This difference is traced back to the use of a strong ρ exchange in Ref. 1. It is then shown that NN interactions which are constrained to fit the NN phase shifts favor an effective weak ρ exchange which will not give rise to spectacular collective effects. The uniqueness of the ρNN interaction as constrained by NN scattering data is further shown by comparing the tensor forces of various interactions. Again NN interactions (including the Reid soft core) which fit NN scattering give a unique prescription for momentum transfers up to 3 fm^{-1}, ruling out a pure π-exchange or (π+ strong ρ)-exchange tensor force.

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Direct Measurement of the $^{12}C + ^{12}C$ Reaction Cross Section between 10 and 83 MeV/Nucleon

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The first results of direct measurements of heavy-ion reaction cross sections, σ_R, with use of the beam attenuation method are reported. For the $^{12}C + ^{12}C$ system σ_R was measured at three incident energies, 112, 360, and 996 MeV. The data show deviations from the geometrical reaction cross section and agree with recent theoretical predictions based on Glauber theory.

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Recent interest in heavy-ion total reaction cross sections, σ_R, stems from articles by DeVries and Peng[1] in which the energy dependence of the nucleon-nucleon total cross section was linked to that of σ_R. Calculations based on the Glauber model predicted a maximum in σ_R for the $^{12}C + ^{12}C$ system at ≈ 200 MeV (laboratory) and a steady decrease above this energy up to the pion threshold. These predictions were confirmed by values of σ_R extracted from $^{12}C + ^{12}C$ elastic scattering data[2] in the energy region between 70 and 300 MeV and at 1016 MeV.[3] A similar conclusion was reached by analysis of $^{16}O + ^{12}C$ elastic scattering.[4] Such analyses (optical model,[3,5] parametrized phase shift,[2] and sum of differences[6]) are, however, model dependent and require precise measurements of the elastic scattering at forward angles, which becomes extremely difficult in the energy region of interest (30 MeV/nucleon $\leq E_{\rm lab} \leq 1000$ MeV/nucleon) where the predicted[1] deviations of σ_R from the geometrical value are to be investigated. Therefore a model-independent method of measuring σ_R directly is of considerable interest for testing whether indeed the nucleon-nucleon behavior dominates the energy variation of σ_R as is predicted by the microscopic calculations.[1] It should also be noted that with the exception of two data points for the system $^{12}C + ^{12}C$ at Bevalac energies[7] no direct measurements of σ_R exist at all for heavy-ion collisions up to now.

This Letter reports direct measurements of σ_R for $^{12}C + ^{12}C$ collisions at $E_{\rm lab} = 9.3$, 30, and 83 MeV/nucleon using the attenuation method.[8] The three experiments were performed at the Grenoble cyclotron (9.33 MeV/nucleon), at the new Grenoble cyclotron facility SARA (30 MeV/nucleon), and at the CERN synchrocyclotron (83 MeV/nucleon), respectively.

The principle of the method is very simple. One measures for a given number of incident beam particles the number of beam and elastically scattered particles after passage through the target. The common feature of these particles is that they have not given rise to a reaction. Therefore the difference between this number and the number of incident beam particles is directly proportional to σ_R. Since the elastic scattering cross section is very strongly forward peaked this objective may be achieved with good accuracy by detecting outgoing particles up to a certain maximum angle beyond which the integrated elastic scattering cross section may be treated as a small correction. For all energies this maximum angle exceeded the grazing angle (see Table I) and therefore no loss of events due to multiple scattering arises. For heavy-ion reactions there is, however, a problem due to the presence of a nonnegligible cross section associated with reaction products at small angles which neccessitates identification of the outgoing particles.

The apparatus is shown schematically in Fig. 1. The number of beam particles incident on the target ($\sim 3\times 10^4$/sec) is defined by the thin scintillator counter "1" and an active collimator "2" as $B = 1 \cdot \bar{2}$ (where the bar designates an anticoincidence). The atomic number of the particles after the target is identified in a thin ΔE plastic scintillator "3" centered on the beam axis. The identification is made by using the two-dimensional spectrum ΔL-t, where ΔL is the light output from counter 3 and t is the time of flight between counters 1 and 3. A similar identification is made in two further rings of scintillators, 4 and 5, arranged symmetrically around the central scintillator. These detectors were supported on radial supports and slightly overlapped the central detector thus providing a continuous detection surface (apart from the radial supports).

