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# Average reaction cross sections for 74- to 112-MeV $\alpha$ particles on $^{127}$I and $^{133}$Cs

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The average reaction cross section for 74- to 112-MeV $\alpha$ particles on $^{127}$I and $^{133}$Cs was measured by a new method using a magnetic spectrograph and a CsI scintillation detector. The result, $\sigma_R = 2220 \pm 50$ mb, is in good agreement with optical model calculations and finite-range microscopic calculations. Zero-range microscopic calculations underpredict $\sigma_R$ by about 10%, while strong absorption theories overpredict $\sigma_R$ by large amounts.

## I. INTRODUCTION

The total reaction cross section $\sigma_R$ is important for several reasons. It provides information about the radii and transparency[1] of nuclei and gives clues to their structure.[2] It is predicted by most nuclear reaction models, including the optical and Fresnel[3] models. For heavy-ion systems it is particularly useful to know $\sigma_R$ when the partial cross sections for several reaction channels are also known, since a "missing" cross section may disclose yet-unknown reaction channels.[4]

There are relatively few direct measurements of $\sigma_R$, particularly at low energies. More often this important quantity is deduced from optical model analyses of elastic-scattering data, or from the quarter-point recipe. Therefore, any special methods which can be used to measure $\sigma_R$ are worth pursuing. The data thus obtained place additional constraints upon optical model parameters, and check the assumptions of the quarter-point method.

Recently, we determined[5-7] energy-averaged $\sigma_R$'s for several light projectiles on $^{\mathrm{nat}}$Si from the energy spectra of these projectiles in silicon detectors. For example, $\sigma_R$ for the $\alpha+$Si system was measured for 27- to 92-MeV incident $\alpha$ particles.[6] Since all reactions initiated by $\alpha+$Si have negative $Q$ values, anomalously small pulses signified reaction events while particles losing all their energy through ionization gave normal pulses. The main experimental requirement was that the projectiles be monoenergetic when incident upon the detector, and in particular that they suffer no energy loss in the aperture in front of it. This requirement was met by detecting $\alpha$ particles which had elastically scattered from deuterons; the recoil deuterons also were detected in a telescope whose aperture was so small that it, not the $\alpha$-telescope aperture, determined the coincident geometry.

We now report a similar measurement of the average $\sigma_R$ of 74- to 112-MeV $\alpha$ particles with the $^{127}$I and $^{133}$Cs nuclei in a CsI scintillation detector. This is an interesting case since each of these isotopes has 100% natural abundance. Their average $\sigma_R$ is a meaningful quantity, since all available theoretical predictions differ by less than 2% for the two nuclei. No direct $\sigma_R$ measurements have been reported for this region of the nuclidic chart, but optical-model parameters exist[8,9] for the nearby nuclei $^{130}$Te and $^{140}$Ce.

The present measurement attains significantly higher accuracy than the previous ones, and differs from them in some fundamental ways. Monoenergetic $\alpha$ particles were obtained by small-angle elastic scattering from a thin Au target, and refocused by a spectrograph onto a CsI detector in its focal plane. The horizontal extent of the image was less than half the width of the slit preceding the CsI detector, and a position-sensitive detector (PSD) between the slit and CsI detector measured the vertical displacement of each particle from the median plane. Therefore, suitable gating by the PSD excluded all particles passing near the slit edges.

The result obtained, $\sigma_R = 2220 \pm 50$ mb for 74 to 112 $\alpha$ particles in CsI, agrees with the optical-model predictions and the prediction of the microscopic theory of Bertsch *et al.*[10] employing finite-range nucleon-nucleon forces. It is significantly larger than predictions of other microscopic theories, and much smaller than predicted by strong absorption models.

## II. THE EXPERIMENT

Primary 84-, 100-, and 120-MeV $\alpha$-particle beams from the Kernfysisch Versneller Instituut (KVI) cyclotron, of intensity ~1 to 5 nA, were scattered at 9° from a 150-$\mu$g/cm$^2$ Au target. The energy losses from target stopping power and elastic scattering (~5 and 50 keV, respectively) were so small that the secondary beams entering the spectrograph[11] were highly monoenergetic. Such a scattered beam is preferable to a reduced direct beam at 0°, because of the greater ease of control of the cyclotron and beam-line parameters during the experiment. Cross sections for elastic scattering at this small angle are so large (~100 b/sr) that $\alpha$ particles reaching the detector after inelastically scattering from low-lying $^{197}$Au levels had negligible effect.

