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Coulomb-Nuclear Interference for High-Spin States Excited by ^{86}Kr, ^{40}Ar, and ^{16}O Projectiles

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We report the first experimental evidence for Coulomb-nuclear interference in the excitation of high-spin states by very heavy projectiles. The data are intepreted with use of a model described previously, and the feasibility of using this method to study the deformed nuclear surface is demonstrated.

Inelastic excitation in the Coulomb-nuclear interference (CNI) region has been studied extensively for ions such as helium,[1] carbon,[2] and oxygen.[3] However, little attention has been given to CNI in the scattering of very heavy projectiles from highly deformed nuclei. Previously[4] we introduced a new theoretical formalism describing such processes. We present here the first experimental data for such systems, and interpret the results with that formalism.

We have studied the systems ^{86}Kr + ^{232}Th, ^{40}Ar + ^{238}U, and ^{16}O + ^{162}Dy, with projectiles from the Berkeley SuperHILAC, and the Oak Ridge isochronous cyclotron. In all cases the de-excitation γ-ray cascade was detected in coincidence with backscattered particles, using standard Ge(Li) and annular silicon-detector arrangements. The annular geometry yielded average particle scattering angles of $\theta_{\text{c.m.}} \sim 165°$.

Thick targets were used, and γ-ray spectra as a function of incident beam energy were generated by taking coincidence cuts in the heavy-ion spectrum, each corresponding to a different effective beam energy. The relation of incident beam energy (checked by time-of-flight measurements) to detected particle energy was determined using elastic kinematics and theoretical stopping powers. With these methods we obtained spectra simultaneously at several different energies, with an estimated uncertainty ~1% in the definition of incident beam energy on a given nucleus in the thick target.

The number of particle-γ coincidences N_γ was determined from the areas of the γ-ray peaks corrected for efficiencies, γ-ray angular distributions, conversion coefficients, and cascade feeding. Because of the backward-scattering particle coincidence requirement only $m \sim 0$ magnetic substates are excited, whether the excitation mechanism is nuclear or Coulomb. Therefore, the γ-ray angular distributions were calculated using the Winther–de Boer formalism.[5] The number of heavy ions N_p detected at a given angle was determined from the relevant energy cut of the singles heavy-ion spectrum, and the excitation probability was defined by $P = N_\gamma / N_p$. We assume in this definition that the projectile follows an approximate Rutherford trajectory, a condition which should be fulfilled for the present subbarrier data.

The excitation functions for various states are displayed in Fig. 1, along with an example representative of results obtained in α-particle experiments.[1] The solid line in each figure represents the result expected for pure Coulomb excitation, calculated as described in Ref. 4, with use of the best experimental values of $B(E2,\ 0 \rightarrow 2)$ and $B(E4,\ 0 \rightarrow 4)$[1,6] and the rotational model. The high accuracy of this method has been discussed by Donangelo *et al.*[7] Calculations with the Winther–de Boer method[5] yield the same probabilities as Ref. 4, to ~±10%. The accuracy of the Winther–de Boer method (and hence the present method) has been demonstrated experimentally for heavy-ion Coulomb excitation.[8] For the highest spins in Fig. 1 we have taken probabilities

