Unexpected Backward-Angle Enhancement in ^{19}F + ^{12}C Scattering

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Backward-angle excitation functions have been measured for the ^{12}C + ^{19}F elastic and inelastic scattering between $E_{\text{c.m.}} = 7.4$ and 24.4 MeV. Three prominent gross structures (18.0, 20.7, and 22.1 MeV) are observed. The corresponding back-angle elastic angular distributions can each be fitted by a $P_{L,0}^2 (\cos\theta)$ function whose L value tracks about one unit above l_{grazing}.

Since the recognition by Braun-Munzinger *et al.*[1] of anomalously large yields in the back-angle ^{28}Si + ^{16}O elastic scattering, there have been a number of investigations aimed at elucidating the phenomenon.[2-11] This effect appears most dramatically in α-conjugate nuclei and diminishes or disappears almost entirely when an odd or non-α-conjugate even nucleus is substituted. Very recently, Dussel *et al.*[12] have made a comprehensive study of all light heavy-ion systems, with $8 < Z_1 + Z_2 < 36$, $A_1 + A_2 > 8$, in terms of the energy associated with a given partition of the total charge and mass between the two colliding ions. A striking, albeit not perfect, correspondence was found between the minimum-energy partition, determined essentially by the binding energies of the colliding pair, and the presence and absence of the back-angle enhancement effect.

We report here the discovery of anomalous back-angle elastic- and inelastic-scattering cross sections in an *odd*-mass system, ^{19}F + ^{12}C, where the 180° gross-structure excitation-function anomalies (elastic-to-Rutherford and peak-to-valley ratios) exceed even those of the prototype ^{28}Si + ^{16}O or ^{12}C systems. This specific system is not, by several megaelectronvolts, a partition predicted by Dussel *et al.* to have enhanced back-angle yields. In fact, three very prominent structures are apparent in the elastic and inelastic excitation functions where the elastic yield at 180° peaks between 6% and 8% of the Rutherford scattering value and the excursion from maximum to minimum in the cross sections is more than a factor of 20:1. At the centroid energies

of these gross structures, limited ($130° < \theta_{\text{c.m.}} < 171°$) angular distributions were measured and oscillatory, backward-rising shapes were found for both the elastic and the inelastic groups. The elastic data can be fitted at each energy by a $P_{L,0}^2 (\cos\theta)$ function whose L value tracks about one unit above the grazing partial wave. The inelastic angular distributions can be shown to be consistent with the same dominant entrance partial wave L as in the elastic angular distributions.

The excitation-function data were measured at Brookhaven National Laboratory with use of a ^{19}F beam incident on a 10-μg/cm^2 natural-carbon target. The forward-recoiling ^{12}C nuclei were momentum analyzed in the Brookhaven National Laboratory quadrupole-triple-dipole magnetic spectrometer and detected in a dual-chamber gas-counter system with the magnet placed at either 0° or 6° in the lab frame ($\pm 2.86°$). The extreme thinness of the targets was mandated by the two low-lying states in ^{19}F ($E_{\text{ex}} = 0.110$ MeV, $\frac{1}{2}^-$, and 0.197 MeV, $\frac{5}{2}^+$) whose excitation we wished to resolve from the elastic scattering. With such a target, 35-keV resolution (full width at half maximum) was achieved and we were able to rule out the presence of any significant excitation of the two-particle, one-hole $\frac{1}{2}^-$ state in ^{19}F. Deposited on the face of the target for normalization purposes was a thin layer of gold whose elastic-scattering group was detected in solid-state monitor counters placed on opposite sides of the beam direction. Despite the fact that no charge state of the odd-mass ^{19}F beam is degen-

erate in magnetic rigidity with the recoiling ^{12}C, it was necessary at 0° to introduce a nickel absorber flap in front of the focal-plane detector to prevent apparently slit-scattered beam from saturating the counter. These absorber foils were varied in thickness from 64 to 135 μm as the incident beam energy was raised and because their use was required no 0° (180° c.m.) data were taken below 45-MeV incident energy. Excitation data were taken between $E_{lab} = 19$ and 46.5 MeV incident energies at 6° (168° c.m.) where there was no need for the focal-plane counter absorber foils. At several energies both the charge-state 6 and charge-state 5 yields of the recoiling ^{12}C ions were measured. Corrections were made for the additional charge-state fractions according to the formula of Betz.[13]

