PHYSICAL REVIEW C VOLUME 14, NUMBER 3 SEPTEMBER 1976

Coulomb-nuclear interference effects in inelastic scattering of ^{16}O from ^{24}Mg†

J. X. Saladin, I. Y. Lee,* R. C. Haight,‡ and D. Vitoux

Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania 15260

(Received 15 March 1976)

Elastic and inelastic scattering of ^{16}O on ^{24}Mg was performed at incident energies between 20 and 42 MeV. The data are analyzed in terms of coupled channel calculations.

[NUCLEAR REACTIONS ^{24}Mg(^{16}O, ^{16}O′), $E = 20–42$ MeV; measured $\sigma(E, \theta = 51.7°)$, $\sigma(E = 42$ MeV, $\theta)$ coupled channel calculation.]

I. INTRODUCTION

Coulomb-nuclear interference phenomena in inelastic scattering were originally investigated in order to study in some detail the question of safe bombarding energies for Coulomb excitation experiments.[1,2] It was soon apparent, however, that such phenomena would be interesting in their own right. Thus Coulomb-nuclear interference experiments have been used to investigate possible differences between charge and optical potential deformations.[3-5] They have also been useful in deciding between two solutions of opposite sign for $E4$ matrix elements obtained from Coulomb excitation experiments.[3-5] These investigations with α particles have shown that a consistent analysis of the data is possible within the framework of coupled channel calculations.

It is of considerable interest to extend this type of investigation to elastic and inelastic scattering of heavy ions. In the present paper we discuss the experimental results and coupled channel analysis of the elastic and inelastic scattering of ^{16}O ions from ^{24}Mg. A preliminary report on this work was given at the Nashville heavy ion conference, where we pointed out the sensitivity of the interference pattern to the diagonal matrix element of the 2^+ state.[6] Similar results were reported at the same conference by Broglia[7] in an analysis of elastic and inelastic scattering experiments of ^{18}O from ^{58}Ni by Videbaek. An extensive study of ^{16}O and ^{18}O scattering from ^{58}Ni and ^{64}Ni including inelastic scattering leading to the first excited states of Ni and ^{18}O has recently been published by Videbaek *et al.*,[8] and a similar investigation of elastic and inelastic scattering of ^{12}C from ^{144}Nd has been reported by Hillis *et al.*[9]

II. EXPERIMENTAL

Elastically and inelastically scattered ^{16}O ions were detected in coincidence with recoil magnesium ions. Either the magnesium ions or oxygen ions were detected in a position-sensitive surface barrier detector. Separation between elastic and inelastic events was based on the fact that the angle between the scattered particle and the recoil nucleus is different for the two types of events. The details of this experimental technique have been described elsewhere.[10, 11]

The data consist of elastic and inelastic excitation functions at a laboratory angle of 51.7° in the energy range between 20 and 42 MeV and angular distributions at a bombarding energy of 42 MeV in the angular range between 23° and 62°. Figure 1 shows the ratio $d\sigma_{2^+}/d\sigma_{0^+}$ as a function of bombard-

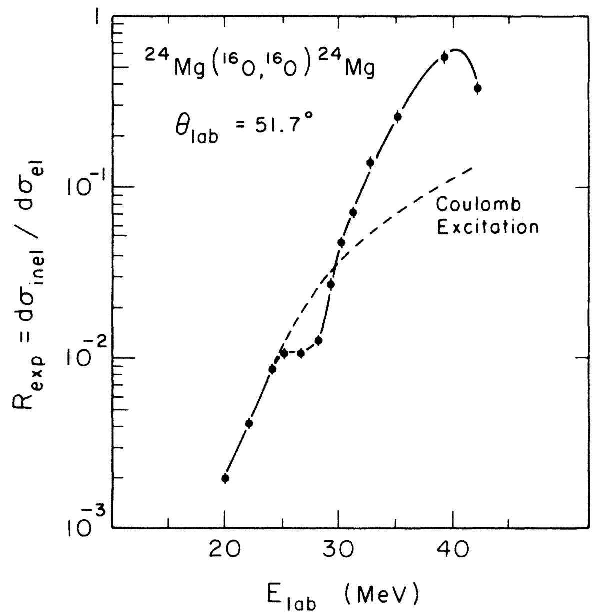

FIG. 1. Ratio of the inelastic cross section to the elastic cross section. The solid line is drawn to guide the eye; the dashed line is the prediction for pure Coulomb excitation.

