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Interference Between Direct Nuclear Reactions and Coulomb Excitation with Alpha Particles on ^{154}Sm, ^{166}Er, and ^{182}W†

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Striking destructive interference effects have been observed in the ^{4}He excitation of the 2^+ and 4^+ ground-state band rotational states in deformed even-A ^{154}Sm, ^{166}Er, and ^{182}W. The $E2$ and $E4$ transition moments and charge deformation parameters, β_{20}^c and β_{40}^c, are given.

[NUCLEAR REACTIONS ^{154}Sm(α,α'), $E=11$–19 MeV; ^{166}Er(α,α'), $E=12.5$–19.5 MeV, ^{182}W(α,α'), $E=13$–21 MeV; measured $\sigma(E_\alpha;\theta=150°)$; deduced $B(E2)$, $B(E4)$. Enriched targets. Extracted model-dependent deformations, β_{20} and β_{40}.]

I. INTRODUCTION

At incident projectile energies sufficiently below the Coulomb barrier so that the projectile is well outside the range of nuclear forces, the elastic and inelastic scattering processes are completely described by Coulomb-excitation theory.[1] Since the cross sections for Coulomb excitation are a strong function of projectile energy, it is desirable to perform such experiments at the highest possible "safe" bombarding energy. A central experimental problem in Coulomb excitation is the continuing development of criteria for "safe" bombarding energies. When both Coulomb excitation and direct nuclear excitation contribute to the target excitation, the amplitudes are coherent and interference occurs. This interference markedly affects the experimental results if the experiments are analyzed under the assumptions of pure Coulomb excitation.

The interference between Coulomb excitation and direct nuclear excitation has been explored using α particles by several workers[2–4] and also investigated using heavy-ion projectiles.[5] In the recent work of Brückner *et al.*,[4] the α-particle excitation probabilities of the 2^+ and 4^+ ground-state band rotational states in ^{152}Sm were investigated in an energy range spanning the classical Coulomb barrier. The results from the sub-Coulomb barrier region were analyzed using Coulomb-excitation theory to yield the electric transition matrix elements $M_{02}(E2)$ and $M_{04}(E4)$ and corresponding charge deformation parameters β_{20}^c and β_{40}^c. The experimental results at higher energies, in the region of the interference minima and above the Coulomb barrier, were analyzed with a deformed optical-model theory for the direct reactions including the effects of Coulomb excitation. The pronounced influence of direct nuclear excitation on Coulomb excitation at energies well below the classical Coulomb barrier has prompted us to investigate this effect for three even-mass targets spanning the rare-earth deformed region, ^{154}Sm, ^{166}Er, and ^{182}W, in a manner similar to that of Brückner *et al.*[4] We were particularly interested in the sensitivity of the derived electric quadrupole and hexadecapole transition moments to projectile energy as well as the influence of the sign of the hexadecapole charge deformation parameter β_{40}^c on the Coulomb-nuclear interference effect.

II. EXPERIMENTAL METHOD AND RESULTS

Elastically and inelastically scattered ^{4}He ions at a laboratory angle of 150° from thin (25 μg/cm^2) isotopically pure targets of ^{154}Sm, ^{166}Er, and ^{182}W on carbon backings (40 μg/cm^2) were observed by means of an Enge split-pole magnetic spectrometer at the Oak Ridge EN tandem Van de Graaff accelerator. These targets were prepared using an electromagnetic isotope separator as described previously.[6] Scattered particles were detected in the spectrometer focal plane with a gas-flow position-sensitive proportional counter in a manner identical to that previously reported by us in studies of the quadrupole and hexadecapole charge deformations of even-mass deformed nuclei in the transuranium region.[6] Excitation functions were measured in 0.5- or 1.0-MeV steps in the energy range 11.0 to 21.0 MeV which spans the classical Coulomb barrier region for these targets.

A representative spectrum is shown in Fig. 1 for the excitation of ^{166}Er with 18.5-MeV α particles. Excitation probabilities for the 2^+, 4^+, and higher states were determined relative to the elastic scattering by integration of the appropriate peak areas. In general, the experimental ratios $d\sigma_{2^+}/d\sigma_{\mathrm{el}}$ were determined to an accuracy of 0.5 to 1% and the ratios $d\sigma_{4^+}/d\sigma_{\mathrm{el}}$ to an accuracy of 3 to 5%.

