Observation and Interpretation of Angular Oscillations in $^{48}Ca(^{14}N, ^{13}C)^{49}Sc$†

C. Chasman, S. Kahana, and M. J. Schneider*

Brookhaven National Laboratory, Upton, New York 11973

(Received 24 August 1973)

We describe a detailed and successful experimental search for fine angular oscillations in the reaction $^{48}Ca(^{14}N, ^{13}C)^{49}Sc$ at a laboratory energy of 50 MeV. Also presented is a qualitative, analytic description of the reaction extracted from the distorted-wave Born-approximation partial-wave analysis in which the universality of the oscillations is clearly indicated.

In recent Letters[1-3] one- and two-particle transfers induced by heavy ions on intermediate-mass nuclei were shown to deviate markedly in angular distribution from the semiclassical strong absorbing shape.[4] These anomalous transfers yielded differential cross sections which were greatest at small angles and could be depicted as either forward peaked or forward rising. Theoretical attempts[1,2] to describe these reactions using the distorted-wave Born approximation (DWBA) demonstrated that the forward strength could be obtained by weakening the absorption in the surface region of nuclear reactions, thus permitting the projectile to come under the influence of the attractive part of the real optical potential. No very great penetration of target and projectile is required; the projectile mean free path is still short and in this sense the absorption remains strong.

A very distinctive consequence of the surface transparency is the appearance in the theoretical differential cross section of fine angular oscillations, a very unclassical, diffractive feature. The angular width of these oscillations, ~ 6° in the ^{14}N reaction of Ref. 2, strongly suggests interference between projectile paths on opposite sides of the target nucleus, the full nuclear radius being required to produce a narrow angular period. The reaction $^{48}Ca(^{14}N, ^{13}C)$ to the ground and 3.08-MeV states of ^{49}Sc was analyzed using a DWBA code including recoil, yet the oscillations persisted. Observation of these oscillations in the single-proton transfer to a reasonably heavy target should then provide definitive confirmation of the "weak absorbing" picture. This Letter outlines a detailed and successful experimental search for fine angular oscillations in the ^{14}N-induced single-proton transfer at a laboratory energy of 50 MeV. Also presented is a qualitative, analytic description of the reaction extracted from the DWBA partial-wave amplitudes, which clearly indicates the universality of the oscillations.

The earlier data presented in Ref. 2 were obtained with a multigap spectrometer facilitating measurement at extreme forward angles and the resolution of the many close-lying states in ^{49}Sc, but at the same time permitting only widely separated angular observations. The ^{14}N-induced transfer has been redone in a scattering chamber with a counter telescope (ΔE detector of nominal thickness 15 μm) and conventional ΔE-E particle identification techniques. Data were taken from 6° to 32° (lab) in angular intervals of 1° to 2°. The rms sum of the angular widths of the incoming beam, beam-defining slit, and detector slit was <0.69°. Statistical accuracy was kept to approximately ± 6% where this precision was deemed necessary to trace out the oscillations. Target thickness was measured to be 127 ± 12 $\mu g/cm^2$. A pileup rejection circuit was included to prevent resolution degradation due to pulses separated by <4 μsec, and the data were corrected for dead time. Neither detector of the telescope showed any resolution degradation during the experiment. Separation of ^{13}C from ^{14}N was clean at all angles except for those few where the "tail" from the ^{14}N elastic peaks on C and O in the target fell near the 3.08-MeV state. Separation of ^{13}C from weaker ^{12}C groups leading to ^{50}Sc states was done carefully, and contributed no more than a 2% estimated error. A strong ^{12}C recoil group prevented extraction of the 3.08-MeV level strength at 8.5° (lab). The data were normalized to a monitor counter, and at the more forward angles to two monitor counters placed symmetrically on either side of the Faraday cup. The data points at 15°, 22.5°, and 30° (lab) confirmed the earlier spectrograph data. Many data points were taken twice in the scattering chamber and were reproduced within their estimated errors.