As illustrated in Fig. 1, for this system the gross structure in the elastic scattering is by far the dominant feature at 180°, almost completely overwhelming any trace of intermediate structure. Three structures are seen ($E_{c.m.} = 18.0$, 20.7, 22.1 MeV) at this angle and there is the hint at the highest measured energy that a fourth structure will occur. Excitation-function data were measured in rather small steps (0.194 MeV, c.m.) to look for the fine structure apparent in other experiments. None was found. At the 168° observation angle, the $E_{c.m.} = 18.0$-MeV structure is seen to have a cross

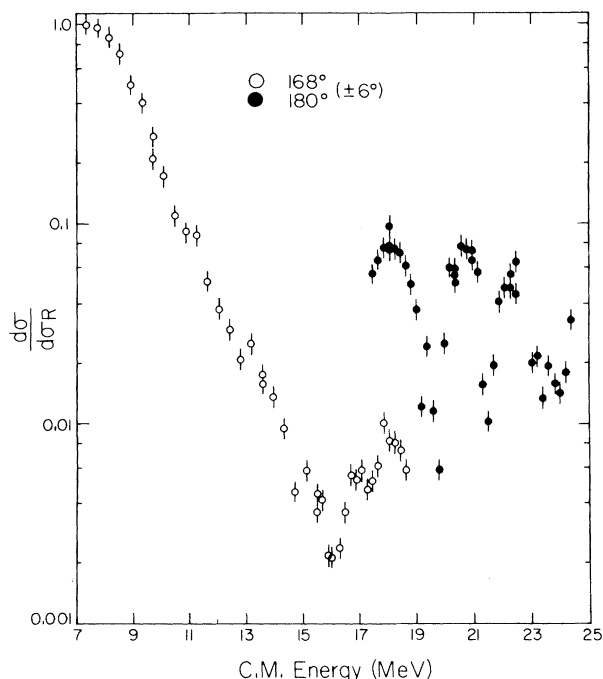section a factor of 10 below the 180° yield, indicating that the angular distribution must be backward rising. The 168° data also give some evidence of lower-energy structures, perhaps at $E_{c.m.} = 11.3$, 13.0, and very slightly at 14.9 MeV. Such structures would, of course, be more evident at 180°. Similar structures at 180° and 168° are also present in the $E_{ex} = 0.197$-MeV data as shown in Fig. 2.

Subsequent to the excitation-function data analysis, an angular-distribution experiment for ^{19}F + ^{12}C at back angles was conducted at Los Alamos National Laboratory. Angular distributions were measured at the above three "resonance" energies, as well as at an "off-resonance" energy $E_{c.m.} = 21.3$ MeV, with the Los Alamos National Laboratory quadrupole–triple-dipole spectrometer. The angular-distribution data for the ground and second excited states of ^{19}F are presented in Figs. 3 and 4. Both groups are seen to yield oscillatory, backward-rising angular distributions whose oscillation frequency increases with increasing beam energy. For spin-0 on spin-0 systems it is usual to extract a "resonant L" value by fitting the back-angle oscillations with a $P^2_{L,0}(\cos\theta)$ function. In this case, with a spin-$\frac{1}{2}$ projectile, such a procedure is also possible since for a given channel spin and parity J^π there is a unique L value which contributes to the S-matrix summation. (This would not necessarily be true for spin-1 or greater projectiles.) Fits to the elastic angular distributions (Fig. 3) can be
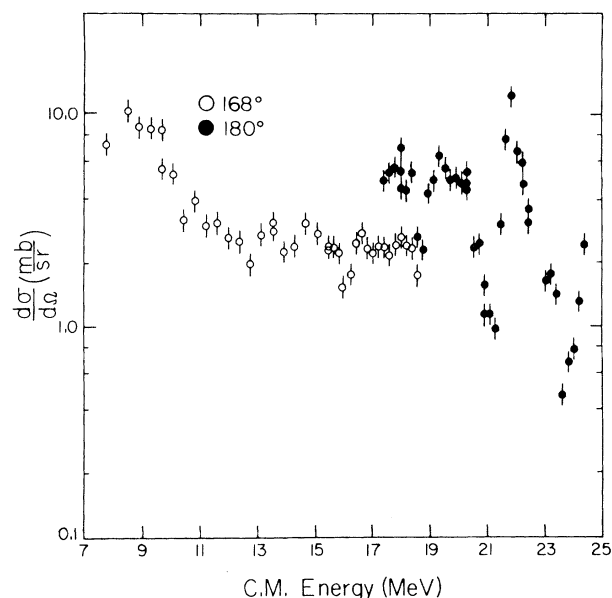

FIG. 1. Excitation functions for ^{19}F + ^{12}C elastic scattering taken at $\theta_{c.m.} = 180°$ and 168°.