The excitation probabilities using the lowest

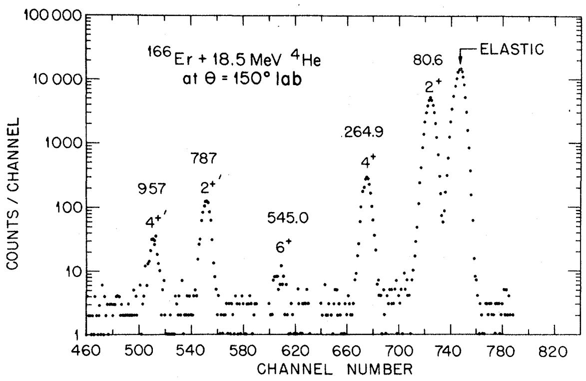

FIG. 1. Spectrum observed for the scattering of 18.5-MeV α particles from ^{166}Er at an angle of 150° (lab).

energy data for the 2^+ and 4^+ members of the ground-state bands as well as higher 2^+ states were analyzed using the semiclassical coupled-channels Coulomb-excitation code of Winther and deBoer[7] which was modified to include $E1$, $E3$, and $E4$ excitations. Rotational $E2$ and $E4$ static and transition moments were used for the intra-ground-state band transitions and the calculations included all possible $E2$ and $E4$ excitations up to and including the 6^+ state. The influences of the higher 2^+, 4^+, and 3^- states on the ground-state band excitation probabilities are very small but they were included in the calculations. We have applied the second-order quantum mechanical corrections to the calculated semiclassical 4^+ excitation probabilities for the pure double $E2$ excitation using the calculations of Alder, Roesel, and Morf.[8] These corrections reduced the calculated semiclassical excitation probability for the double $E2$ process by ~5% for the cases studied here.

The matrix elements $\langle 2^+ \| \mathfrak{M}(E2) \| 0^+ \rangle$ and $\langle 4^+ \| \mathfrak{M}(E4) \| 0^+ \rangle$ and the $E2$ elements for observed higher states were extracted from the 11.0-MeV data for ^{154}Sm, the 12.5-MeV data for ^{166}Er, and the 13.0-MeV data for ^{182}W. The experimental excitation probabilities for the 4^+ states exceeded the calculated probabilities by ~6% for ^{166}Er and ^{182}W and ~20% for ^{154}Sm if only $E2$ excitations were considered. The excess 4^+ excitation was interpreted as due to the presence of $E4$ excitations.

In the analyses, we have used the sign convention for $\langle 2^+ \| \mathfrak{M}(E2) \| 0^+ \rangle$ and all other $E2$ intra-ground-state band rotational matrix elements which correspond to the prolate quadrupole shape ($\beta_{20} > 0$). Theory[9,10] and previous experimental information both from (α, α') inelastic scattering[11,12] and from recent Coulomb excitation experiments[13-16] support the prolate quadrupole shape ($\beta_{20} > 0$) and indicate that the hexadecapole deformation β_{40} is positive for ^{154}Sm, nearly zero for ^{166}Er, and negative for ^{182}W. We have, in a similar fashion, derived the $E4$ transition moments $\langle 4^+ \| \mathfrak{M}(E4) \| 0^+ \rangle$ assuming $\beta_{40} > 0$ for ^{154}Sm and ^{166}Er and $\beta_{40} < 0$ for ^{182}W.

The matrix elements $\langle 2^+ \| \mathfrak{M}(E2) \| 0^+$ and $\langle 4^+ \| \mathfrak{M}(E4) \| 0^+ \rangle$ as derived above are listed in Table I together with the charge deformation parameters β_{20}^c and β_{40}^c for the uniform or homogeneous distribution and for the deformed Fermi distribution (modified "c" distribution). The matrix elements are related to the volume integral via

$$\langle I_f = \lambda \| \mathfrak{M}(E\lambda) \| I_i = 0 \rangle = \int r^\lambda Y_{\lambda 0}(\theta) \rho(r, \theta) d\tau \quad (1)$$

using $R(\theta) = R_0[1 + \beta_{20} Y_{20}(\theta) + \beta_{40} Y_{40}(\theta)]$ for the shape of the nuclear surface. For the uniform charge distribution,

$$\rho(r, \theta) = \frac{3Ze}{4\pi (r_0 A^{1/3})^3} \quad \text{for } r \leq R(\theta) \quad (2)$$

using $r_0 = 1.2$ fm and for the deformed Fermi distribution,

$$\rho(r, \theta) = \frac{\rho_0}{e^x + 1}, \quad (3)$$

where

$$x = \frac{r - R(\theta)}{a}$$

TABLE I. Experimental transition moments and charge deformation parameters derived from Coulomb-excitation measurements with ^{4}He ions for ^{154}Sm, ^{166}Er, and ^{182}W. Errors include in addition to the usual statistical uncertainties, an uncertainty corresponding to $a \pm 50$ keV possible error in the incident beam energy.

