[17]In Ref. 15, a model with an enlarged gauge group is constructed in which all such "self-energy" diagrams are finite. The result is, to a good approximation, equivalent to cutting off the divergence in the SU(2) ⊗ U(1) theory with a mass comparable to M_W.

[18]Cheng and Li, Ref. 5.

Effect of Inelastic Excitation on Elastic Scattering of Heavy Ions

C. E. Thorn, M. J. LeVine, J. J. Kolata, C. Flaum, and P. D. Bond
*Brookhaven National Laboratory, Upton, New York 11973**

and

J.-C. Sens
Centre de Recherches Nucléaires et Université Louis Pasteur, 67037 Strasbourg-Cédex, France

(Received 1 November 1976)

The elastic-scattering angular distribution of 90-MeV ^{18}O on ^{184}W exhibits a dramatic deviation from the typical Fresnel shape, which cannot be reproduced by standard optical-model calculations. The effect, a decrease in the elastic cross section below the Rutherford cross section even at forward angles, is due primarily to Coulomb excitation, and will be even more pronounced for heavier projectiles.

Recent analyses of two-nucleon transfer reactions induced by heavy ions on deformed rare-earth targets have shown the necessity of explicitly including the strong coupling within the ground-state rotational band (GSB) in order to reproduce the observed angular distributions.[1] The present experiment was undertaken to look for evidence of this strong coupling in the elastic-scattering angular distributions.

The typical angular distribution for heavy-ion elastic scattering has a form characteristic of Fresnel diffraction (see, e.g., the $^{18}O+^{208}Pb$ data in Fig. 1). Most previous measurements of heavy-ion "elastic scattering" from deformed targets have obtained similar angular distributions, but have suffered from energy resolution insufficient to resolve low-lying members of the GSB from the ground state.[2] Recently, a survey of elastic scattering of ^{12}C ions from various Nd isotopes,[3] in which the 2^+ states were resolved, revealed a systematic damping of the oscillations in the ratio $\sigma_{el}/\sigma_{Ruth}$ with increasing target deformation. The angular distributions were still of the Fresnel diffraction form, however. In this Letter we demonstrate that, for projectiles with sufficiently large Z, inelastic excitation can drastically modify the shape of the elastic-scattering angular distribution, even at angles well forward of the grazing angle.

The experiments were performed with 70-MeV ^{12}C and 90-MeV ^{18}O beams from the Brookhaven National Laboratory (BNL) tandem Van de Graaff facility. Great care was taken to minimize motion of the beam spot on the target since elastic scattering can be quite sensitive to small variations in scattering angle. The beam position was monitored by two silicon surface-barrier detec-

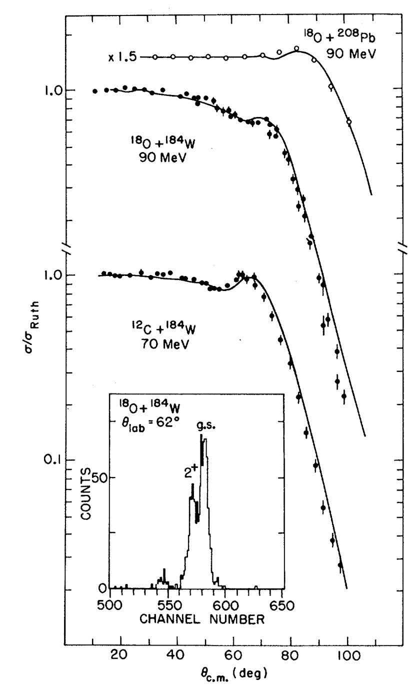

FIG. 1. Elastic-scattering angular distributions. Error bars represent random errors arising from statistics and uncertainties in fitting to the peaks. The curves are coupled-channels calculations using the parameters of Table I. Inset: A typical position spectrum from the focal-plane detector, showing the clear resolution of the ground and first excited states in ^{184}W.

tors placed on either side of the beam, and also by measuring the current on a collimator located upstream from the target position.

