Surface Resonances in Backward-Angle Heavy-Ion Scattering

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Backward-angle excitation functions ($\theta_{c.m.} = 180° \pm 5°$) have been measured for the systems $^{16}O + ^{28}Si$ and $^{12}C + ^{28}Si$ for elastic and inelastic scattering to the first excited state in ^{28}Si. Over the investigated energy range, $17 \lesssim E_{c.m.} \lesssim 37$ MeV, the elastic and inelastic data exhibit gross structure resonances of widths between 1 and 2 MeV modulated by a finer structure for $^{12}C + ^{28}Si$ ($\Delta E_{c.m.} \lesssim 250$ keV). Shape resonances with different principal quantum numbers are suggested as an explanation of the resonances.

The study of the energy dependence of elastic and inelastic heavy-ion scattering has revealed the existence of narrow and correlated structures for systems like $^{12}C + ^{12}C$ and $^{12}C + ^{16}O$.[1] For heavier systems such resonant structure has not yet been established.[2-4] However, the recently found[5] pronounced oscillations and backward rise in angular distributions for elastic and inelastic scattering of ^{16}O on ^{28}Si at $E_{c.m.} = 35$ MeV suggested the existence of a resonance in the grazing partial wave. To test this hypothesis and to search for other possible structures we have investigated the energy dependence of the elastic and inelastic scattering for the systems $^{12}C + ^{28}Si$ and $^{16}O + ^{28}Si$. Extensive excitation functions have been measured for both systems at far backward angles ($\theta_{c.m.} = 180° \pm 5°$) in the energy range $17 \lesssim E_{c.m.} \lesssim 37$ MeV. This angular range is far behind the grazing angle for all measured energies and, therefore, most likely to contain information on orbiting resonances or molecular structure.

The excitation functions for both systems exhibit a surprisingly strong and regular structure with width of about 1–2 MeV and large peak-to-valley ratio. For the system $^{12}C + ^{28}Si$ this gross structure is modulated by a finer structure of less than 250 keV width. This presents the first clear evidence for gross and intermediate structure for nuclear systems heavier than $^{16}O + ^{16}O$.

The experiments used the ^{28}Si beam of the Brookhaven National Laboratory (BNL) tandem Van de Graaff facility to bombard self-supporting Al_2O_3 targets of ~ 100 $\mu g/cm^2$ and carbon targets of ~ 50 $\mu g/cm^2$ areal density. Elastically and inelastically scattered ^{16}O and ^{12}C recoils were detected at $\theta_{lab} = 0° \pm 2.5°$ in the BNL quadrupole-three-dipole spectrometer. At $\theta_{lab} = 0°$ the elastic recoils $^{16}O^{8+}$ and $^{12}C^{6+}$ have exactly the same magnetic rigidity as one of the charge states of the beam. Therefore, the Si beam was stopped in front of the focal-plane detector by Haver foils of 10–25-μm thickness depending on beam energy. A ~ 5 mg/cm^2-thick layer of Au was evaporated on the Havar foils to reduce the reactions produced by the Si beam in the Havar material. To further reduce background, a Ni foil of ~ 1.5-mg/cm^2 thickness was placed directly behind the target to remove the degeneracy in magnetic rigidity between beam and recoiling target ions. A double-wire proportional counter served as focal-plane detector, which, in addition to the position measurement, provided a unique identification of the recoiling ^{12}C and ^{16}O ions. At all energies the energy resolution was sufficient to completely resolve transitions to the ground state and first excited state in ^{28}Si ($E^* = 1.78$ MeV).

Relative cross sections were obtained by normalizing on two symmetrically placed monitor counters ($\theta_{mon} = \pm 19°$) which recorded ^{28}Si ions elastically scattered off the Ni foil and (for $^{12}C + ^{28}Si$) off a thin Au layer evaporated on the C target. Many repeated points insured the constancy of the target thickness. The (small) corrections for the energy dependence of the charge-state distributions were obtained using the tables of Marion and Young.[6] The accuracy of the relative cross sections is better than $\pm 10\%$. The absolute normalization for both systems, accurate to $\pm 30\%$, was obtained by measuring ^{28}Si ions at small angles where the cross section follows the Rutherford law.