The thicknesses of the scintillators and the length of the time-of-flight path for the three energies are given in Table I together with the resulting opening angles of the detector arrangement. The values of the respective grazing angles are also indicated.

The light output and time-of-flight information from each of detectors 3, 4, and 5 were stored on magnetic tape. For the central detector 3 a narrow time window including the beam and elastically scattered particles was excluded from the recorded information in order to limit the count rate at the computer. A raw or uncorrected reaction cross section $\sigma_R(a)$ can be defined without using the recorded information. We define

$$\sigma_R(a) = [B \cdot \bar{3}(\text{target in}) - B \cdot \bar{3}(\text{target out})]/TB, \quad (1)$$

where $\bar{3}$ denotes the anticoincident events of central counter 3 and T is the target thickness in ap-

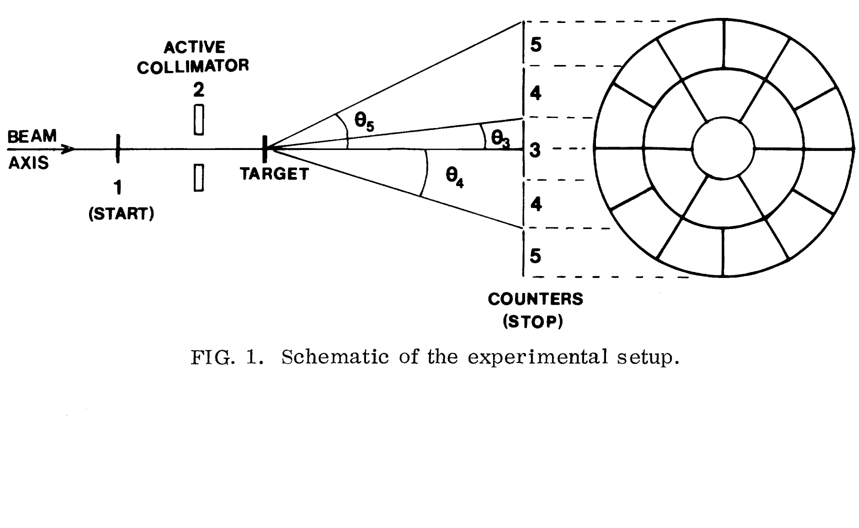

FIG. 1. Schematic of the experimental setup.

TABLE I. Scintillator thickness, distances between the various counters, and the resulting opening angles of the detectors behind the target. In each case, the three values given correspond to the three energies of 9.3, 30, and 83 MeV/nucleon, respectively. The diameter of active collimator 2 was 5, 3, and 3 mm, and the laboratory grazing angle was 4.23, 1.2, and 0.44 deg, respectively, for these three energies.

	Distances (cm) Counter 2	Target	Counter 3	Counter	Scintillators Thickness (mm)	Type	Angles (deg)	
Counter 1	13	36	154	1	0.03	NE 102	θ_3	2.14
	52	75	293		0.125	Ref. 9		1.19
	52	75	493		0.2	Ref. 9		0.604
Counter 2		23	141	2	0.4	NE 102	θ_4	5.79
		23	241		1.0	NE 102		3.19
		23	441		1.0	NE 102		1.64
Target			118	3,4,5	0.2	Ref. 9	θ_5	10.55
			218		1.0	Ref. 9		5.79
			418		5.0	NE 110		3.01

propriate units. The target-in/target-out measurements are necessary to correct for reactions induced in counters 1 and 3. In practice a series of target-in/target-out measurements was made in order to monitor the stability of the result against small, ever present, variations in the beam intensity and position. It was found that $\sigma_R(a)$ was stable to within ~2%. Here one should note that our method is very rapid. In spite of the low beam intensity it requires only a few hours for completion of a given measurement.

