Study of One- and Two-Nucleon Transfer Reactions Induced by ^{16}O Ions Incident on the Even Zr Isotopes

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Transitions to known single-particle states in ^{91,93,95,97}Nb are observed in the (^{16}O, ^{15}N) reaction induced by the bombardment of ^{90,92,94,96}Zr with 60 MeV ^{16}O ions. Other strong transitions are also observed in this reaction, however, and evidence is presented which suggests that the final states observed are proton plus core vibrational states. The (^{16}O, ^{14}C) reaction is found to populate many states in ^{92,94}Mo and possibly ^{96}Mo, but few in ^{98}Mo. The number and intensity of the states observed show a marked dependence on the neutron number of the target nucleus. The ^{12}C energy spectra for all the targets indicate that for the nuclei and incident energies used in the present experiments the main mechanism of the (^{16}O, ^{12}C) reaction is breakup of the ^{16}O projectile.

Nuclear reactions induced by the bombardment of separated isotopes of ^{90,92,94,96}Zr with 60 MeV ^{16}O ions have been investigated. The oxygen beams were supplied by the model FN tandem Van de Graaff accelerator of the Niels Bohr Institute. The target enrichments and thicknesses were as follows: ^{90}Zr (98%, 110 μg/cm^2), ^{92}Zr (95%, 115 μg/cm^2), ^{94}Zr (96%, 100 μg/cm^2), and ^{96}Zr (85%, 50 μg/cm^2).

The reaction products were detected in a ΔE-E counter telescope consisting of 13-μm ΔE and 100-μm E silicon surface-barrier detectors. The ΔE and E pulses in coincidence were stored

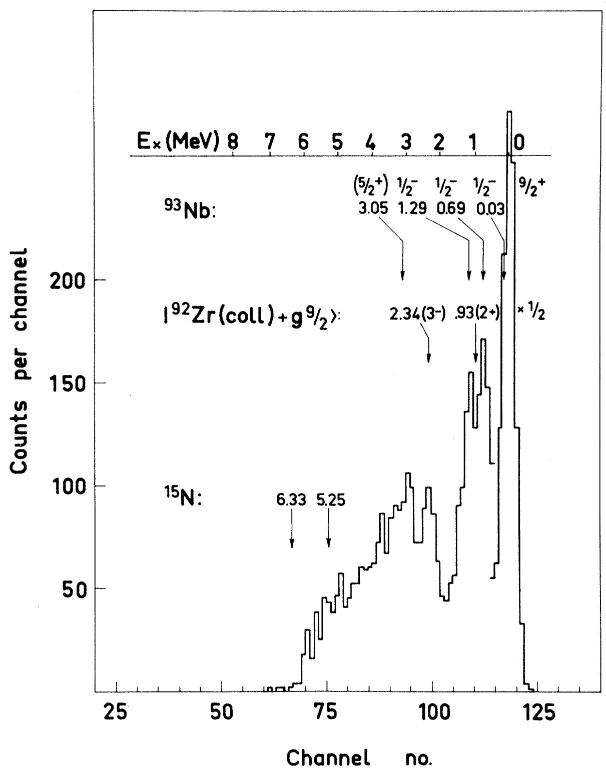

FIG. 1. ^{92}Zr(^{16}O, ^{15}N) spectrum obtained at $\theta_L = 60°$ and $E_L = 60$ MeV. The positions of proton single-particle states with $S > 0.1$ as determined from the (^{3}He,d) study of Cates, Ball, and Newman (Ref. 1) are indicated. Also indicated are predicted core excited states and the ^{93}Nb ground state populated with excitation of the 5.25 and 6.33 MeV states in ^{15}N.