Results are shown in Fig. 1 and indicate a remarkable concurrence of data and DWBA. Angular distributions predicted from DWBA (Ref.
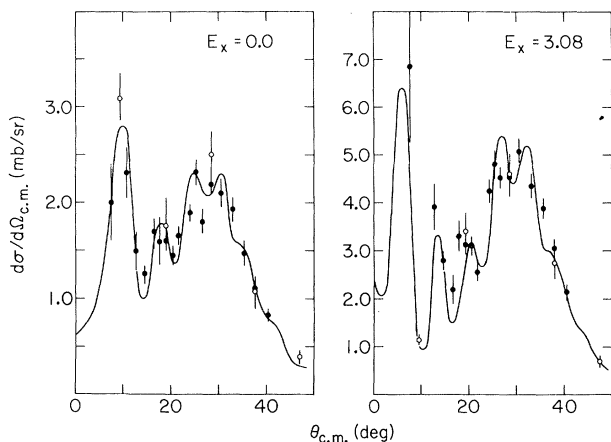
FIG. 1. ^{48}Ca(^{14}N, ^{13}C) angular distributions to the ground state and 3.08-MeV state of ^{49}Sc, for $E_b = 50$ MeV. Scattering-chamber data are shown as closed circles; earlier multigap spectrometer data as open circles. Curves are DWBA calculations including recoil (with negligible contributions from non-normal L transfers). Optical parameters are given in Ref. 2.
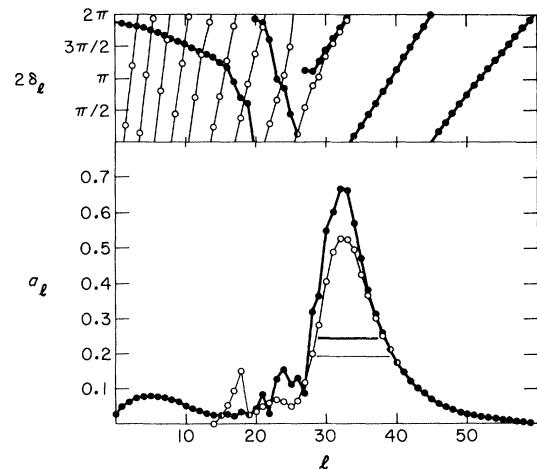

FIG. 2. $M = 0$, $L = 4$ amplitudes a_l and phases $2\delta_l$ from DWBA [Eq. (1)]. Thick lines with closed circles are for weak absorption (parameters from Ref. 2), while thin lines with open circles are for stronger absorption, i.e., W increased from 10 to 40 MeV. Horizontal lines are $1/e$ levels. For $l \gtrsim 38$, amplitudes and phases are identical for strong and weak absorbing cases.

2) for the ground and 3.08-MeV states of ^{49}Sc are reproduced in detail over the angular range observed. Both magnitude and phase of the angular oscillations are well predicted. Oscillatory behavior is suggested at the grazing angle, but the data are convincing at more forward angles where the magnitude of oscillation is greater. Especially dramatic are the sharp rise for the 3.08-MeV level and sharp decrease in the ground-state cross section at 7.5°(c.m.), in agreement with the weak-absorption prediction.

The optical parameters used in the transfer calculations[2] yielded good fits to the elastic data. Of course there are ambiguities in the optical parameters even within the constraint imposed by the elastic data. However, setting $W \approx 0.2V$ for $V \le 200$ MeV (i.e., keeping the absorption more or less at a constant weak level in the surface region) leaves the transfer results essentially unaltered.

Rather than further discussing manipulation of the optical-model parameters, we would like to elicit from the DWBA output a description of the transfer process demonstrating the evolution with weakening absorption from a smooth classical to an oscillating diffractive shape. Our analysis is based on a quite general partial-wave expression for the $M = 0$ contribution to the ground-state cross section:

$$\sigma^0(\theta) \sim |\sum_l (2l + 1)^{1/2} P_l{}^0(\cos\theta) a_l \exp(2i\delta_l)|^2. \quad (1)$$

The $M \neq 0$ amplitudes which are important but contribute incoherently can be treated similarly. Plotted in Fig. 2 are a_l and $2\delta_l$ calculated from the weakly absorbing optical parameters used in Fig. 1 (Ref. 2, $W = 10$ MeV) and, in addition, for a strong absorption ($W = 40$ MeV). The angular distribution for $W = 40$ is smooth, peaked at 30°, and greatly reduced (75%) in the one remaining forward peak at 9°.

Of notable importance for both weak and strong amplitudes are (1) the dominance by a group of l's centered at $l = l_0 = 33$, and (2) the more or less linear variation with l of the phases for these groups. The central group of l's is effectively narrower and the phase variation somewhat less for $W = 10$ MeV. The phase $2\delta_l$ for large l is the sum of the elastic phases in the entrance and exit channels; indeed for purely Coulomb transfer $2(\delta_l - \delta_{l-1}) - 2\arctan(\eta/l) = \psi(l)$, the classical scattering angle. The dramatic change in slope of the weak absorbing phases at $l = 26$ indicates the eventual dominance of the attractive nuclear potential at surface separations. This change in phase is also effective in decreasing the number of important l's for the weak situation.