TABLE I. Parameters used in coupled channel calculations.

$\langle 0^+ \| \mathfrak{M}(E2) \| 2^+ \rangle$	0.205 eb
$\langle 2^+ \| \mathfrak{M}(E2) \| 2^+ \rangle$	−0.40 eb
β_2^c	0.55
r_0 [see Eq. (2)]	1.1 fm
β_2^N	0.26
R	$1.31(A_p^{1/3}+A_T^{1/3})$ fm
V	$(7.5+0.5E)$ MeV
W	$(0.4+0.15E)$ MeV
a_v	0.49 fm
a_w	0.30 fm

ing energy. The solid line is drawn to guide the eye and the dashed line represents the prediction for pure Coulomb excitation.

III. INTERPRETATION

The data were analyzed within the framework of the rigid rotor model, using the coupled channel codes AROSA[12] and INTE[13] for pure Coulomb excitation and Coulomb-nuclear interference. The procedure was similar to that used in a previously published analysis of α scattering on rare earth nuclei.[5]

A Coulomb excitation experiment[11] gave the value for the reduced matrix elements $\langle 0^+ \| \mathfrak{M}(E2) \| 2^+ \rangle = 0.205\ e\text{b}$ and $\langle 2^+ \| \mathfrak{M}(E2) \| 2^+ \rangle = -0.4\ e\text{b}$. The charge deformation parameter β_2^c was derived from the reduced transition matrix element $\langle 0^+ \| \mathfrak{M}(E2) \| 2^+ \rangle$ within the framework of the axially symmetric rigid rotor model using a deformed Fermi charge distribution (modified "C" distribution).

$$\rho(r,\theta)=\frac{\rho_0}{1+\exp\{[r-r(\theta)]/a\}} \tag{1}$$

with

$$r(\theta)=r_0A_T^{1/3}(1+\beta_2^c Y_{20}) , \tag{2}$$

where A_T is the mass number of the target and r_0 is chosen such that

$$\int \rho(r,\theta)\, d\tau = Z_T e . \tag{3}$$

Here Z_T is the charge number of the target, and the central density ρ_0 is chosen such that for $\beta_2^c=0$ and $r_0=1.1$ fm, Eq. (3) is fulfilled. The connection between the transition matrix element and the charge distribution is given by

$$\langle 0^+ \| \mathfrak{M}(E2) \| 2^+ \rangle = \int r^2 Y_{20}\, \rho(r,\theta)\, d\tau .$$

A deformed optical potential of the Woods Saxon type was used as described in Ref. 5. The parameters were taken from the work of Siemssen[14] in which elastic scattering data from 19 to 32 MeV at a scattering angle of 90° were fitted. The deformation parameter β_2^N of the optical potential was calculated from the charge deformation parameter β_2^c using a scaling procedure given by Hendrie.[15] Table I summarizes the parameters used in the calculation.

The solid lines in Fig. 2 are the result of this calculation which does not involve any adjustable parameters. There is good agreement with the experimental data.