	$\langle 2^+ \| \mathfrak{M}(E2) \| 0^+ \rangle$ (e b)	$\langle 4^+ \| \mathfrak{M}(E4) \| 0^+ \rangle$ (e b^2)	Uniform distribution [a] β_{20}	Uniform distribution [a] β_{40}	Deformed Fermi distribution [a] β_{20}	Deformed Fermi distribution [a] β_{40}
^{154}Sm	2.063 ± 0.015	$+0.58 \pm 0.14$	0.274 ± 0.012	$+0.112 \pm 0.039$	0.301 ± 0.012	$+0.112 \pm 0.040$
^{166}Er	2.378 ± 0.011	$+0.32 \pm 0.16$	0.301 ± 0.011	$+0.020 \pm 0.039$	0.329 ± 0.012	$+0.019 \pm 0.040$
^{182}W	2.053 ± 0.015	$-0.63^{+0.34}_{-0.16}$	0.266 ± 0.009	-0.181 ± 0.060	0.290 ± 0.010	-0.187 ± 0.062

[a] See text for explanation of the deformed charge distributions and the relationship to the measured transition moments.

and

$$\rho_0 = Ze \Big/ \int \frac{d\tau}{1+\exp[(r - r_0 A^{1/3})/a]};$$

we have used $a = 0.6$ fm and $r_0 = 1.1$ fm. The deformation parameters β_{20} and β_{40} were determined by evaluating Eq. (1) using an iterative numerical procedure until the measured moments were reproduced. The central charge density was held constant at the value it would have had for zero deformation and $R_0 = r_0 A^{1/3}$ was adjusted slightly in order to conserve total nuclear charge for the deformed shape.

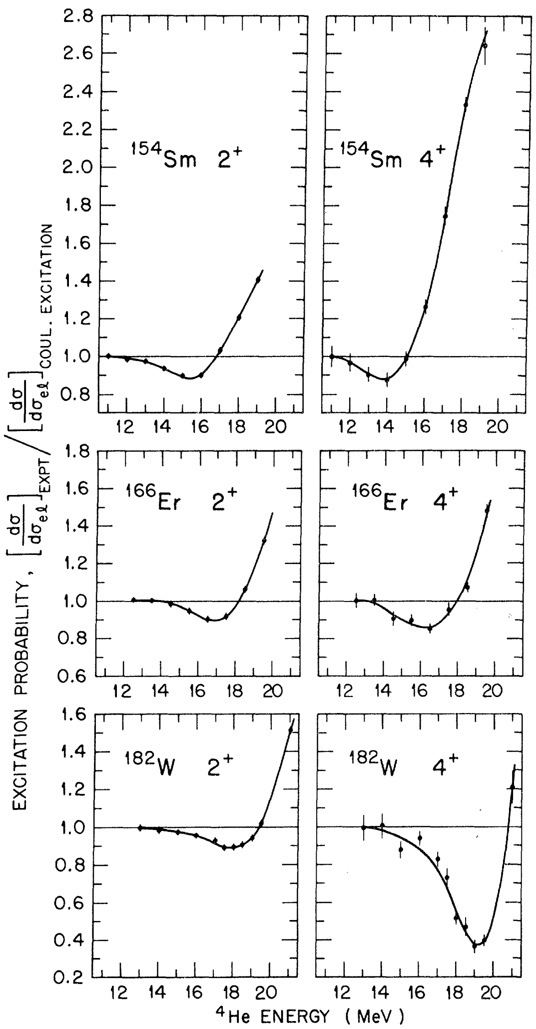

FIG. 2. Energy dependence of the ratios of experimental 2^+ and 4^+ excitation probabilities for ^{4}He ions to the calculated excitation probability expected for pure Coulomb excitation for ^{154}Sm, ^{166}Er, and ^{182}W. Measurements were performed at 150° (lab) and the curves connecting the experimental data points have been drawn to guide the eye.

