Energy-Dependent Structure in $^{28}Si + ^{28}Si$ Scattering

R. R. Betts, S. B. DiCenzo, and J. F. Petersen
A. W. Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520
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Data for $^{28}Si + ^{28}Si$ elastic and inelastic scattering are presented for a range of bombarding energies from 80 to 150 MeV. The experimental results show strong evidence for resonancelike effects similar to those seen in light systems. The inelastic data suggest the dominance of multistep processes.

The observation of dramatic structures in excitation functions for elastic scattering of $^{12}C + ^{12}C$,[1] $^{12}C + ^{16}O$,[2] and $^{16}O + ^{16}O$[3] has led to a tremendous amount of experimental and theoretical activity in recent years.[4] The broad structures in these excitation functions are generally taken to arise from orbiting or shape resonances in a potential which is only weakly absorbing for the surface partial waves. The fine structure seen superimposed on the gross structure is still lacking a definitive explanation although this too has been the subject of a large body of work. More recently, similar structures have been observed in the large-angle scattering of ^{16}O (Ref. 5) and ^{12}C (Ref. 6) from ^{28}Si as well as in the (^{16}O, ^{12}C) reaction on ^{24}Mg.[7] Thus far, however, there is no evidence for resonance effects in systems in which at least one of the partners is not O or C. Studies of heavier systems have, in the main, been limited to energies close to the barrier,[8] and experiments at higher energies[9] so far do not show resonance effects. The question of whether or not resonances will occur in heavier systems is therefore an open one. In this Letter, we present data for $^{28}Si + ^{28}Si$ elastic and inelastic scattering over a range of energies from twice to four times the Coulomb barrier. The data clearly show resonancelike behavior reminiscent of that seen in lighter systems. This therefore provides, for the first time, direct experimental evidence for the occurrence of resonances in a system not involving C or O.

The experiments were performed using ^{28}Si beams from the Yale and Brookhaven MP tandem accelerators. The targets were metallic Si evaporated onto 15-μgm/cm^2 C backings and were typically 400 keV (lab) thick. The elastic and inelastic events were identified by use of a kinematic coincidence arrangement with a solid angle of 6×10^{-3} sr and an angular acceptance in the Θ direction of $\pm0.9°$ (lab). Despite the large angular acceptance, good energy resolution was preserved by summing the energy signals of the scattered and recoil particles, thus providing an energy signal independent of scattering angle. Excitation functions for elastic and inelastic scattering were measured at laboratory angles of 45° and 40° over the energy range 90–150 MeV (lab) in 1-MeV steps.

A spectrum obtained at a bombarding energy of 120 MeV and a laboratory angle of 45° is shown in Fig. 1. The energy resolution is approximately 1 MeV and results mainly from target thickness effects. The peaks corresponding to elastic scattering and single inelastic scattering to the 1.78-MeV 2^+ state in ^{28}Si are clearly resolved and unambiguously identified. For Q values less than -3 MeV the identification of the peaks is less clear. Both inelastic scattering and α-transfer reactions are kinematically allowed as indicated by the arrows. The measured Q value, however, leads us to identify the third peak in the spectrum as predominantly due to mutual excita-

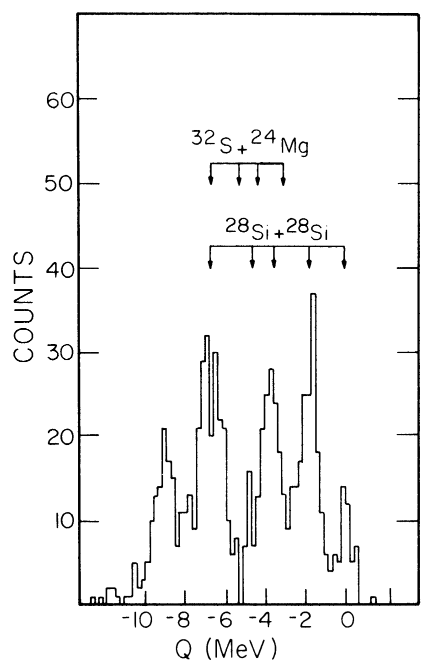

FIG. 1. Spectrum of $^{28}Si + ^{28}Si$ obtained at $E_{lab} = 120$ MeV. The arrows indicate the expected energies of ^{28}Si elastic and inelastic scattering as well as for the $^{28}Si(^{28}Si, ^{24}Mg)^{32}S$ reaction.