It is interesting to inquire about the sensitivity of the nuclear Coulomb interference to higher order effects. The dashed lines in Fig. 2 are the result of calculations in which the signs of the deformation parameters β_2^N, β_2^c and the diagonal matrix element $\langle 2^+ \| \mathfrak{M}(E2) \| 2^+ \rangle$ are changed, keeping all other parameters the same. There is little change in the elastic prediction; however, the excitation function for the 2^+ state shows a shift in the position of the interference minimum by about 1 MeV

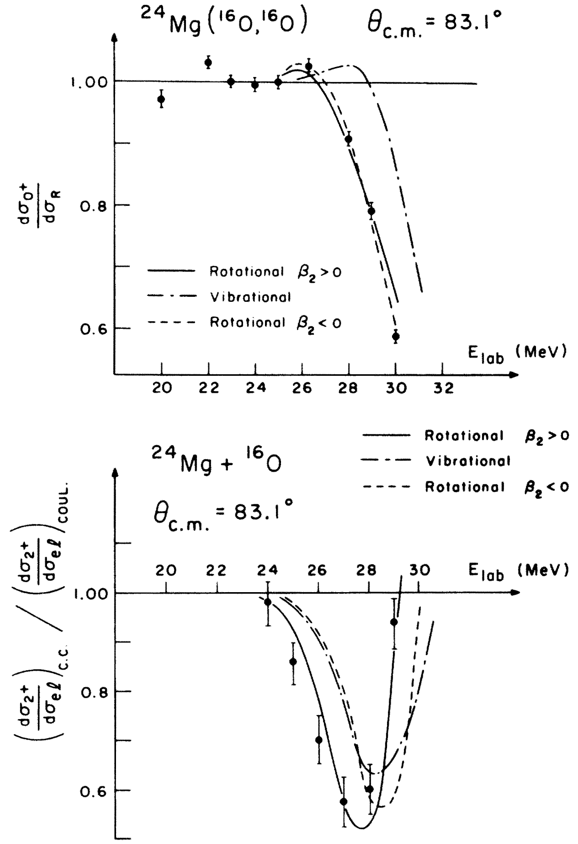

FIG. 2. Experimental and calculated excitation functions for elastic and inelastic scattering of ^{16}O by ^{24}Mg.

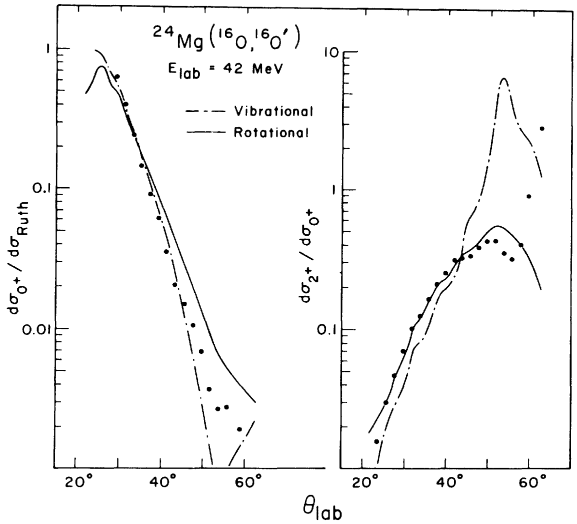

FIG. 3. Experimental and calculated angular distributions for elastic and inelastic scattering of ^{16}O by ^{24}Mg at $E_{\text{lab}} = 42$ MeV.

to the high energy side and the minimum is more shallow. To further investigate the sensitivity to the details of the form factor, a calculation was performed assuming the 2^+ state to be a one quadrupole phonon level. The root mean square deformation was adjusted such as to give the correct value for the matrix element $\langle 0^+ \| \mathfrak{M}(E2) \| 2^+ \rangle$. The result of this calculation is illustrated by the dash-dotted line in Fig. 2. The excitation function for the 2^+ state has a still shallower minimum and the position of the minimum is between that of the two rotational cases.