The spectrograph produced a line image of the elastic $\alpha$-particle group approximately 1.5 mm wide by 2 cm high. The linewidth was measured by directing the secondary beam onto a silicon PSD, about 4 cm long and covered by a mask containing four rectangular apertures. From the mask "shadow" the position calibration, and then the linewidth, were obtained.

The central component of the measuring telescope was a 1-cm$^3$ CsI scintillation crystal, read by a photodiode and covered by a 25-$\mu$m Al foil. The telescope entrance slit, 5 mm wide by 8 mm high, was made from Ta 3mm thick. The elastic group was centered horizontally in this slit by adjusting the spectrograph magnetic field, as determined by NMR; vertical centering was accomplished by mechanical movement of the detector platform. Large variations in field could be made without changing the counting rate; it was thus verified that the beam was too narrow to strike the vertical edges of the slit. A 500-$\mu$m Si PSD was placed between the slit and the CsI detector and oriented so that it measured the vertical coordinate of the $\alpha$ particles. An event was accepted for analysis only when the PSD output signal showed that the $\alpha$ particle passed within $\pm 2$ mm of the detector axis. Thus, even though the image was taller than the slit, all particles which could have scattered from its top or bottom edges were excluded from consideration.

## III. DATA ANALYSIS

The analysis begins with determination of the reaction probability $\eta(E_0)$, or the probability that a particle incident upon the detector with energy $E_0$ will undergo inelastic scattering or a reaction before being stopped by ionization processes. Since all reactions for the $\alpha+{}^{127}$I and $\alpha+{}^{133}$Ca systems have negative $Q$ values, all such events produce anomalously small pulses.

Energy spectra for $\alpha$ particles in CsI were accumulated with certain gating requirements on the signals from the PSD preceding it. Thus we selected only those $\alpha$ particles which passed within $\pm 2$ mm of the slit center and, of these, only the 50% whose energy losses were closest to the mean energy loss. The energy spectrum for 74-MeV $\alpha$ particles (the residual energy, after 84-MeV $\alpha$'s passed through the PSD and the Al foil) is shown in Fig. 1.

Despite the good resolution achieved ($<1\%$ FWHM) the tail of the full-energy peak was broad enough to mask inelastic scattering to the low-lying states of the two detector nuclei. Since all spectra showed a broad minimum between 5 and 10 MeV missing energy (inset, Fig. 1), we estimated that the number of reaction events with missing energy between 0 to 5 MeV equaled the number between 5 and 10 MeV. The total number of reaction events was then obtained by adding this number to