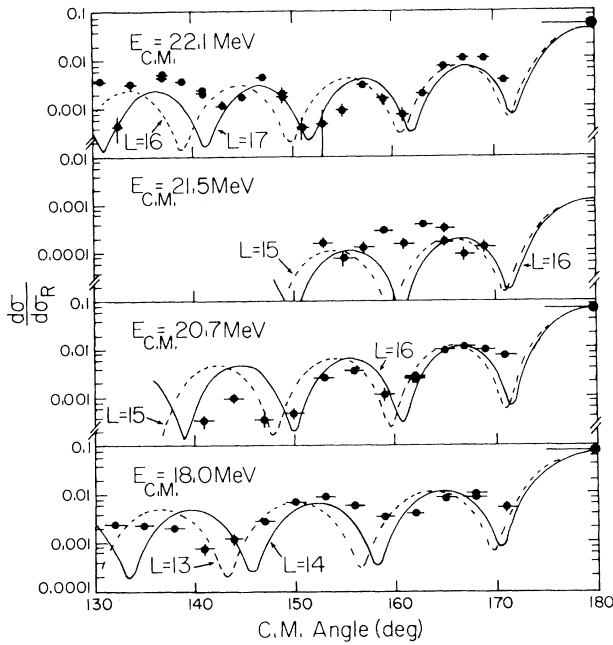FIG. 2. Excitation functions for ^{19}F + ^{12}C inelastic scattering going to the ^{19}F* $\frac{5}{2}^+$ state at 0.197 MeV.

FIG. 3. Angular distributions for ^{19}F + ^{12}C elastic scattering taken at three incident energies, $E_{c.m.} = 18.0$, 20.7, and 22.1 MeV, which are near maxima in the gross structures of the excitation-function data. The fourth energy, $E_{c.m.} = 21.3$ MeV, corresponds to a deep minimum in the excitation-function data. The curves through the data are angle-averaged $P_{L,0}^2(\cos\theta)$ functions normalized to the experimental yields.

obtained with $P_{L,0}^2(\cos\theta)$ shapes whose L value tracks about one unit above the grazing partial wave: $E_{c.m.} = 18.0$ MeV, $L = 14$, $l_{gr} = 13$; $E_{c.m.} = 20.7$, $L = 16$, $l_{gr} = 15$; $E_{c.m.} = 22.1$, $L = 17$, $l_{gr} = 16$. The grazing partial-wave values were obtained with the optical-potential parameters of Voos
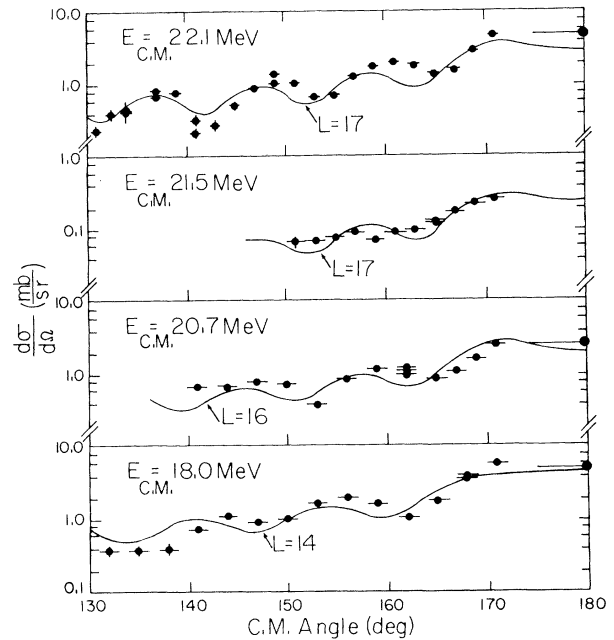

FIG. 4. Angular distributions for the inelastic scattering exciting the ^{19}F* state at 0.197 MeV. The curves through the data represent an incoherent sum $(M = 0, 1, 2)$ of angle-averaged $P_{L,M}^2(\cos\theta)$ functions having the same L values as the fits to the elastic "resonant" angular distributions shown in Fig. 3.