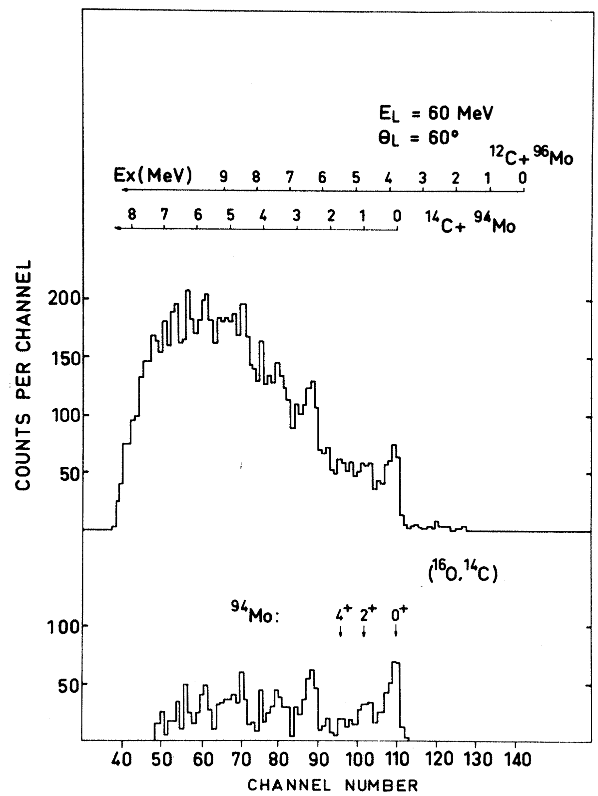

FIG. 2. ^{92}Zr(^{16}O, C) spectra recorded simultaneously with the data shown in Fig. 1. The complete carbon spectrum is shown at the top. The (^{16}O, ^{14}C) spectrum obtained after unfolding the ^{12}C background using the corresponding ΔE spectrum is shown at the bottom. Peaks corresponding to known levels in ^{94}Mo are indicated (Ref. 2).

as a 16- by 256-channel spectrum in a two-dimensional pulse-height analyzer. Individual runs were stored on paper tape and analyzed off line with the aid of an RC-4000 computer and light-pen display. The overall energy resolution was between 200 and 400 keV (full width at half-maximum). The energy calibration of the counter telescope was done using elastically scattered ^{16}O and ^{12}C beams of several different energies.

The reaction products ^{12}C, ^{14}C, ^{15}N, ^{16}O, ^{17}O, and ^{18}O were identified either from the ΔE signal or from the Q value to known states in the residual nuclei. Angular distributions were measured for reaction products from ^{96}Zr as was the elastic ^{16}O scattering. The angular distributions for the reaction products were all found to be peaked at $\theta_L = 60°$. This angle is also the angle at which the elastic-scattering cross sections begin to deviate from pure Rutherford scattering.

Particle spectra for the targets ^{90,92,94}Zr were then measured at $\theta_L = 60°$. Spectra obtained for the (^{16}O, ^{15}N), (^{16}O, ^{12}C), and (^{16}O, ^{14}C) reactions on ^{92}Zr are shown in Figs. 1 and 2. The ^{14}C spectrum contains some background from the (^{16}O, ^{12}C) reaction. No evidence for ^{13}C was found.

The strengths of the (^{16}O, ^{15}N) reactions to states in ^{91,93,95,97}Nb are given in Table I and compared with the results of a study of the (^{3}He, d) reaction by Cates, Ball, and Newman.[1] It is seen that all the proton single-particle states observed in (^{3}He, d) with a spectroscopic factor >0.1 can be identified in the (^{16}O, ^{15}N) reaction. Furthermore, other levels which correspond closely in excitation energy to the 2$^+$ and 3$^-$ collective vibrations in the related target nuclei are also populated with intensities comparable to the single-particle states. The absolute strengths are seen to be strongly correlated to the collec-

Table I. Zr(^{16}O, ^{15}N)Nb cross-section data.

Target Q_0 (MeV)	Ex (MeV)	$\sigma_t(\theta_L=60°)^a$ (mb/sr)	(^{3}He,d)^b J^π	S	$I^{\pi c}$	$B(E\lambda, 0\to I)^d$ (s.p.units)	$\sigma_{corr.}/(B(E\lambda)^e$
^{90}Zr	0	1.39	9/2+	0.87	0+		
-6.86	0.10		1/2-	0.42			
	1.61	0.03	1/2-	0.19			
	2.18	0.04			2+	3	0.03
	2.75	0.08			3-	9	0.02
	3.36	0.15	5/2+	0.36			
^{92}Zr	0	1.50	9/2+	0.79	0+		
-6.10	0.03		1/2-	0.53			
	0.69	0.39	1/2-	0.24			
	0.93	0.08			2+	8	0.02
	1.29	0.31	1/2-	0.17			
	2.34	0.26			3-	13	0.03
	3.0	0.26	(5/2+)	(0.2)			
^{94}Zr	0	1.43	9/2+	0.86	0+		
-5.32	0.26		1/2-	0.34			
	0.75	0.34	1/2-	0.10			
	0.92				2+	4	-
	1.6	0.41	f)	-			
	2.05	0.52			3-	15	0.05
^{96}Zr	0	2.09	9/2+	0.95	0+		
-4.66	0.74	0.13	1/2-	0.08			
	1.26	0.37	1/2-	0.20			
	1.73	0.60			2+	2	0.07
	1.75		5/2+	0.18			
	1.89	0.87			3-	17	0.05
	2.09	0.33	5/2+	0.14			