It should be noted, that first order distorted wave Born approximation (DWBA) calculations would in all three cases give the same result. It is therefore clear, that higher order effects make significant contributions and cannot be neglected. Exploratory calculations including the 4^+ state showed that it had little effect on the 2^+ cross sections. This is presumably due to the very weak excitation of the 4^+ state under the present experimental conditions. Thus the most important higher order contribution is associated with the β_2 deformation of the 2^+ state, i.e., an analog to the so-called reorientation effect in Coulomb excitation. Calculations show that the effect can be observed not only in excitation functions but also in angular distributions. Its systematic investigation may in fact provide a new method for determining sign and magnitude of deformation parameters of excited states.[7] In comparing deformation parameters derived in this manner with those obtained from Coulomb excitation one should keep in mind that both are model dependent. The former depend on the form of parametrization, the parameter values of the optical potential, and on the additional model assumptions which are made regarding the form factors. In the case of Coulomb excitation it is necessary to introduce a model for the charge distribution in order to extract deformation parameters from the model independent matrix elements.

Figure 3 shows the angular distribution at 42 MeV which is well above the Coulomb barrier. The solid lines represent the results of a rotational calculation with positive β_2 and the dashed-dotted lines are the results of a vibrational calculation. The parameters are those given in Table I. The rotational calculation gives a significantly better fit to the inelastic cross section. The fit to the elastic cross section is not too impressive, which might be attributed to the fact that the optical potential parameters are obtained from a DWBA analysis of data with energy below 32 MeV. At the higher energies where the inelastic cross section to the 2^+ and the 4^+ states are comparable to that for elastic scattering, one does not expect this potential to give a good fit.

---

†Work supported by National Science Foundation.

*Present address: Lawrence Berkeley, Berkeley, California 94720.

‡Present address: Lawerence Livermore Laboratory, Livermore, California 94550.

[1] B. Wakefield, I. M. Nagib, R. P. Harper, I. Hall, and A. Christy, Phys. Lett. 31B, 56 (1970).

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

[3] W. Bruckner, D. Husar, D. Pelte, K. Traxel, M. Samuel, and U. Smilansky, Nucl. Phys. A231, 159 (1974).

[4] I. Y. Lee, J. X. Saladin, C. Baktash, J. E. Holden, and J. O'Brien, Phys. Rev. Lett. 33, 383 (1974).

[5] I. Y. Lee, J. X. Saladin, J. Holden, J. O'Brien, C. Baktash, C. Bemis, Jr., P. H. Stelson, F. K. McGowan, W. T. Miler, J. L. C. Ford, Jr., R. L. Robinson, and W. Tuttle, Phys. Rev. C 12, 1485 (1975).

[6] J. X. Saladin, I. Y. Lee, R. C. Haight, and D. Vitoux, in *Proceedings of the International Conference on Reactions Between Complex Nuclei, Nashville, 1974,* edited by R. L. Robinson *et al*. (North-Holland Amsterdam/American Elsevier, New York, 1974), Vol. I, p. 15.

[7] R. A. Broglia, in *Proceedings of the International Conference on Reactions Between Complex Nuclei* (See Ref. 6), Vol. 2, p. 303; and references therein.

[8] F. Videbaek, P. R. Christensen, O. Hansen, and K. Ulbak, Nucl. Phys. A256, 301 (1976).

[9] D. L. Hillis, E. E. Gross, D. C. Hensley, L. D. Rickertsen, C. R. Bingham, A. Scott, and F. T. Baker, Phys. Rev. Lett. 36, 304 (1976).

[10] R. C. Haight, J. X. Saladin, and D. Vitoux, Nucl. In-

strum. Methods 91, 445 (1971).

[11] D. Vitoux, R. C. Haight, and J. X. Saladin, Phys. Rev. C 3, 718 (1971).

[12] F. Rosel, J. X. Saladin, and K. Alder, Comp. Phys. Commun. 8, 35 (1974).

[13] I. Y. Lee, Ph.D. thesis, University of Pittsburgh, 1974 (unpublished).

[14] R. H. Siemssen, in Proceedings of the Symposium on Heavy Ion Scattering, Argonne National Laboratory, 1971 (unpublished), ANL-7839, p. 145.

[15] D. L. Hendrie, Phys. Rev. Lett. 31, 478 (1973).