$et\ al.$ [14] who measured ^{19}F + ^{12}C elastic scattering at c.m. energies 15.5 and 23.2 MeV.

Besides being correlated in energy with the elastic gross structures, the inelastic excitation-function structures can be shown to have angular distributions correlated in L with the elastic angular distributions. The inelastic differential cross section for exciting the $\frac{5}{2}^+$ level is given by

$$\frac{d\sigma}{d\Omega}(\theta)_{inel} = \sum_{m_a, m_a'} \left| \frac{1}{2ik} \sum_{J,L,L'} \langle L\frac{1}{2}0m_a | Jm_a \rangle \langle L'\frac{5}{2}(m_a - m_a')m_a' | Jm_a \rangle \right.$$

$$\left. \times [(2L+1)(2L'+1)]^{1/2} e^{i(\sigma_L + \sigma_{L'})} \left[\frac{(L-M')!}{(L+M')!} \right]^{1/2} S_{L,L'}^J P_{L',M'}(\cos\theta) \right|^2, \quad (1)$$

where $M' = |m_a - m_a'| = 0, 1, 2, 3$.

Again, for a given J^π channel spin and parity, only one incident partial wave L contributes. However, three outgoing partial waves $L' = L - 2, L, L + 2$ can be coupled coherently to produce the differential cross section. If a single L is dominant in Eq. (1), then the allowed $P_{L',M'}(\cos\theta)$ become in phase at the backward angles which can lead to a backward-rising shape. In fact, if only the diagonal $L' = L_{elastic}$ term is considered in Eq. (1), then an ad hoc superposition of $P_{L,M}^2(\cos\theta)$ functions

$(M = 0, 1, 2$ ignoring the noncentral $M = 3$ contribution) results in the qualitatively acceptable fits to the inelastic angular distributions illustrated in Fig. 4. In these fits, the $M = 2$ contribution is the most important, the $M = 1$ fills in the oscillations, and the $M = 0$ contribution yields the finite cross section at 180°.

The "off-resonance" angular-distribution data are also given in the figures and within their statistical accuracy there is no evidence of oscillation,

although there is somewhat of a backward rising no-
ticeable in the excited-state angular distribution.
The failure of the "off-resonance" elastic and in-
elastic angular distributions to show oscillation here
is inconsistent with the pronounced oscillation seen
"off resonance" in $^{28}Si + ^{16}O$ (Ref. 9, Fig. 11), but
is similar to the behavior of the $^{28}Si + ^{12}C$ system
"off resonance."

Counting the three lower-energy structures which
are just visible in the 168° data, and presuming that
there is a new structure occurring somewhat above
$E_{c.m.} = 24$ MeV, there are likely to be seven fairly
equally spaced gross-structure peaks eventually un-
covered in the 180° elastic scattering between
$E_{c.m.} = 11$ and 25 MeV. So far the L sequence (14,
16, and 17) is also more regular than in previously
measured systems, but clearly more angular-
distribution data are required to verify this point.
At present, though, one should note that in the ad-
jacent, α-conjugate scattering system, $^{20}Ne + ^{12}C$,
the L sequence was found to be extremely erratic
($L = 15$, 14, 19 at $E_{c.m.} = 27.2$, 27.8, and 28.2) in
an energy region where the l_{gr} value was 20–21. In
that system, it was thus concluded that the grazing
partial wave could not be a determining factor in
understanding the backward-angle structure. This
was the same conclusion reached in the $^{28}Si + ^{12}C$
and $^{32}S + ^{12}C$ analyses whereas for the present data
and for $^{28}Si + ^{16}O$ l_{gr} is apparently determinant.

To summarize, we have measured the near-180°
$^{19}F + ^{12}C$ elastic and inelastic excitation functions
between $E_{c.m.} = 7.4$ and 24.4 MeV. Three major
structures are observed in this range, with a likeli-
hood of at least four others also being present. The
appearance of backward-angle enhancement here
does not seem to fit well into the energy-partition
systematics reported by Dussel *et al.* Nonetheless,
the simplicity and the dramatic prominence of the
effect in $^{19}F + ^{12}C$ should play an important role in
unraveling the nature of enhanced back-angle
heavy-ion elastic scattering.

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