[a] Assuming $\sigma_{el}(\theta_L = 60°) = 518$ mb/sr (Ref. 3).
[b] Data taken from (^{3}He,d), Ref. 1.
[c] The spin and parity of the Zr core state that couples with the $g_{9/2}$ proton.
[d] Ref. 4.
[e] σ_{corr} is $\sigma_t(\theta)$ reduced by the empirical ξ dependence shown in Fig. 4.
[f] Observed in (^{3}He,d) work (Ref. 1).

tive excitations in the target nuclei. These states may thus be interpreted as the $g_{9/2}$ proton plus core vibrational states predicted by the weak coupling model.[5] The neutron plus core vibrational states in the odd Zr isotopes have been observed as analog resonances in proton inelastic scattering.[6] The splittings of these multiplets are typically less than a few hundred keV. Such a splitting would not be observed with the resolution of the present experiment. Also listed in Table I are the transition strengths divided by the known $B(E\lambda)$ values. Those reduced strengths are not constant. This is not to be expected, either, because in the (^{16}O, ^{15}N) reaction, such states will mainly be populated in a multistep reaction in which interference may be important. Of the proton weak-coupling states identified in ^{91,93,95,97}Nb, only those in ^{93}Nb can be observed by inelastic scattering directly.

The cross sections for the (^{16}O, ^{14}C) reaction at $\theta_L = 60°$ are shown schematically in Fig. 3. The 0^+ to 0^+ ground state transitions show a strong dependence on neutron number. In the case of the targets ^{90}Zr and ^{92}Zr several other strong transitions are observed. However, the weak intensity or absence of both the ground-state and the excited-state transitions for ^{94}Zr and ^{96}Zr contradicts all of the empirical and theoretical systematics developed for two-neutron transfer reactions using light ions.[7]

All of the carbon spectra observed have the same general character as the ones shown in Fig. 2 with the maximum cross section occurring at about 38 MeV of outgoing ^{12}C energy. No strong peaks due to (^{16}O, ^{12}C) were observed.

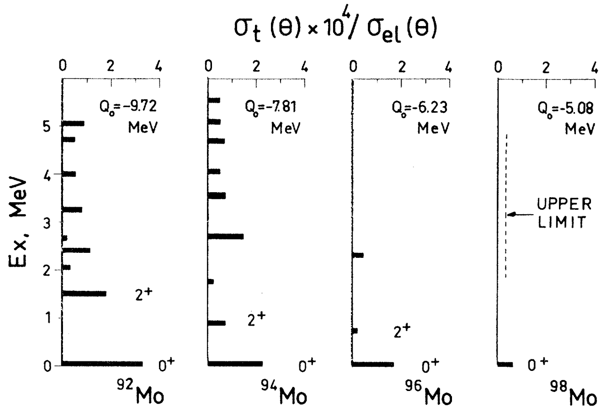

FIG. 3. Schematic representation of the transition strengths for ^{90,92,94,96}Zr(^{16}O, ^{14}C)^{92,94,96,98}Mo observed at $\theta_L = 60°$ and $E_L = 60$ MeV. Known spins and parities are shown (Ref. 2).

This is in contrast to observation[8] of the (^{16}O, ^{12}C) reaction reported for the mass region $A \sim 50$. The (^{16}O, ^{12}C) cross section integrated over the whole energy spectrum is nearly the same, independent of the target. The angular distribution measured in ^{96}Zr increases smoothly with decreasing angle. It is concluded that the ^{12}C observed from the (^{16}O, ^{12}C) reaction in the present experiment is due primarily to break up of the ^{16}O projectile.