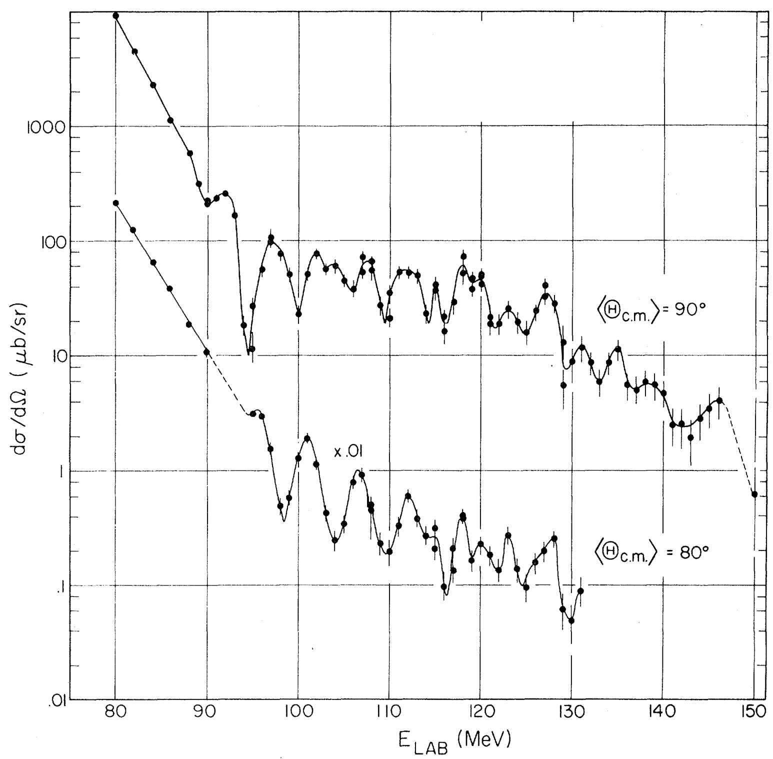

FIG. 2. Elastic scattering excitation functions at $\langle\Theta_{c.m.}\rangle = 90°$ and 80°. The curves are drawn to guide the eye.

tion of both ^{28}Si nuclei to their first 2^+ states ($Q = -3.56$), but also containing a contribution from single excitation of the 4.62-MeV 4^+ state. The fourth peak we suggest to be due to the 6.88-MeV 3^- state. For $Q < -9$ MeV, single-nucleon transfer reactions can also compete and may give rise to the last peak in the spectrum, but this also corresponds to excitation energy to a known 1^- state in ^{28}Si. The efficiency, as calculated from the geometry of the setup, was 100% for $-5 \leq Q \leq 0$ MeV over the entire bombarding energy range. For $Q < -5$ MeV, at the lower end of the bombarding energy range, significant corrections must be applied to the data thus allowing the possibility of large (25%) systematic uncertainties in the cross sections quoted. Specifically, we refer to the data shown for the 3^- transition for $E_{lab} < 100$ MeV.

The excitation functions for elastic scattering at $\langle\Theta_{c.m.}\rangle = 90°$ and 80° are shown in Fig. 2. The data show several features:

(1) For $E_{lab} \lesssim 90$ MeV the yield falls steeply with increasing energy, characteristic of scattering with strong absorption.

(2) Above $E_{lab} = 90$ MeV the cross sections level off and show broad regular oscillations[10] with a period of approximately 5 MeV and widths of 3 MeV. These continue up to 110 MeV or so for the 80° data but only to 100 MeV for the 90° data. There is no obvious correlation between the gross structures observed at these two angles.

(3) A narrower structure with width 1–2 MeV appears at $E_{lab} = 105$ MeV (90°) and $E_{lab} = 115$ MeV (80°). For energies above 110 MeV, there seems to be a high degree of correlation between the two sets of data.

(4) At energies above 130 MeV the yields begin to fall off more steeply—dropping an order of magnitude by the time 150 MeV is reached.

These features are all quite similar to those observed, for example, in $^{16}O + ^{16}O$ scattering. The steep falloff characteristic of strong absorption is broken by the appearance of broad structures of more or less constant magnitude which are themselves modulated by a narrower structure. At higher energies the cross section again declines, but more gently than in the low-energy region.