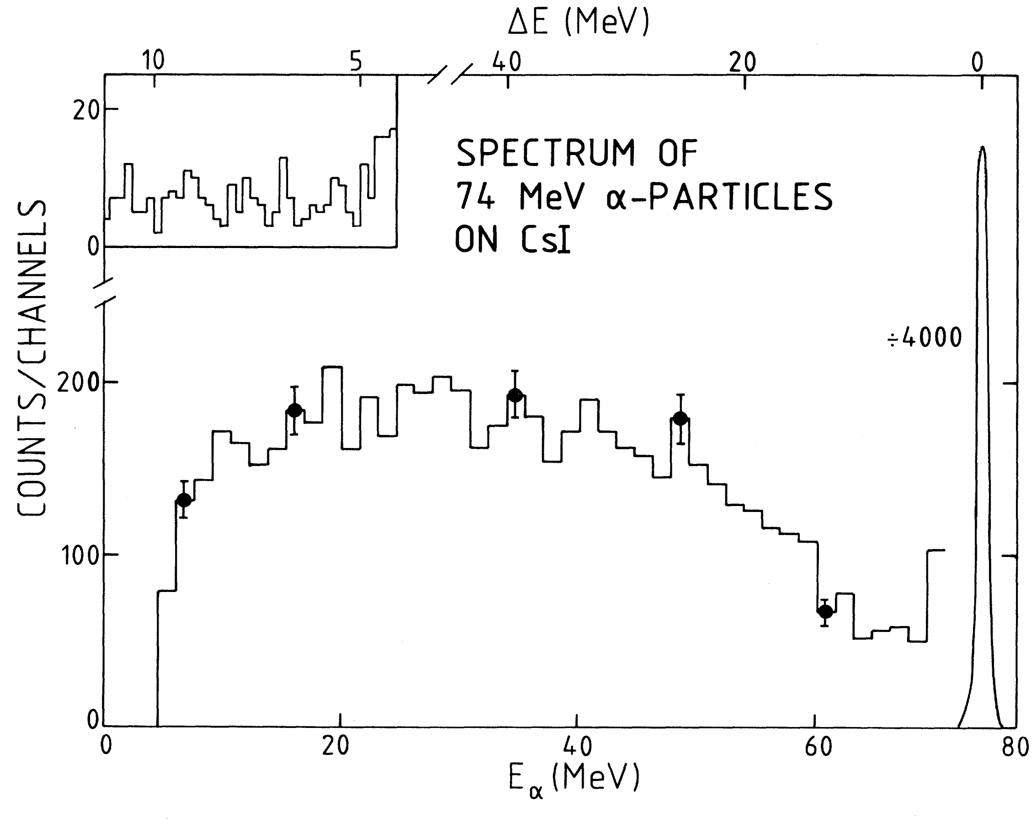

FIG. 1. Recorded energy spectrum of 74-MeV $\alpha$ particles incident upon a 1-cm-thick CsI scintillation detector. Upper scale shows missing energy $\Delta E$ due to nuclear reactions of negative $Q$. Inset shows expanded spectrum in region of reaction tail near the stopped peak. Some typical error bars are shown.

the events observed below $\Delta E_\alpha = 5$ MeV. To conservatively estimate the error thus introduced, an uncertainty equal to half the number of assumed low-missing-energy events was included in quadrature with the statistical uncertainty.

The contamination of our data by large-angle elastic-scattering events was negligible. To lose more than 5 MeV, an $\alpha$ particle must scatter by more than 80° from Cs or I. Using the $^{130}$Te optical model potential we calculated the integrated cross section for such scattering to be less than 0.001 mb.

The measured reaction probability is just the ratio of counts in the reaction tail (including the correction for events with low missing energy) to total counts. Reaction probabilities obtained at the three bombarding energies are given in Table I. Statistically consistent results were obtained in runs with different beam intensities and linear amplifier integration times.

We now define the energy-averaged reaction cross section and show how it is obtained from $\eta$. Consider first $N$ particles traversing matter containing a single nuclear species. The fraction lost to reactions in a path element of length $dx$, in which their energy loss is $dE$, is

$$-dN/N = \nu\sigma\,dx = (\nu\sigma/S)dE \ , \tag{1}$$

where $\nu$ is Avogadro's number and $\sigma$ is the reaction cross section; for convenience we let $S$ be the stopping power $dE/dx$. When Eq. (1) is integrated, and the definition of the reaction probability $\eta$ is introduced, we obtain

$$1-\eta = \exp\left[-\nu\int_0^{E_0}(\sigma/S)dE\right] \tag{2}$$

when the particles have incident energy $E_0$. Similarly, if two target species of mass numbers $A_1$ and $A_2$ are present in equal numbers, and $\eta$ is measured for two incident energies $E_a$ and $E_b$, one can show straightforwardly that

$$\frac{1-\eta_a}{1-\eta_b} = \exp\left[-\nu\int_{E_b}^{E_a}\frac{\sigma_1 A_1+\sigma_2 A_2}{S_1 A_1+S_2 A_2}dE\right] . \tag{3}$$

This experiment therefore measures an average cross section $\bar{\sigma}$ defined by

$$\bar{\sigma} = \int_{E_b}^{E_a}\frac{\sigma_1 A_1+\sigma_2 A_2}{S_1 A_1+S_2 A_2}dE \Big/ \int_{E_b}^{E_a}\frac{A_1+A_2}{S_1 A_1+S_2 A_2}dE \tag{4}$$

which is obtained from the experimental data by the prescription

$$\bar{\sigma} = \ln\left[\frac{1-\eta_a}{1-\eta_b}\right] \Big/ \left[\nu(A_1+A_2)\int_{E_b}^{E_a}\frac{dE}{S_1 A_1+S_2 A_2}\right] . \tag{5}$$