If we characterize the a_l and δ_l curves by the approximate forms

$$a(l) = a(l_0)\exp[-(l - l_0)^2/\Gamma^2], \quad (2a)$$

$$2\delta_l \approx \psi(l_0)l, \quad (2b)$$

note that[5] for large l and $\theta > l^{-1}$

$$P_l \sim (2/\pi l \sin\theta)^{1/2} \cos[(l + \tfrac{1}{2})\theta - \tfrac{1}{4}\pi] = (1/2\pi l \sin\theta)^{1/2}[(e^{i[(l+1/2)\theta - \pi/4]} + \text{c.c.}],$$

and replace summations by integrals, we obtain

$$\sigma(\theta) \sim (\sin\theta)^{-1}|\exp[-\tfrac{1}{4}\Gamma^2(\theta - \psi)^2]\exp\{-i[(l_0 + \tfrac{1}{2})\theta - \pi/4]\} + \exp[-\tfrac{1}{4}\Gamma^2(\theta + \psi)^2]\exp\{i[(l_0 + \tfrac{1}{2})\theta - \pi/4]\}|^2. \quad (3)$$

Although the basis for the above analysis has been the output of a detailed DWBA calculation, our end result clearly parallels the diffraction models of Frahn and Venter[6] and Dar.[7] By using $P_l(1) = 1$ we obtain in similar fashion a forward cross section $\sim (2l_0 + 1)\exp(-\psi^2\Gamma^2/2)$ intimately related to the magnitude of the fine angular oscillations produced by interference between the two terms in Eq. (3). Equation (3) yields a description of the transfer process in terms of the three parameters l_0, ψ, and Γ. A smooth, peaked, angular distribution obtains when the "physical" scattering [first term in (3)] at $\theta = \psi(l_0)$ dominates; diffractive oscillations of period $2\pi/2l_0$ appear when the "unphysical" scattering at $\theta = -\psi(l_0)$ (second term) is appreciable in the physical region $0 < \theta < \pi$. The separation of these two contributions, which arise from the positive- and negative-frequency parts of P_l and are associated with opposite sides of the nucleus, was accomplished by the Gaussian wave packet in l space. Clearly the degree of diffraction is controlled by the scattering angle ψ and by the l width Γ. At low energies ψ is large, the peaks at $\pm\psi$ are widely separated, and a smooth bell-shaped angular distribution results. For a weak absorption *both* Γ and ψ are smaller and the onset of oscillations is lowered in energy. Since we expect that roughly $\psi \sim 1/E$ and $\Gamma \sim \Delta l \sim E^{1/2}$ (E is the energy in the center-of-mass system relative to the barrier), a forward-peaked, diffractive cross section seems inevitable at sufficiently high energy. These qualitative features seem just what is required to describe our data.

Finally a few words should be said about absolute magnitudes of cross sections. With weakly absorbing potentials the narrowing of the l-space distributions is partly accomplished by *adding* to the amplitude of the dominant partial waves in the nuclear surface, increasing the overall prediction of strength. Assuming that the ^{49}Sc ground state is pure $f_{7/2}$ (proton), we extract from the data and from DWBA for (^{14}N, ^{13}C), $C^2S(p_{1/2})$ $= 0.46 \pm 0.08$, consistent with $1p$-shell information.[8] We may then predict for the $2p_{3/2}(3.08-$

MeV) state a spectroscopic factor 0.54 ± 0.08, in good agreement with the (^{3}He, d) result of ~ 0.6.[9] There is thus no need for an artificial increase in strength, especially significant in light of our inclusion of recoil.

The implications of the present work for other heavy-ion–induced few-nucleon–transfer reactions are clear. The appearance at some threshold energy of a diffractive differential cross-section will be controlled by the level of absorption, and presumably also by details of the form factor such as the angular momentum and number of nucleons being transferred. It should be possible to exploit these features of the reaction mechanism to extract structural information.

The authors are appreciative of many helpful conversations with and cooperation from A. J. Baltz and E. H. Auerbach. One of the authors (S.K.) is especially grateful to B. F. Bayman for discussions on the qualitative treatment of the DWBA amplitudes.

[1]E. H. Auerbach, A. J. Baltz, P. D. Bond, C. Chasman, J. D. Garrett, K. W. Jones, S. Kahana, M. J. Levine, M. Schneider, A. Z. Schwarzschild, and C. E. Thorn, Phys. Rev. Lett. 30, 1078 (1973).

[2]M. Schneider, C. Chasman, E. H. Auerbach, A. J. Baltz, and S. Kahana, Phys. Rev. Lett. 31, 320 (1973).

[3]J. Ball, P. R. Christensen, O. Hansen, J. S. Larsen, D. Sinclair, F. Videbaek, R. A. Broglia, and R. Liotta, Phys. Lett. B45, 107 (1973).

[4]G. C. Morrison, J. Phys. (Paris), Colloq. 6, 69 (1971).

[5]L. D. Landau and E. M. Lifshitz, *Quantum Mechanics* (Pergamon, New York, 1958).

[6]W. E. Frahn and R. H. Venter, Nucl. Phys. 59, 651 (1964).

[7]A. Dar, Phys. Rev. 139, B1193 (1965).

[8]S. Cohen and D. Kurath, Nucl. Phys. A101, 1 (1967).

[9]G. Bruge, H. Faraggi, H. Duc Long, and P. Roussel, Commisariat à l'Energie Atomique Report No. CEA-N 1232, 1970 (unpublished), p. 124.