The final value of σ_R is obtained as

$$\sigma_R = \sigma_R'(a) - \sigma_{\mathrm{elastic}}(\theta > \theta_3), \qquad (2)$$

where $\sigma_R'(a)$ is obtained from $\sigma_R(a)$ by subtracting a correction due to reaction products falling into counter 3 [cf. correction (c) below]. The major part of $\sigma_{\mathrm{el}}(\theta > \theta_3)$ is measured by counter rings 4 and 5 [cf. correction (b) for $\sigma_{\mathrm{el}}(\theta > \theta_5)$]. The time and ΔL resolution was, however, not sufficiently good for unambiguous separation of elastic scattering from inelastic scattering and from neutron-transfer reactions [cf. correction (a)]. Thus, these measured quantities are subject to some corrections which are described in the following. It should be emphasized that the sum of these corrections does not exceed 10% of the reaction cross section. The explicit values of these corrections, the corresponding references, and the final results for σ_R are listed in Table II.

(a) Determination of events scattered elastically into the outer detector rings 4 and 5: In these counters the elastic component was identified by off-line analysis of the ΔL-t spectra. The ΔL-t information was sufficiently good for charge separation at all energies whereas the corrections due to neutron transfer were based on existing

TABLE II. List of the quantities used for the extraction of σ_R. If no reference is indicated for an individual correction that particular value was obtained by interpolation (see text). The sign of each correction is also indicated. The transparency T is defined by the equation $T(E) = 1 - \sigma_R(E)/\sigma_R(9.33\ \mathrm{MeV/nucleon})$.

E_{lab} (MeV/nucleon)	$\sigma_R(a) - \sigma_{\mathrm{el}}(4+5)$ (mb)	Neutron transfer (mb)	Inelastic excitation of ^{12}C (mb)	$\sigma_{\mathrm{el}}(\theta > \theta_5)$ (mb)	Reaction products in counter 3 (mb)	σ_R (mb)	Transparency relative to σ_R (9.33 MeV/nucleon)
9.33	1550 ± 30	$+7 \pm 5$ (Ref. 11)	$+15 \pm 10$ (Ref. 10)	-168 ± 15 (Ref. 10)	$+40 \pm 10$	1444 ± 50	0%
30	1253 ± 30	$+12 \pm 8$	$+30 \pm 20$	-10 ± 5	$+30 \pm 15$	1315 ± 40	9%
83	898 ± 10	$+12 \pm 5$ (Ref. 12)	$+50 \pm 20$ (Ref. 3)	-18 ± 4 (Ref. 3)	$+18 \pm 4$	960 ± 25	34%

data in the literature for the two extreme energies and were estimated for the measurement at 30 MeV/nucleon. The time resolution of our detection system (~0.4 nsec) defines the energy band over which we integrate and in which contributions due to inelastic excitation of the ^{12}C nuclei have to be subtracted (over the angular range spanned by our detector arrangement). The cross section of this correction could also be determined from existing data at 9.33 and 83 MeV/nucleon and was interpolated to 30 MeV/nucleon.

(b) Correction for elastic scattering outside the cone covered by our detector arrangement: This correction was determined from existing data at 9.33 and 83 MeV/nucleon. At 30 MeV/nucleon we performed optical-model calculations and checked that the value of the integrated elastic cross section outside the cone covered by our detectors is not very sensitive to the parameters used. Furthermore, the resulting calculated reaction cross section agrees with our experimental value of 1315 ± 40 mb.

(c) Correction for reaction products falling into the time window set on the central scintillator 3: An extrapolation into this region was performed by assuming the corresponding ΔL-t spectrum to be similar to the one of counters 4 and 5.

The final values of the reaction cross sections obtained are

$$\sigma_R = 1444 \pm 50 \text{ mb},\ 1315 \pm 40 \text{ mb}, \text{ and } 960 \pm 25 \text{ mb}$$

at 9.33, 30, and 83 MeV/nucleon, respectively. The errors contain a contribution of about 1% due to counting statistics and some 2% due to the error in target thickness measurement (made by α ranging). The remaining error comes from the uncertainties in estimating the above corrections. Our data are displayed in Fig. 2. The agreement with the already existing data is apparent.

We find thus experimental evidence for the deviation of $\sigma_R(^{12}C + ^{12}C)$ from the geometrical reaction cross section (see Fig. 2). This can be expressed in terms of an energy-dependent transparency[1] which varies from 0% to 30% in the investigated energy range (see Table II). Furthermore, the trend of σ_R predicted by the microscopic calculation of Ref. 1 is confirmed by our experiment.