TABLE I. Reaction probability for 74- to 112-MeV $\alpha$ particles incident upon natural CsI.

| $E_\alpha$ (MeV) | $\eta$ (%) |
|---|---|
| 74 | 0.653±0.012 |
| 91 | 1.012±0.020 |
| 112 | 1.487±0.013 |

TABLE II. Energy-averaged reaction cross sections for $\alpha$ particles on CsI.

| Energy interval (MeV) | $\bar{\sigma}_R$ (mb) |
|---|---|
| 74–91 | 2330±150 |
| 91–112 | 2150±110 |
| 74–112 | 2220±50 |

Stopping powers in Eq. (5) were taken from the Williamson[12] tables and are within 1% of those given by Ziegler.[13] The absolute values of the bombarding energies, which define the limits of integration, were known to about 0.5 MeV. Had the nominal values been used, their uncertainties would have compromised the data analysis. However, the spectrograph NMR frequency determined the energies, relative to each other, to much better than 0.1 MeV. When the highest energy was taken to be 120.00 MeV, the two lower ones were found to be 84.52 and 100.12 MeV. After traversing the PSD and the Al foil, the three groups had mean energies 74.15, 91.14, and 112.28 MeV.

Averaged cross sections for these three intervals are given in Table II. The ratio of $\sigma_R$ from 74 to 91 MeV, to that at 91 to 112 MeV, is 1.08±0.08. Optical-model calculations, for example, predict about a 2% increase over that interval which is statistically consistent with this result. The datum for the 74- to 112-MeV interval is most precise since longer runs were taken at the highest and lowest energies. The results for $\sigma_R$ changed by less than 1% when we instead normalized to the lower or middle nominal bombarding energy, since the *difference* in the integration limits in Eq. (5) stayed nearly constant.

## IV. COMPARISON WITH THEORETICAL MODELS

### A. Optical models

Optical-model potential parameters (OMP) were obtained by Leonard, Stewart, and Baron[8] (LSB) for elastic scattering of 42-MeV $\alpha$ particles on the nearby nucleus $^{130}$Te. These parameters and the optical-model code SNOOPY8Q (Ref. 14) were used to calculate $\sigma_R$, and subsequently $\eta$. The results are compared with our experimental data in Fig. 2 (solid curve) and Table III.

For these calculations, the real potential depth $V_0$ was taken to have a linear energy dependence extrapolating to zero at $E_\alpha = 3500$ MeV, as recommended by Nadasen and Roos.[15] However, the results changed negligibly when $V_0$ was held constant; for example, the energy dependence changed $\sigma_R$ by only 0.1% at $E_\alpha = 100$ MeV. The calculations were done for nuclei with average $Z = 52$. When the calculations were redone for $Z = 54$ (that of $^{130}$Te), $\sigma_R$ dropped by about 1%.

Other optical-model calculations were done using the $^{140}$Ce OMP's of Baker and Tickle,[9] who use a much deeper real potential than do LSB (189 MeV versus 34 MeV). The fit to our data (dashed line, Fig. 2) is somewhat better. One could argue that the potential depths found for this heavier nucleus should be reduced by about 7% for CsI. Doing so reduces $\sigma_R$, though by less than 1%.