The observed spacing of the gross structures is consistent with the occurrence of a series of resonances in the grazing partial waves. A quarter-point analysis[11] of the forward-angle elastic scattering at 100 MeV indicates that the grazing partial wave is $L=34$ at that energy. Insertion of this value into the usual expression for the grazing partial wave,

$$E_{\text{c.m.}} = V(R) + [L_{\text{gr}}(L_{\text{gr}}+1)\hbar^2/2\mu R^2], \qquad (1)$$

gives the observed spacing of 5.5 MeV (lab) if $R = 8.73$ fm ($r_0 = 1.44$ fm)—a completely usual value. This suggests that it will be possible, as in the $^{16}O + ^{16}O$ case,[12] to describe these data with use of surface-transparent optical potentials. Preliminary calculations do indicate that such surface transparency is necessary to reproduce these oscillations and that surface-nontransparent potentials, while they are able to produce a levelling off of the cross section, are unable to account for the observed structure.

The data for the inelastic transitions at $\Theta_{\text{lab}} = 45°$ are shown in Fig. 3. The overall behavior of these inelastic cross sections is quite similar to that of the elastic scattering, namely, a falloff characteristic of strong absorption, interrupted by a leveling at about 100 MeV and finally a more gentle decline above 130 MeV. The structure in each inelastic excitation function is less pronounced than for the elastic channel, but is well correlated with the data for that transition at $\Theta_{\text{lab}} = 40°$ (not shown). Further, the structure observed in the single 2^+ yield is very similar to that in the elastic channel—at least in the locations of maxima and minima. The total cross section for these transitions is, of course, dominated by the forward-angle yield, but it will be of interest to see if this shows any structure as a function of energy similar to that seen in lighter systems.[13]

It is perhaps significant that whereas the falloff from 80 to 100 MeV is quite different for each of the transitions, there is a close similarity of the gross features of all three inelastic yields and of the elastic yield at higher energies, indicating a common mechanism. This, together with the relative strength of the inelastic cross section at these angles, suggests a process in which several inelastic excitations and deexcitations have taken place, the time scale of the collisions being such that the steady-state relative populations have been reached. This dominance of multiple-step processes would be consistent with some of the current interpretations[4] of $^{12}C + ^{12}C$ and $^{16}O + ^{16}O$ scattering.

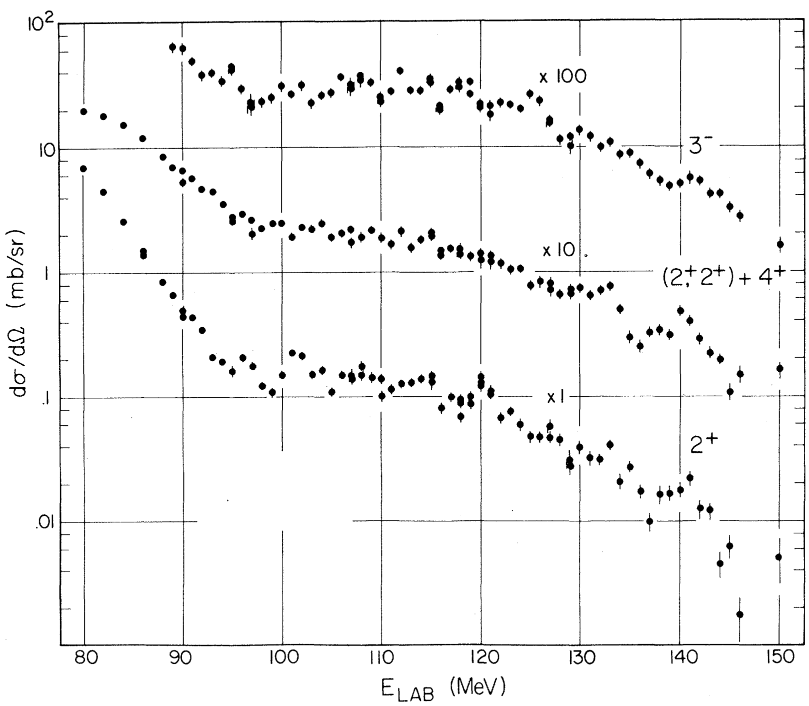

FIG. 3. Excitation functions for the single 2^+, mutual $2^+ + 4^+$, and 3^- inelastic scattering at $\Theta_{\text{lab}} = 45°$. In the case of the 3^- yield the error bars are merely statistical and do not reflect the possible systematic errors discussed in the text.