A recent direct measurement of the $\alpha + ^{12}C$ reaction cross section yielded similar results.[13] We note thus that for incident energies $E_{lab} \gtrsim 20$ MeV/nucleon the reaction cross section $\sigma_R(E)$ for light projectiles such as protons and α particles[1,13] as well as for composite ones like ^{12}C all exhibit a similar behavior resembling $\sigma_T(N,N)$, the total cross section for nucleon-nucleon collisions.

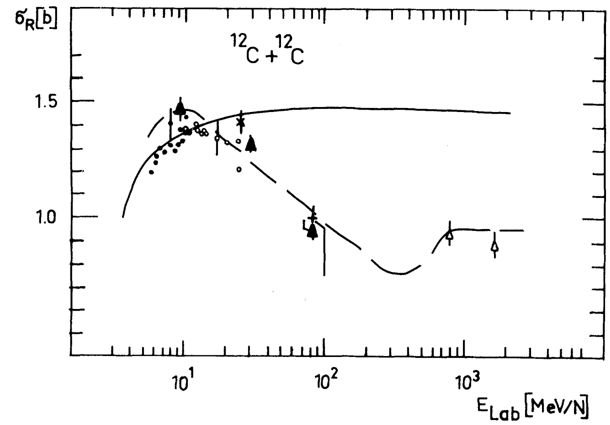

FIG. 2. Total reaction cross section for $^{12}C + ^{12}C$ collisions as a function of incident energy. The three values measured with our direct method are indicated by the solid triangles. The agreement with other data is apparent. The solid circles were obtained by a parametrized phase-shift analysis (Ref. 2) of the data from Ref. 10; the other data points (only typical error bars are given) labeled open circles, crosses, plusses, and open triangles are taken from Refs. 2, 5, 3, and 7, respectively. There is thus experimental evidence for the deviation of $\sigma_R(^{12}C + ^{12}C)$ from the geometrical cross section which is illustrated by the solid curve (from Ref. 1). Furthermore, the trend of the microscopic calculation (broken curve, from Ref. 1) based on the Glauber theory is in agreement with our data.

The extension of reaction cross section measurements to higher energies and heavier systems may enable us to conclude whether for composite projectiles an important fraction of σ_R can be attributed to individual nucleon-nucleon collisions as for the $\alpha + ^{12}C$ case,[13] or whether collective effects play an important role.

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Alpha-Particle Angular Distributions with Respect to Spin Direction

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Angular distribution of alpha particles with respect to the spin direction of residual nuclei from fusion of 176-MeV ^{20}Ne with ^{150}Nd has been measured with the spin spectrometer. Below the Coulomb barrier, the ratio of the 90° to 0° yields with respect to spin direction increases with decreasing E_α. This effect is not shown by a statistical-model calculation using penetrabilities for spherical potentials, which suggests that the α-emitting nuclei are deformed with their longest axis perpendicular to the spin direction. If so, the deformation increases as the spin rises from ~ 34 to $64\hbar$.

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The shape and structure of the nucleus at high excitation and their evolution with spin are subjects of current interest. These properties of highly excited nuclei can be investigated by measurements of evaporated α particles.[1-3] We report here for the first time measurements of angular distributions of evaporated α particles with respect to spin direction, using the unique properties of the spin spectrometer.[4-6] The spectrometer, a 4π γ-ray multidetector system, determines the magnitude and the orientation of the spin of the residual nuclei on an event-by-event basis. This provides a sensitive method[7] to investigate changes in nuclear shape as a function of spin.

A 176.6-MeV ^{20}Ne beam from the Oak Ridge isochronous cyclotron bombarded a 1.1-mg/cm^2 Nd target enriched to 96.1% in mass 150. The α particles were measured in nine Si surface-barrier $\Delta E, E$ telescopes, of which two were at 80° and one was at 90° to the beam (~89° and 97° c.m.). The ΔE detectors had a thickness of 75 μm and an acceptance cone of ~6° half-angle. A Si detector at 8° identified evaporation residues