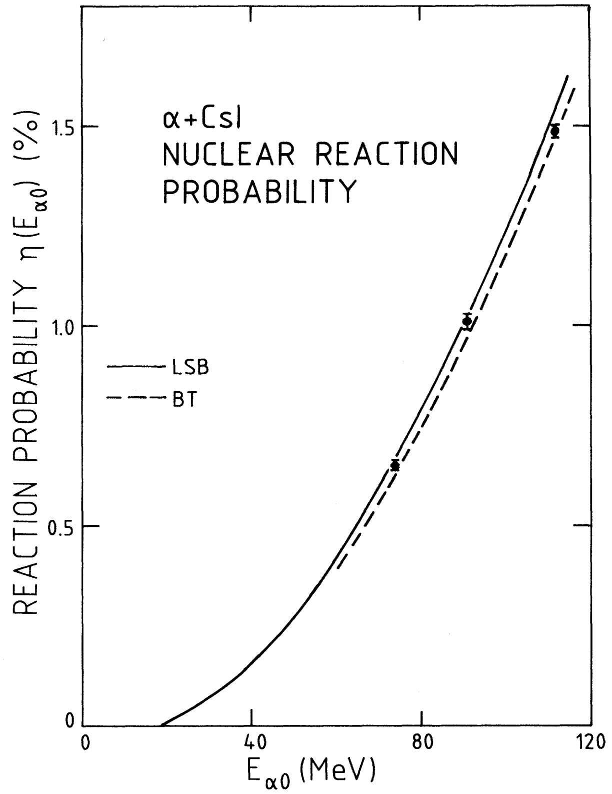

FIG. 2. Measured total nuclear reaction probabilities for 74- to 112-MeV $\alpha$ particles incident upon CsI, plotted versus their initial energy. Predictions obtained using the optical model parameter sets of Leonard, Stewart, and Baron (Ref. 8) and Baker and Tickle (Ref. 9) are shown by solid and dashed curves, respectively.

### B. Microscopic models

The microscopic model of DeVries and Peng,[1] in which $\sigma_R$ is determined by considering all possible collisions between nucleon pairs in the projectile and target nuclei, was used to calculate $\sigma_R$. The two main ingredients of such calculations are the total nucleon-nucleon cross sections, obtained as described in Ref. 16, and the nuclear matter density distributions. Three-parameter Gaussian density distributions were assumed for the nuclei of interest. Since parameters are unavailable for $^{127}$I, they were obtained by averaging those reported[17] for $^{116}$Sn and $^{138}$Ba, whose average proton and neutron numbers are the same as that of $^{127}$I. Parameters for $^{133}$Cs were obtained similarly by averaging those reported for $^{124}$Sn and $^{142}$Nd.

TABLE III. Measurement and predictions of $\bar{\sigma}_R$ for $\alpha$+CsI system, averaged (as explained in text) over the interval 74 to 112 MeV.

| | $\bar{\sigma}_R$ (mb) | Ref. |
|---|---|---|
| Measurement | 2220±50 | Present work |
| Optical model (LSB) | 2294 | 8 |
| Optical model (BT) | 2205 | 9 |
| DeVries-Peng | 2079 | 1 |
| Bertsch (zero-range) | 2073 | 10 |
| Bertsch (finite-range) | 2266 | 10 |
| Bass | 2570 | 19 |
| Gupta-Kailas | 2730 | 18 |
| Schröder-Huizenga | 3110 | 20 |

Bertsch, Brown, and Sagawa[10] presented a microscopic model in which nucleon-nucleon interactions take place between independent tubes of matter, aligned with the beam direction, in the projectile and target. This simplifies the calculations so that finite-range nucleon-nucleon forces are readily incorporated. Our average $\sigma_R$ (see Table III) calculated with their method and zero-range forces is nearly identical to the DeVries-Peng value, as was found[16] for the $\alpha$+Si system. Using finite range for the *N-N* force raises $\sigma_R$ by about 10%, as was found for other systems.[10,16] It is striking that this model, which seems the most physically realistic of all we consider, also gives the best agreement with our measurement. However, we must point out that, for the $\alpha$+Si system, the zero-range theory gave the better agreement with experiment.[16]

### C. Strong absorption models

Finally, we present results calculated with several strong absorption models.[18–20] These models assume, basically, that a reaction occurs whenever nuclear matter is in contact, and have been used most often to predict $\sigma_R$ for heavy-ion collisions. Formulas for all the models we consider are tabulated in Ref. 18, Table I. For the two Gupta-Kailas[18] models, $\sigma_R$ ranges from 2705 mb ($\alpha$+I, model II) to 2757 mb ($\alpha$+Cs, Model I); an average of the four values is given in our Table III. The Bass[19] prediction is closest to the present $\alpha$+CsI measurement. However, for heavy-ion systems, the energy dependence of its interaction radius is in poorer agreement with experimental data than that of the Gupta-Kailas models. All three of these models substantially overpredict the $\alpha$+CsI $\sigma_R$.