The measured excitation functions for elastic and inelastic scattering to the first excited state in ^{28}Si are presented in Figs. 1 and 2. For both systems, the excitation functions are dominated

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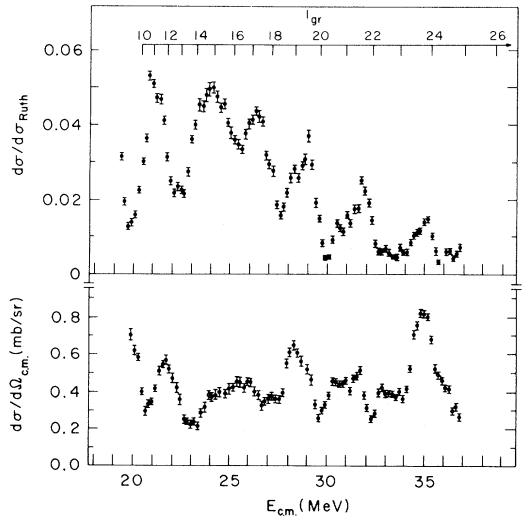

FIG. 1. Excitation functions at $\theta_{c.m.} = 180°$ averaged over $\pm 5°$ (see text) for $^{28}Si(^{16}O,^{16}O)^{28}Si$ (g.s.) (upper part) and $^{28}Si(^{16}O,^{16}O)^{28}Si$ (2^+, 1.78 MeV) (lower part). The energy scale has been corrected for energy loss in the target. The energy dependence of the grazing angular momentum l_{gr} is calculated using the potential of Ref. 7.

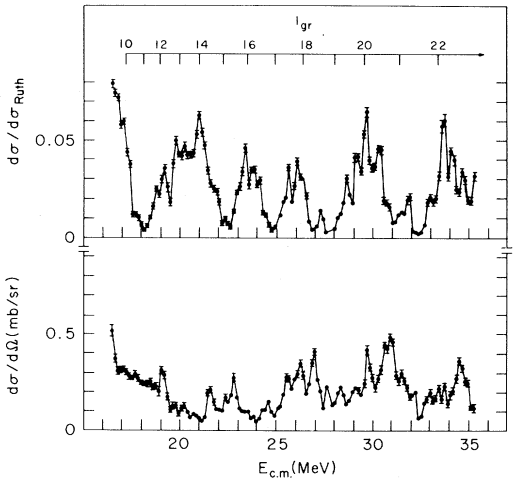

FIG. 2. Excitation functions at $\theta_{c.m.} = 180°$ averaged over $\pm 5°$ (see text) for $^{28}Si(^{12}C,^{12}C)^{28}Si$ (g.s.) (upper part) and $^{28}Si(^{12}C,^{12}C)^{28}Si$ (2^+, 1.78 MeV) (lower part). The energy dependence of the grazing angular momentum l_{gr} is calculated using the potential of Ref. 7.

by regularly spaced structures with large peak-to-valley ratios. This gross structure has widths varying between 1 and 2 MeV. A strong correlation between the peaks in the elastic and inelastic excitation functions is observed for the $^{16}O+^{28}Si$ system, indicating a resonance character. The correlation in the $^{12}C+^{28}Si$ is not as obvious. Also for this system, each of the gross structure peaks exhibits a finer structure whose width of approximately 250 keV is completely determined by the energy loss of the beam in the target.[8] Hence, the investigated excitation functions show resonancelike structures reminiscent of the ones observed for the systems $^{12}C+^{12}C$, $^{16}O+^{16}O$, and $^{16}O+^{12}C$,[1,9] but completely unexpected for such heavy systems.