In summary and conclusion, data for $^{28}Si + ^{28}Si$ show all the features associated with surface transparency that have been observed in much lighter systems. The gross structure in the excitation functions would seem to be amenable to an optical-model analysis using surface-transparent optical potentials. Data for the inelastic scattering show features similar to those of the elastic scattering indicating the likely importance, and perhaps dominance, of multiple-step processes in the underlying mechanism leading to surface transparency. Clearly much more work, both experimental and theoretical, is required.

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[1]W. Reilly *et al.*, Nuovo Cimento 13A, 897 (1973).

[2]R. E. Malmin *et al.*, Phys. Rev. Lett. 28, 1590 (1972).

[3]J. V. Maher *et al.*, Phys. Rev. 188, 1665 (1969).

[4]D. A. Bromley, in *Nuclear Molecular Phenomena*, edited by N. Cindro (North-Holland, Amsterdam, 1978) p. 3; R. H. Siemssen, *ibid.* p. 79; R. Konnecke, W. Greiner, and W. Scheid, *ibid.* p. 109; Y. Abe, *ibid.* p. 211.

[5]P. Braun-Munzinger *et al.*, Phys. Rev. Lett. 38, 944 (1977).

[6]M. R. Clover *et al.*, Phys. Rev. Lett. 40, 1008 (1978).

[7]M. Paul *et al.*, Phys. Rev. Lett. 40, 1310 (1978).

[8]H. Emling *et al.*, Nucl. Phys. A239, 172 (1975); M. Richter *et al.*, *ibid.* A278, 163 (1977).

[9]A. Ferguson, in *Proceedings of the Symposium on Heavy Ion Scattering, Argone National Laboratory, 1971*, edited by R. H. Siemssen (Argonne National Laboratory, Argonne, Ill., 1971), ANL-7837, p. 187; H. Doubre *et al.*, Phys. Rev. C 15, 693 (1977).

[10]H. Doubre *et al.*, Institut de Physique Nucléaire, Université de Paris-Sud, Annual Report, 1977 (unpublished), p. N11, report broad structures at $E_L = 92$ and 97 MeV in agreement with the present data.

[11]W. E. Frahn, Ann. Phys. (New York) 72, 524 (1972).

[12]A. Gobbi *et al.*, Phys. Rev. C 7, 30 (1973).

[13]T. M. Cormier *et al.*, Phys. Rev. Lett. 40, 924 (1978); J. J. Kolata *et al.*, (to be published).

Resonance in the Two-Nucleon Transfer Reaction $^{12}C(^{12}C, ^{10}B)^{14}N$

M. R. Clover,[a] T. M. Cormier, B. R. Fulton, and B. J. Herman
Nuclear Structure Research Laboratory, University of Rochester, Rochester, New York 14627
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The energy dependence of the reation $^{12}C(^{12}C, ^{10}B)^{14}N$ has been studied in the range $E_{c.m.} = 22–42$ MeV. A striking resonance is observed at $E_{c.m.} = 30.75$ MeV which correlates with a very pronounced structure in the $^{12}C + ^{12}C$ inelastic channels. The total resonance cross section observed in the $^{10}B + ^{14}N$ channel implies a reduced partial width comparable to those of the inelastic channels. These data suggest, for the first time, the possible importance of nucleon degrees of freedom in the structure of the $^{12}C + ^{12}C$ resonances.

During the last twenty years a considerable effort has been directed towards a study of the $^{12}C + ^{12}C$ system, particularly the nature of the intermediate-structure resonances. The initial studies[1] of the light-particle decay channels at energies below the Coulomb barrier have been extended to many times the barrier energy and supplemented by detailed excitation functions both for the elastic and inelastic scattering and for fusion channels.[2-6] Reviews of the available data have recently been given by Bromley[7] and Feshbach.[8]

With the single exception of the $^{8}Be + ^{16}O$ exit channel,[9] no studies have been made of the few-nucleon transfer channels of the $^{12}C + ^{12}C$ system. These channels have large negative Q values, and consequently only participate above an energy of $E_{c.m.} = 18–21$ MeV, beginning in the region of the (12^+)-(14^+) resonance strength.[9] An additional feature of the large negative Q values is that the reactions are severely kinematically mismatched and direct-transfer strength is expected to be suppressed. The $^{8}Be + ^{16}O$ channel is the exception, with a near-zero ground-state Q value, and studies[9] have indeed yielded evidence for a band of resonances in the region $E_{c.m.} = 9–20$ MeV which have been assigned spins ranging from 6^+ to 12^+. More recently, the observation of a strong sequence of resonances in the single and mutual 2_1^+ inelastic channels at higher energies[3] has been interpreted on the basis of energy system-