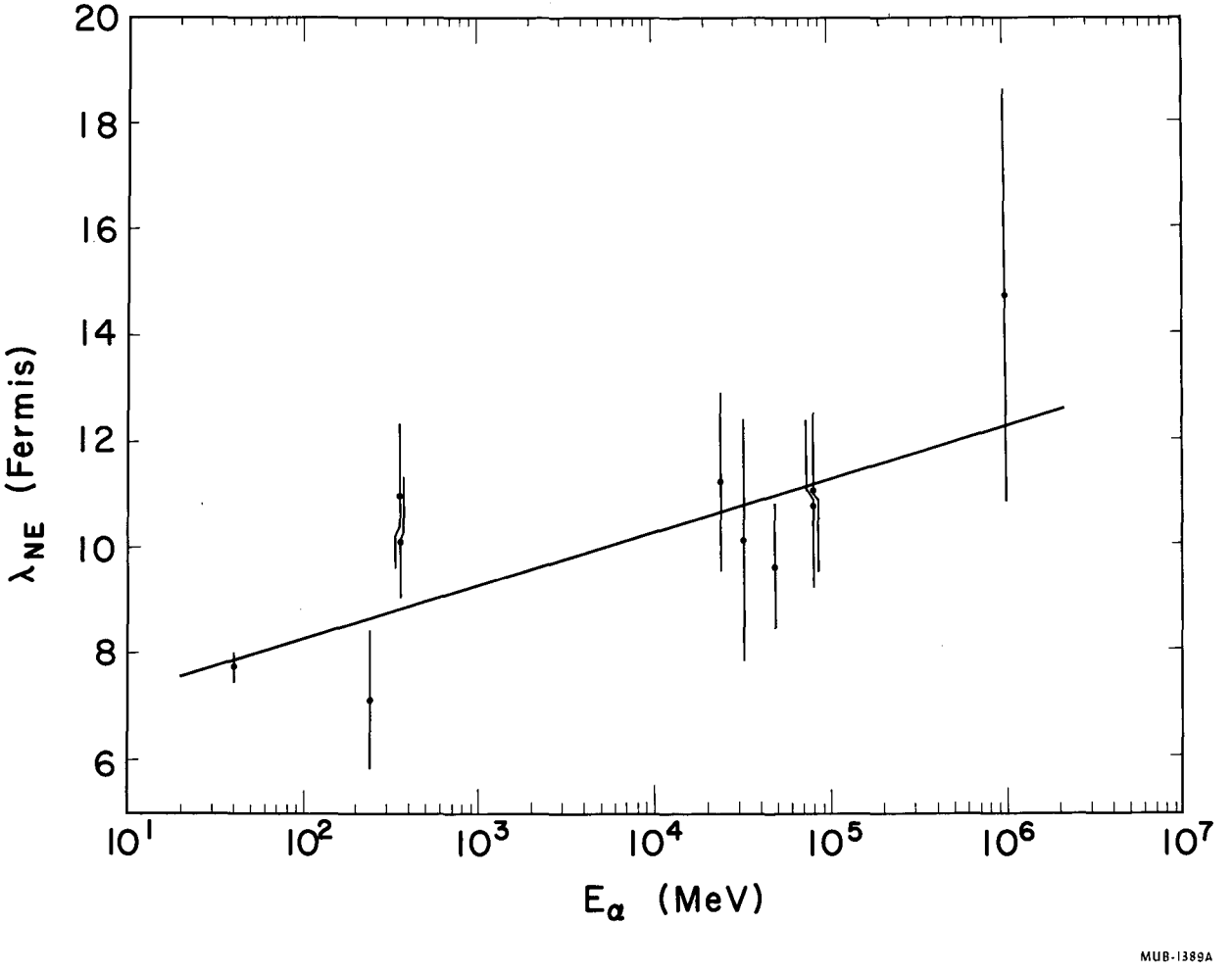

Fig. 4. The non-elastic mean free path λ_{NE} versus energy in nuclear matter of density $\rho o/20$ where ρo is the central nuclear density.

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