Further support for a resonance interpretation of the observed structures is obtained from the elastic angular distributions since, for energies corresponding to peaks in the excitation functions, they are of the form of a Legendre polynomial $|P_l(\cos\theta)|^2$ in the angular range $140 \leq \theta_{c.m.} \leq 180°$.[5,10-13] No such shapes are observed at energies corresponding to minima in the excitation function.[11,13] Analysis of the "on-resonance" angular distributions yields information about their spins. For the system $^{16}O+^{28}Si$, four angular distributions have been measured for the peaks at $E_{c.m.} = 21$, 26, 32, and 35 MeV. The corresponding resonance spins extracted from these data are (in units of $\hbar$) $l = 9$, 17, 22, and 24, the experimental uncertainty being one unit of $\hbar$. For the $^{12}C+^{28}Si$ system, a spin sequence of $l = 15\hbar$ ($E_{c.m.} = 23.3$ MeV), $l = 18\hbar$ ($E_{c.m.} = 26.0$ MeV) and $l = 18\hbar$ ($E_{c.m.} = 30.2$ MeV) has been obtained by Ost.[13] This interpretation of these angular distributions may be complicated by the fine structure apparrent in Fig. 2. For the system $^{16}O+^{28}Si$, the observed energy dependence of the resonance spins closely follows the one of the grazing angular momentum (see Fig. 1). In both systems, however, the observed spins do not fall into a single rotational sequence, in contrast to the behavior of lighter systems.[9]

The seemingly irregular spin sequence, however, qualitatively can be understood as due to a series of shape resonances in the ion-ion potential. This is illustrated in Fig. 3, where for the system $^{16}O+^{28}Si$ the potential resonances are calculated as a function of energy using the real Woods-Saxon equivalent of a folding potential determined by Satchler.[14] Note the various rotational bands corresponding to states with different principal quantum numbers. The moments of inertia of these bands are considerably smaller than that of the grazing trajectory (full line in Fig. 3). The assumption that the observed structures are surface resonances, i.e., confined to a relatively narrow region around the grazing trajectory, leads to a nonrotational behavior of the excitation function due to the crossing of the

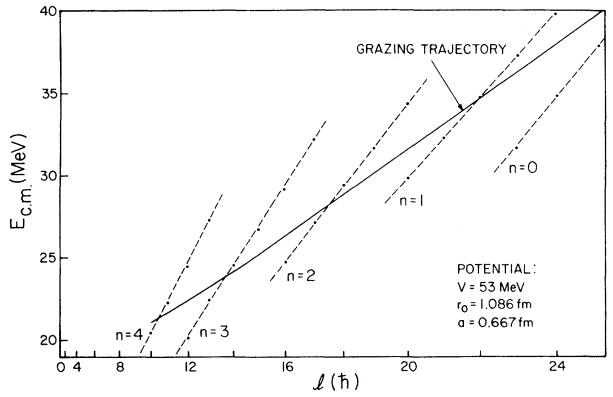

FIG. 3. Potential resonances calculated for the system $^{16}O + ^{28}Si$ using the real Woods-Saxon equivalent of the folding potential of Ref. 14. The different rotational bands (dashed lines) are classified according to their principal quantum number n. The grazing trajectory for this potential is indicated by the solid line.

grazing trajectory with rotational bands with different principal quantum numbers. For example, selection of only states close to the grazing trajectory yields a series of shape resonances for the present potential of $l = 11$ ($E_{c.m.} = 22.3$ MeV), $l = 14$ ($E_{c.m.} = 24.5$ MeV), $l = 17$ ($E_{c.m.} = 27.1$ MeV), $l = 18$ ($E_{c.m.} = 29.4$ MeV), $l = 21$ ($E_{c.m.} = 32.3$ MeV), and $l = 22$ ($E_{c.m.} = 34.7$ MeV). Note that the calculated average resonance spacing of $\Delta E = 2.5$ MeV qualitatively agrees with the data. Furthermore, at a given energy, resonances with different angular momenta and different principal quantum numbers such as $l = 19$, $n = 2$ and $l = 21$, $n = 1$ at $E \approx 32$ MeV may overlap, further complicating the interpretation of the angular distributions. These features are due to the fact that the potential is deep enough, even for $l = 22$, to allow for several quasibound states with different principal quantum numbers.

The above calculations are intended only to illustrate a possible explanation of the data. Clearly some form of absorption has to be included in a more realistic calculation, which also should take into account the effects of channel coupling. These will influence both position and widths of the calculated resonances. An experimental test of this picture will require detailed angular distributions at many closely spaced energies.