The targets were 10 $\mu g/cm^2$ of WO_x enriched to >95% in ^{184}W, evaporated onto 10-$\mu g/cm^2$ C backing foils. The scattered ions were detected and identified by a 75-cm-long dual proportional counter in the focal plane of the BNL QDDD spectrometer. The front counter measured both position and the energy loss, ΔE, of the ions and the rear counter measured the residual energy loss, E_2. A two-dimensional map of position versus E_2 was used to identify the particles. The spectrometer was typically operated with a solid angle of 0.5 msr and an acceptance angle of $\pm 0.25°$. Under these conditions, an energy resolution of 60 keV full width at half-maximum (FWHM) for ^{12}C and 80 keV FWHM for ^{18}O was obtained, which was sufficient to extract the 111-keV, 2^+ state and the ground-state yields at most angles (see inset in Fig. 1) by fitting the peak shapes. Measurements were made on the 6^+ and 8^+ charge states of ^{12}C and ^{18}O, respectively, and at some angles on the 5^+ and 7^+ charge states so that the data could be corrected for the small effect of the energy-dependent charge-state distributions. Elastic scattering from impurities with $A < 160$ was investigated and amounted at most to a 0.6% correction to the elastic yield.

The angular distributions observed for elastic scattering of ^{18}O and ^{12}C on ^{184}W are shown in Fig. 1, as a ratio to the Rutherford cross section. The ^{18}O data, taken in two separate runs, demonstrated excellent reproducibility within experimental errors which are often smaller than the data points shown. In addition to the random uncertainties illustrated by the error bars, there exists a small systematic error corresponding to an uncertainty of $\pm 0.25°$ in determining the absolute angle. This error is negligible at all but the most forward angles where it can change the ratio $\sigma_{el}/\sigma_{Ruth}$ by as much as 5%.

It is quite clear from these data that heavy-ion elastic-scattering angular distributions need not always be of the "standard" form. Dramatic deviations from Rutherford scattering are evident for $^{18}O + ^{184}W$ at angles as far forward as 40° (i.e., nearly 40° forward of the grazing angle), and the characteristic rise above Rutherford never appears. The reduction in the cross section at 70°, near the expected maximum in $\sigma_{el}/\sigma_{Ruth}$, exceeds 30%. A very similar angular distribution has been observed for the elastic scattering of ^{16}O on ^{186}W (not illustrated) so that the effect is not as-

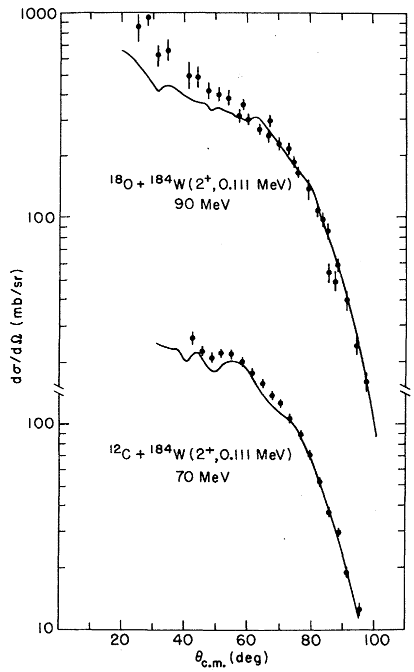

FIG. 2. Angular distributions for the inelastic scattering to the ^{184}W 2^+ state. The curves represent coupled-channels calculations described in the text.

sociated with a special property of ^{18}O other than its charge. The $^{12}C + ^{184}W$ angular distribution (Fig. 1) is not as striking, but here also a reduction in cross section is observed. In this case the cross section barely manages to return to σ_{Ruth} before the dropoff.