III. DISCUSSION

Our $E2$ and $E4$ transition moments for ^{154}Sm, ^{166}Er, and $E2$ transition moment for ^{182}W compare reasonably well with the results of previous α-particle Coulomb-excitation experiments.[13-17] It should be emphasized, however, that the relatively small differences in the $\langle 2^+ \| \mathfrak{M}(E2) \| 0^+ \rangle$ values between the various experiments listed above could well be explained by small uncertainties in the incident ^{4}He ion energy. For example, a 50-keV error in the absolute ^{4}He ion energy at 11 MeV would introduce a systematic error of 1.6% in the $B(E2,\ 0^+ \to 2^+)$ value for ^{154}Sm. Since the derivation of the $E4$ transition moments depends sensitively on the $B(E2)$ values, the difference in the $E4$ moments between the various workers may well be due to this effect also. Our $E2$ and $E4$ transition moments listed in Table I include the uncertainty associated with a possible ±50 keV uncertainty in the incident ^{4}He ion energy. We have also derived $B(E2,\ 0^+ \to 2^{+\prime})$ values of $0.142 \pm 0.005\ e^2 b^2$ and $0.124 \pm 0.010\ e^2 b^2$ for the 787- and 1221-keV states in ^{166}Er and ^{182}W, respectively, from these experiments.

Using the matrix elements given in Table I, the excitation probabilities for the 2^+ and 4^+ states, assuming only Coulomb excitation, were calculated and compared to the experimental excitation probabilities for the higher energy measurements. This comparison is shown in Fig. 2 for the 2^+ and 4^+ states in ^{154}Sm, ^{166}Er, and ^{182}W where we have plotted the ratios of excitation probabilities $(d\sigma/d\sigma_{el})_{expt.}/(d\sigma/d\sigma_{el})_{calc.}$ as a function of the ^{4}He bombarding energy. Deviations from pure Coulomb excitation and the onset of contributions from direct nuclear excitations are immediately obvious from these figures. As the bombarding energy is increased, the experimental excitation probability decreases below that expected for pure Coulomb excitation due to the interference with the direct nuclear excitations. The experimental excitation probability eventually exceeds that expected from Coulomb excitation for the highest energies where direct nuclear excitations are the dominant excitation mechanism. We have observed similar interference effects for the 787-keV 2^+ state in ^{166}Er and the 1221-keV 2^+ state in ^{182}W. These effects are qualitatively similar to those observed for the 2^+ ground-state band states although with much poorer statistical accuracy.

Several qualitative features about the curves shown in Fig. 2 are of interest. Deviations from pure Coulomb excitation (1–2%) can occur at quite low bombarding energies which correspond to a distance d of ~8 fm between the surfaces of the projectile and target if we assume spherical surfaces with radii of $1.2A^{1/3}$ fm. The distance d is given by the following relation:

$$d(\mathrm{fm}) = 0.7199\left(1+\frac{A_1}{A_2}\right)\frac{Z_1Z_2}{E(\mathrm{MeV})_{\mathrm{lab}}}\left[1+\csc(\tfrac{1}{2}\theta_{\mathrm{c.m.}})\right] - \left[r_0(A_1{}^{1/3}+A_2{}^{1/3})\right] . \quad (4)$$

The maximum interference effect for the 2^+ states occurs at an average distance of 3.8 fm between the surfaces while the distance d for the interference minima for the 4^+ states appears to depend upon the strength of the direct nuclear excitations leading to the 4^+ states. In the case of ^{154}Sm, the 4^+ excitation via the direct nuclear mechanism far exceeds that of Coulomb excitation only 2–3 MeV above the interference minimum for the 2^+ state. In this case, the interference minimum for the 4^+ state occurs at a lower energy (greater separation distance) than the 2^+ state. For ^{182}W, the opposite appears to be true. Here, the excitation of the 4^+ state via the direct nuclear mechanisms appears to be somewhat weaker and the interference minimum occurs at a higher energy (smaller separation distance) than the 2^+ state. The depth of the destructive interference minimum is very much larger in the ^{182}W case than for ^{154}Sm or ^{166}Er. The 4^+ interference minimum for ^{166}Er occurs at approximately the same energy as for the 2^+ state.