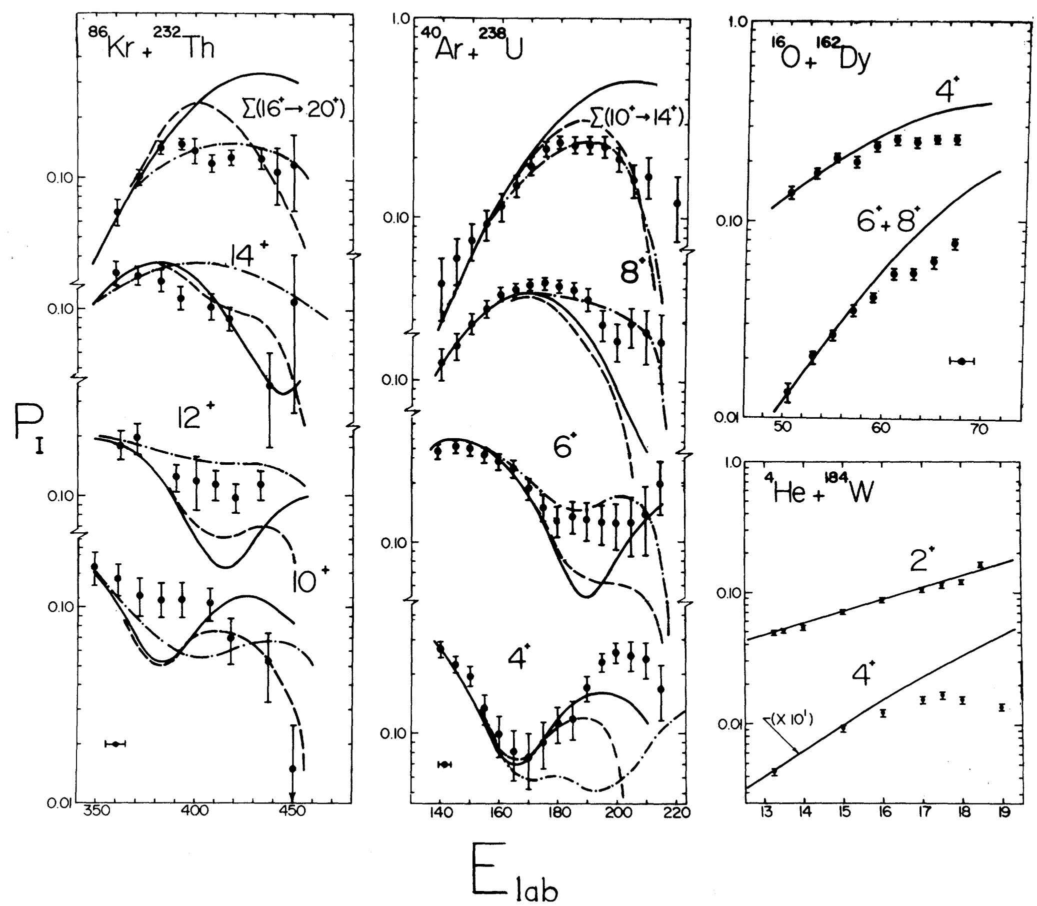

FIG. 1. Excitation functions in the CNI region. The solid line is a calculation for pure Coulomb excitation. ^{4}He data are from Ref. 1. The approximate energy uncertainty is indicated by the horizontal bars at the bottom corners. Dashed and dash-dotted lines are calculations using a nuclear potential as described in Ref. 4. The potential parameters are taken from Refs. 9 (dashed) and 10 (dash-dotted), and correspond to potentials III and II, respectively, in Ref. 4.

summed over 2–3 states to minimize errors in correcting for feeding, but the dominant contribution is from the lowest state in the sum.

Several things should be noted concerning these examples: (1) The probabilities agree well with Coulomb excitation calculations at low energies. (2) The interference effects are large. (3) In contrast to the usual α-particle results, there are a variety of *constructive* and *destructive* interferences in the regions where CNI first begins. (4) The sign, strength, and energy for onset and extrema of the interference are state dependent.

We now demonstrate that the general features of these data are explained by the simple model underlying the calculations of Ref. 4. To conserve space, we assume some familiarity with that model in the following discussion. The excitation probability for backward scattering from a deformed rotor can be written as

$$P \approx p_1 + p_2 + 2(p_1 p_2)^{1/2} \sin[\mathrm{Re}(\Phi_2 - \Phi_1)] \qquad (1)$$

("allowed states"),

$$P \approx p e^{-2\,\mathrm{Im}\,\Phi} \qquad (\text{"forbidden states"}), \qquad (2)$$

where the three terms in Eq. (1) arise from the coherent contribution of two different initial rotor orientation angles for a particular state. The classical action in units of $\hbar$ is denoted by Φ, and the lower-case p's are the purely classical probabilities for a given initial orientation. Only a single exponentially damped term contributes to P for classically forbidden states (the highest-spin states).