No evidence was found for reactions leaving the ejected particle in an excited state. It should be noted, however, that the peak shapes of states

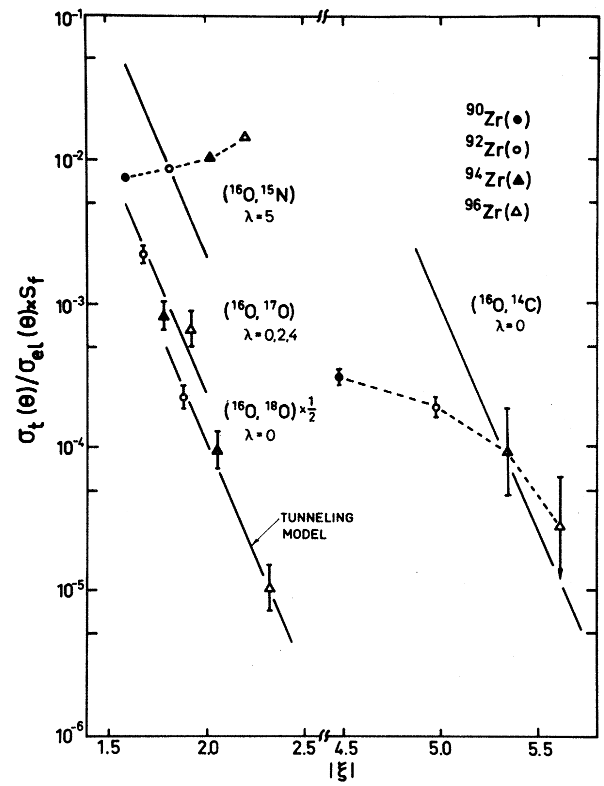

FIG. 4. The ξ dependence as determined in the present experiment for one- and two-nucleon transfer reactions. Only ground state transitions leading to the same configuration are included. The values of S_f for the single-proton and single-neutron transfers are taken from the (^{3}He,d) study of Cates, Ball, and Newman (Ref. 1) and the (d,t) work of Cohen *et al.* (Ref. 13), respectively. The (^{16}O, ^{14}C) data have been reduced assuming $S_f = 5$ for all the Mo isotopes. The (^{16}O, ^{18}O) data have been reduced assuming $S_f = (N-50)/2$, where N is the target neutron number. The allowed λ values for a one-step process are indicated. The curves have been calculated using Eq. (1) with $P(\theta, \xi, Q)$ calculated from the expression given by Dar (Ref. 10). The binding energies and Q values have not been corrected for Coulomb effects (Refs. 11 and 12). The calculated curves have been arbitrarily normalized to the data.

populated by these reactions will be Doppler broadened due to the decay of the reaction products while in flight.

The interpretation of heavy-ion reaction spectra is complicated, however, by the strong kinematic effects as expressed in the dependence of the transfer cross section on Q value and the value of $\xi \equiv \eta_f - \eta_i$, where η is the Coulomb parameter. These dependences for neutron transfers can be obtained from the semiclassical expression for $\sigma_t(\theta)$, the single-neutron transfer cross sections[3,9,10]:

$$\sigma_t(\theta) = S_i S_f (\textstyle\sum_\lambda C_\lambda) P(\theta, \xi, Q) \sigma_{\mathrm{el}}(\theta), \tag{1}$$

where $S_i S_f$ is the product of spectroscopic factors in the projectile and target, C_λ is a coefficient depending on the angular momentum transfer λ, and $P(\theta, \xi, Q)$ is the tunneling probability. The quantity $\sigma_{\mathrm{el}}(\theta)$ is the elastic scattering cross section. Charged-particle transfers have been analyzed using the tunneling model by introducing effective binding energies and Q values.[11,12] Multinucleon transfers can be calculated using Eq. (1) by assuming a cluster transfer. All of the simple tunneling models predict maximum cross section for $|\xi|$ minimum. This corresponds to the maximum overlap of Coulomb trajectories in the initial and final channels.

In Fig. 4 we show the dependence of the one- and two-nucleon transfers for specific transitions observed in the present experiment. The curves shown are the predictions of the simple tunneling theory arbitrarily normalized. It is seen that the simple tunneling model gives the correct ξ dependence for neutron transfers, even well above the Coulomb barrier (~45 MeV incident energy). The proton transfers show a very different dependence.

It can be concluded that while heavy-ion reactions can populate a wide variety of nuclear states, the intensity of a given transition depends to a very large extent on kinematic effects.

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