## V. CONCLUSIONS

This method for determining $\sigma_R$ with a spectrograph is superior to the earlier method[5–7] for measurements using "detector" (Si, Ge, I, Cs) nuclei. Copious and highly monoenergetic particle beams are obtained, and the choice of projectile is not limited by requiring a detectable recoil nucleus. It is well suited for measurements at Van de Graaf accelerators, where the bombarding energy can be measured precisely and changed in small steps. The average $\sigma_R$ can then be obtained for small, accurately defined intervals.

The experimental result is much better predicted by the optical model and microscopic theories than by the strong absorption theories. This was also found to be true for the $\alpha$+Si and $^{12}$C+$^{12}$C systems.[16,21]

The optical-model potential[9] with 189-MeV real-well depth predicts $\sigma_R$ more accurately than the shallow potential.[8] $\alpha$-nucleus real-well depths in the 100- to 200-MeV range are considered more realistic.[22]

The microscopic theory of DeVries and Peng, which explains $\sigma_R$ as resulting from individual nucleon-nucleon collisions, underpredicts our result by about 10% as it does for the nearby $\alpha+{}^{90}\mathrm{Zr}$ system in this energy range.[1] The finite-range Bertsch prediction is more accurate than that for zero range, but the opposite is true for the $\alpha+\mathrm{Si}$ system.[16] While the microscopic theories are instructive and useful, we still lack a single theory which accurately fits all experimental data.

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[1] R. M. DeVries and J. C. Peng, Phys. Rev. C **22**, 1055 (1980).
[2] P. G. Hansen and B. Jonson, Europhys. Lett. **4**, 409 (1987).
[3] W. E. Frahn, Ann. Phys. (N.Y.) **72**, 524 (1972).
[4] J. R. Birkelund, J. R. Huizenga, H. Freisesleben, K. L. Wolf, J. P. Unik, and V. E. Viola, Jr., Phys. Rev. C **13**, 133 (1976).
[5] R. E. Warner, C. P. Browne, S. E. Darden, J. J. Kolata, A. Rollefson, P. A. Kimoto, and A. Galonsky, Phys. Rev. C **37**, 1884 (1988).
[6] R. E. Warner, A. M. van den Berg, K. M. Berland, J. D. Hinnefeld, Z. Zhang, Y. T. Zhu, X. Q. Hu, and S. Li, Phys. Rev. C **40**, 2473 (1989).
[7] R. E. Warner *et al.*, Nucl. Phys. **A516**, 416 (1990).
[8] R. F. Leonard, W. F. Stewart, and N. Baron, Phys. Rev. **162**, 1125 (1967).
[9] F. T. Baker and R. Tickle, Phys. Rev. C **5**, 182 (1972).
[10] G. F. Bertsch, B. A. Brown, and H. Sagawa, Phys. Rev. C **39**, 1154 (1989).
[11] A. G. Drentje, H. A. Enge, and S. B. Kowalski, Nucl. Instrum. Methods **122**, 485 (1974).
[12] C. F. Williamson, J.-P. Boujot, and J. Picard, Commissariat d'Energie Atomique Report No. R3042, Saclay, 1966.
[13] J. F. Ziegler, *The Stopping and Ranges of Particles in Matter* (Pergamon, New York, 1977), Vol. 4.
[14] P. Schwandt, private communication.
[15] A. Nadasen and P. G. Roos, Bull. Am. Phys. Soc. **29**, 1040 (1984).
[16] R. E. Warner and G. N. Felder, Phys. Rev. C **42**, 2252 (1990).
[17] C. W. de Jager, H. de Vries, and C. de Vries, At. Data Nucl. Data Tables **14**, 479 (1974).
[18] S. K. Gupta and S. Kailas, Z. Phys. A **317**, 75 (1984).
[19] R. Bass, *Nuclear Reactions with Heavy Ions. Texts and Monographs in Physics* (Springer-Verlag, Berlin, Heidelberg, New York, 1980).
[20] W. V. Schröder and J. R. Huizenga, Annu. Rev. Nucl. Sci. **27**, 465 (1977).
[21] S. Kox *et al.*, Phys. Rev. C **35**, 1678 (1987).
[22] L. W. Put and A. M. J. Paans, Nucl. Phys. **A291**, 93 (1977).