In the following we assume only that the nuclear interaction can be approximated by a smooth complex potential which is largely real in the surface region. Then to a good approximation, the initial effect of the potential is confined to the phases of Eqs. (1) and (2), decreasing the real phase difference in Eq. (1), and increasing the imaginary phase of Eq. (2); with the small p's not affected very much.[4] Therefore, in this region the effect of the CNI can be predicted from the effect of the nuclear potential on the sine term in Eq. (1), and the exponential damping factor in Eq. (2). Remembering that the oscillations in the pure Coulomb excitation probabilities for allowed states arise from the sine term (see, e.g., Ref. 4), and that the forbidden states (highest spins) are characterized by steeply rising excitation functions, the following general rule emerges: *The initial Coulomb-nuclear interference will be constructive (destructive) if the excitation function for pure Coulomb excitation is approaching or at a minimum (maximum).* Consulting Fig. 1, we note that this simple prediction holds for every case displayed except for the 4^+ state in the ^{40}Ar + ^{238}U reaction. This is probably associated with the interference beginning in this case at a higher energy (~195 MeV), where p_k's are also affected, and the conditions for the above rule are not fulfilled.

From the rule and Fig. 1 it is apparent why only destructive initial interferences are seen for α-particle rotational excitation of 2^+ and 4^+ states. For sub-barrier scattering, the monopole-quadrupole interaction is not sufficient with α particles for either the 2^+ or 4^+ probability to have passed its first maximum, and the CNI is always destructive. That is, a critical value of the quadrupole coupling strength $\bar{q}_2$ is necessary for constructive initial interference when the simple rule applies. In practical terms, for well-deformed targets the Z of the projectile must exceed a value lying roughly in the region between Ne and Ar projectiles, before the initial interference may be constructive. It follows that the seemingly different *qualitative* behavior of α-particle and ^{16}O CNI compared to heavier-particle CNI actually arises from the same physics. This does not preclude the possibility of *quantitative* differences, to be discussed shortly.

We emphasize that the simple rule discussed here becomes less valid for deeper penetration into the complex nuclear potential. In that case, one must rely on detailed calculations.[4] However, the agreement of the results quoted here with the rule suggests that it is applicable for a large number of cases, and that the basic model of Ref. 4 is correct. As pointed out in Ref. 4, experiments of this type are expected to be delicate probes of the surface nuclear potential, due to the sensitivity of inelastic excitation to the phases in Eqs. (1) and (2). The existence of this sensitivity requires only that the model underlying those calculations be qualitatively correct. The results presented here demonstrate that this is so.

To calculate excitation probabilities in the CNI region, it is necessary to define a nuclear potential. The few experimental potentials available for very heavy ions are suspect because the true elastic events are not experimentally separated from a number of quasielastic ones. Despite this, the quasielastic peak is often used as if it were an elastic peak to determine a potential. The dashed and dash-dotted curves in Fig. 1

show calculations, described in Ref. 4, using complex deformed Woods-Saxon potentials determined in this manner from $^{40}Ar + ^{238}U$ and $^{84}Kr + ^{208}Pb$ scattering.[9,10]

The qualitative effect of these potentials, particularly the one of Ref. 10, is seen to be correct for several cases. However, they do not consistently fit all of the states for a particular system. For example, the potential of Ref. 10 (dash-dotted curve) seems approximately correct for the 12^+ and the sum of the 16^+ to 20^+ states in the Kr reaction, but misses badly for the 10^+ and 14^+ states. These results are not surprising in view of the above discussion and that of Ref. 4, and they suggest the following: (1) Nuclear potentials determined from experiments in which elastic and and inelastic components are not cleanly separated are not adequate to describe inelastic excitation in deformed nuclei. (2) The fact that these potentials fit some states but not others suggests that all states are not equivalent for determining nuclear potentials, and that inelastic excitation may carry information about the nuclear potential beyond that contained in the elastic scattering. (3) The success of the experimental method described here, and the calculations of Ref. 4, demonstrate that it is now possible to probe the nuclear surface by studying excitation of collectively coupled states directly, rather than by approximating their effect on the elastic channel as in Love, Teresawa, and Satchler.[11] In our opinion, this is necessary to describe properly the scattering of heavy ions from deformed nuclei.

The methods described here make it feasible to determine nuclear potentials in deformed systems by the requirement that they fit all inelastic states simultaneously. Because this is expected to place severe restrictions on the class of acceptable potentials,[4] a systematic determination of potential parameters by these methods should yield fundamental information about the structure of the deformed nuclear surface which cannot be obtained by more traditional methods.

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