The interpretation of the present data in terms of a series of molecular shape resonances is similar to the one proposed in Ref. 9. This model also yields a natural explanation for the observed intermediate structure as due to a coupling between different shape resonances (doorway states).[15]

To summarize, we have observed for the systems $^{12}C + ^{28}Si$ and $^{16}O + ^{28}Si$ a series of gross structure resonances which are modulated for $^{12}C + ^{28}Si$ by a structure of intermediate width. The measured spin sequences do not follow a single rotational band. An interpretation of the data is suggested in terms of shape resonances with different principal quantum numbers in the ion-ion potential. This establishes the previously suggested[5] connection between the present data and the molecular resonances observed in the lighter systems and hopefully brings us closer to a detailed understanding of these phenomena.

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Reflex Tetrode with Unidirectional Ion Flow

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Experimental results are reported which show that the backward-directed (and unusable) ion current in a reflex triode can be almost completely suppressed by adding a second anode, made of aluminized Mylar, 0.5 cm from the existing polyethylene anode. Proton-generation efficiencies in excess of 50% have been obtained.

During the last few years, remarkable progress has been made on the development of pulsed, high-current, ion sources.[1-9] Presently, pulsed ion sources are available[1,3] at power levels in excess of 0.2 TW, and even higher power levels are anticipated in the near future. Among the various ion sources the reflex triode has several attractive features. For example, it can operate in the presence of a magnetic field and its ion current can be considerably higher than that predicted for bipolar flow. However, the reflex triode has the undesirable feature that about one-half of the ion current flows toward the cathode of the device and thus is wasted. Therefore, under the best conditions, the optimum efficiency of an ordinary reflex triode cannot exceed 50%. For any practical device the efficiency is less than 30%.

In this Letter we report results which demonstrate that by adding a second anode to an ordinary reflex triode the wasted ion current can be reduced to $\lesssim 5\%$, i.e., $\gtrsim 95\%$ of the ion current propagates toward the virtual cathode and thus can be extracted out of the source and utilized. So far, ion-generation efficiencies in excess of 50% have been obtained.

The reflex-tetrode configuration with double anode is illustrated schematically in Fig. 1(a). A 5-cm-diam graphite cathode, maintained at ground potential, is located ~1.5 cm from the first anode, A_1. This anode consists of a 6-μm-thick aluminized Mylar foil. The second anode, A_2, is placed ≈ 0.5 cm from A_1 toward the virtual cathode and is made of a 13-μm-thick polyethylene foil which is the primary source of protons. The anodes are mounted on the edges of a 12.7-cm i.d. aluminum ring that is connected to the seven-ohm line (SOL) generator, which is operated in positive polarity. Typical peak output voltage of this generator is ~500 kV with a pulse width of ~50 nsec (full width at half-maximum). The experiments are performed with an axial magnetic field of ~5.6 kG.

The motivation for using this double-anode geometry was to obtain an electric potential profile in which protons from the anode plasma would be preferentially accelerated in the forward direction, i.e., toward the virtual cathode. In an ordinary reflex triode, the potential is more or less symmetric in the vicinity of the anode, so protons are emitted in both the forward and backward directions in approximately equal numbers. The addition of the second anode modifies the potential in such a way that most of the ions emitted at A_2 are unable to reach A_1, as may be seen

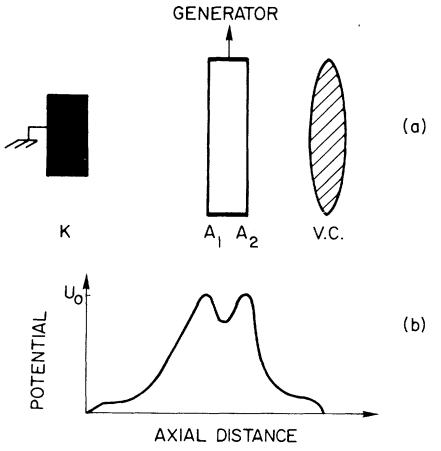

FIG. 1. (a) Schematic of reflex tetrode. (b) Qualitative electric potential profile of this configuration.

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