The angular distributions for inelastic scattering of ^{12}C and ^{18}O to the ^{184}W 2^+ state are shown in Fig. 2. At forward angles the 2^+ cross section for ^{18}O scattering rises to greater than 500 mb/sr and at the most backward angles the 2^+ yield is greater than the elastic yield. With such a large population of the 2^+ state it is not surprising that attempts to fit the $^{18}O + ^{184}W$ elastic scattering with a standard optical-model calculation were unsuccessful. If the particles travel on Coulomb trajectories, an assumption which should be valid for the $^{18}O + ^{184}W$ experiment where the Sommerfeld parameter $\eta = 42$, removal of flux from the elastic channel at a c.m. angle of 45° would require an imaginary potential whose range extends to >19 fm. Since this is well beyond the range of the nuclear potential, one must conclude that the primary mechanism for the absorption is Coulomb excitation; hence the implication that the elastic scattering cannot be fitted with standard optical-model potentials, which allow only short-range absorption, is inescapable (see also

TABLE I. Parameters used in the coupled-channels calculations. The optical-model parameters refer to real and imaginary Woods-Saxon wells of identical geometry, with radius $R = r_0(A_1^{1/3} + A_2^{1/3})$. The Coulomb matrix element $\langle 0 \| \mathfrak{M}(E2) \| 2 \rangle$ and $\beta_N R$ were taken from Ref. 6, and the rotational model was used to calculate the static quadrupole moment.

Reaction	V (MeV)	W (MeV)	r_0 (fm)	a (fm)	$\langle 0 \| \mathfrak{M}(E2) \| 2 \rangle$ ($e \cdot$ b)	$\beta_N R$ (fm)
$^{18}O + ^{184}W$	−40	−25	1.290	0.508	1.94	1.554
$^{12}C + ^{184}W$	−40	−15	1.256	0.550	1.94	1.554
$^{18}O + ^{208}Pb$	−40	−23.5	1.271	0.550	⋯	⋯

Weber[4]).

The hypothesis that the observed effects in the elastic scattering are due to strong coupling to the 2^+ member of the GSB was tested with coupled-channels calculations using a modified version of a code due to Pelte and Smilansky.[5] The Coulomb-excitation matrix elements and deformation parameters (Table I) used in the analysis, which included only the 0^+ and 2^+ members of the GSB, were taken from the literature.[6] In order to compare our results to previous low-resolution experiments, the GSB differential cross sections were added, resulting in the familiar Fresnel shape even for the $^{18}O + ^{184}W$ case. We obtained optical-model parameters (Table I) by fitting this sum in a standard optical-model calculation.[7] The coupled-channels calculations using these parameters show remarkable agreement with both the experimental elastic scattering cross sections (Fig. 1) and the inelastic scattering to the 2^+ state (Fig. 2). No further attempt to obtain a better fit to the data was made. It should be noted that the coupled-channels calculations reproduce both the strong effect in the $^{18}O + ^{184}W$ scattering and the small change in shape displayed by the $^{12}C + ^{184}W$ elastic angular distribution.

In summary, a high-resolution experiment on elastic scattering of heavy ions from deformed targets has demonstrated that strong coupling (principally Coulomb excitation) can dramatically influence elastic-scattering angular distributions at angles far forward of the grazing peak. Even larger deviations from Rutherford scattering at forward angles can be expected with heavier projectiles.

The authors would like to thank Dr. J. Vaagen for stimulating this investigation. One of us (J.C.S.) would like to acknowledge the hospitality accorded him by the Physics Department of Brookhaven National Laboratory.

*Work supported by the U. S. Energy Research and Development Administration.

[1]K. A. Erb *et al.*, Phys. Rev. Lett. 33, 1102 (1974); R. J. Ascuitto *et al.*, Phys. Lett. 55B, 289 (1975).

[2]See, for example, J. R. Birkelund *et al.*, Phys. Rev. C 13, 133 (1976).

[3]D. L. Hillis *et al.*, ORNL Physics Division Annual Progress Report No. ORNL-5137, 1975 (unpublished), p. 46.

[4]D. J. Weber *et al.*, Bull. Am. Phys. Soc. 21, 1006 (1976).

[5]Coupled-Channels Code from D. Pelte and U. Smilansky, unpublished. This code was modified to allow coupled channels to partial wave 200, and to incorporate a routine which allows the calculation of Coulomb wave functions for large ρ and η.

[6]I. Y. Lee *et al.*, Phys. Rev. Lett. 33, 383 (1974).

[7]Code A-Three, E. H. Auerbach, unpublished.