Our results for ^{154}Sm, ^{166}Er, and ^{182}W are significantly different than the results obtained by Brückner *et al.*[4] for ^{152}Sm. While the interference for the 2^+ states appear similar to that of ^{152}Sm, we observe substantial interference for the 4^+ states which appears unlike that observed for ^{152}Sm. Moreover, we observe substantial differences between the three cases studied here for the 4^+ excitation curves which are most probably related to the magnitude and sign of the hexadecapole deformation parameter β_{40}. For ^{154}Sm β_{40} is large and positive, for ^{166}Er $\beta_{40} \sim 0$, and for ^{182}W β_{40} is large and negative which could explain the large interference effect observed for the 4^+ state in ^{182}W. Theoretical studies using a coupled-channels reaction code are in progress[18] and should shed considerable light on the nature of the interference effect between Coulomb and direct nuclear excitations for these cases.

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[1] K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Rev. Mod. Phys. 28, 432 (1956).

[2] M. Samuel and V. Smilansky, Phys. Lett. 28B, 318 (1968).

[3] R. J. Pryor, F. Roesel, J. X. Saladin, and K. Alder, Phys. Lett. 32B, 26 (1970).

[4] W. Brückner, J. G. Merdinger, D. Pelte, V. Smilansky, and K. Traxel, Phys. Rev. Lett. 30, 57 (1973).

[5] F. Videbok, I. Chernov, P. R. Christensen, and E. E. Gross, Phys. Rev. Lett. 28, 1072 (1972); P. R. Christensen, I. Chernov, E. E. Gross, R. Stokstad, and F. Videbok, Nucl. Phys. A207, 433 (1973); V. I. Chuev, Yu. A. Glukhov, V. I. Manko, B. G. Novatskii, A. A. Ogloblin, S. B. Sakuta, and D. N. Stepanov, Phys. Lett. 42B, 63 (1972); F. D. Becchetti, D. G. Kovar, B. G. Harvey, J. Mahoney, B. Mayer, and F. G. Pühlhofer, Phys. Rev. C 6, 2215 (1972).

[6] J. L. C. Ford, Jr., P. H. Stelson, C. E. Bemis, Jr., F. K. McGowan, R. L. Robinson, and W. T. Milner, Phys. Rev. Lett. 27, 1232 (1971); F. K. McGowan, C. E. Bemis, Jr., J. L. C. Ford, Jr., W. T. Milner, R. L. Robinson, and P. H. Stelson, Phys. Rev. Lett. 27, 1741 (1971); C. E. Bemis, Jr., F. K. McGowan, J. L. C. Ford, Jr., W. T. Milner, P. H. Stelson, and R. L. Robinson, Phys. Rev. C 8, 1466 (1973).

[7] A. Winther and J. deBoer, in *Coulomb Excitation*, edited by K. Alder and A. Winther (Academic, New York, 1966), p. 103.

[8] K. Alder, F. Roesel, and R. Morf, Nucl. Phys. A186, 499 (1972).

[9] U. Götz, H. C. Pauli, K. Alder, and K. Junker, Nucl. Phys. A192, 1 (1972).

[10] P. Möller, Nucl. Phys. A142, 1 (1970).

[11] D. L. Hendrie, N. K. Glendenning, B. G. Harvey, O. N. Jarvis, H. H. Duhin, J. Sandinos, and J. Mahoney, Phys. Lett. 26B, 127 (1968).

[12] A. A. Aponick, C. M. Chesterfield, D. A. Bromley, and N. K. Glendenning, Nucl. Phys. A159, 367 (1970).

[13] F. S. Stephens, R. M. Diamond, and J. deBoer, Phys. Rev. Lett. 27, 1151 (1971).

[14] T. K. Saylor, J. X. Saladin, I. Y. Lee, and K. A. Erb, Phys. Lett. 42B, 51 (1972).

[15] K. A. Erb, J. E. Holden, I. Y. Lee, J. Y. Saladin, and T. K. Saylor, Phys. Rev. Lett. 29, 1010 (1972).

[16] A. H. Shaw, J. S. Greenberg, and R. W. Hadsell, Bull. Am. Phys. Soc. 17, 29 (1972).

[17] R. G. Stockstad and B. Persson, Phys. Rev. 170, 1072 (1968).

[18] G. R. Satchler, private communication.