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Four-Nucleon Transfer from ^{16}O to ^{90}Zr near the Coulomb Barrier*

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The transfer of two neutrons and two protons is found to be the dominant reaction process in ^{16}O + ^{90}Zr near the Coulomb barrier. The reaction was identified from γ-ray spectra measured in coincidence with backward-angle charged particles. A band of excited states in the residual nucleus is found to be selectively populated. The energy dependence of the centroid energy of this band is studied and compared with theories of sub-Coulomb transfer reactions.

We have combined the techniques of charged-particle and γ-ray spectroscopy to study heavy-ion–induced transfer of particles at bombarding energies near the Coulomb barrier. Since at such energies reaction products are expected to emerge preferentially at backward angles,[1] an annular particle detector placed close behind the target will span the most intense part of the angular distribution with large solid angle. This permits the detection of coincident γ rays with very good coincidence efficiency and identification of the dominant reaction processes by analysis of the coincident γ spectra.

Employing this technique in studying the ^{16}O + ^{90}Zr system,[2] we find that the dominant reaction channel near the Coulomb barrier is the transfer of two neutrons and two protons, which we will henceforth refer to as "α" transfer. We find that in the residual nucleus ^{94}Mo a narrow band of states is selectively populated and has unusual γ-ray decay properties. The back-angle transfer cross section to these states becomes observable at bombarding energies characteristic of the interference minimum of Coulomb excitation and nuclear inelastic scattering (48 MeV lab) and reaches a maximum estimated to be 0.28 mb/sr at a bombarding energy of 51 MeV (lab). At the latter energy the energy centroid of the band of states populated in the residual nucleus is at 6.5 MeV excitation.

In the present experiment a beam of ^{16}O ions from the München MP tandem accelerator was focused onto a 98% enriched metallic ^{90}Zr target of 0.8 mg/cm^2 thickness. A 60-μm annular detector—covered by a 0.45-mg/cm^2 Ni foil—was placed 4.5 cm behind the target, so it spanned an angular range of 166° to 175.5°. γ rays were observed at 90° to the beam axis at 4 cm distance from the target. Particle and γ energies and particle-γ time differences for each coincident event were recorded on magnetic tape by the on-line PDP 8/10 computer system. Single-parameter spectra were accumulated simultaneously. The beam was integrated in a Faraday cup and

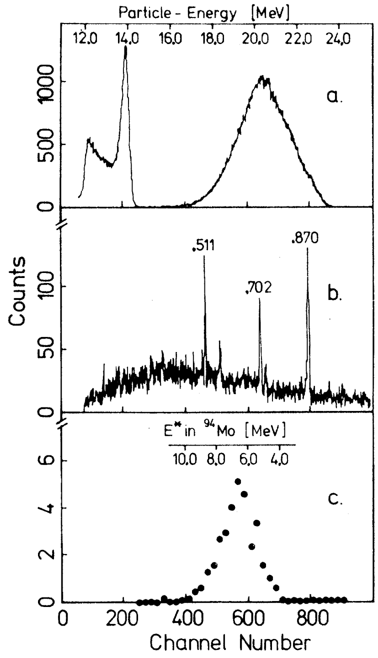

FIG. 1. Coincident particle and γ-ray spectra at bombarding energy 51.0 MeV. For details we refer to the text.

also monitored by measuring elastic ^{16}O scattering at 90°. An excitation function was measured at 15 bombarding energies between 42.5 and 57.0 MeV.

Coincident particle and γ spectra measured at 51 MeV bombarding energy are shown in Fig. 1. Figure 1(a) shows the particle spectrum which is coincident with all γ rays. By studying the coincident γ spectra we have determined that various energy regions of the particle spectrum coincide closely with different particle types. In particular, the sharp peak at the low end of the spectrum is produced by α particles which pass through the 60-μm particle detector. The broad peak at the high end of the spectrum is found to have two components which comprise essentially the upper and lower half of the peak, the upper half produced by inelastic ^{16}O and the lower half by ^{12}C ions. This is illustrated in Fig. 1(b) where we see a spectrum of γ rays with energies below 1 MeV in coincidence with the lower half of the broad peak shown in Fig. 1(a). Here we see that there are three prominent γ-ray lines at 0.870, 0.702, and 0.511 MeV which correspond within 0.5 keV to the $2^+ \to 0^+$ and $4^+ \to 2^+$ transitions in ^{94}Mo[3] and to annihilation radiation, the latter indicating the possible importance of higher-energy γ rays. A number of weaker γ-ray lines which are attributed to the decay of known states in ^{94}Mo[4] have been found by summation of spectra accumulated at various bombarding energies. Table I summarizes the intensities of these lines. It is interesting to note that about 32% of the strength of the $2^+ \to 0^+$ intensity can be accounted for by the preceding $4^+ \to 2^+$ transition, and 64% accounted for by transitions from 1^+ or 2^+ states with excitation energies of less than 2.8 MeV. Thus direct transitions to the 2^+ state from the band of states populated directly by the transfer reaction appear to be relatively unlikely.

In a separate measurement a search was made for higher-energy transitions with energies up to 5.5 MeV. While there are true-coincidence events at these energies, no well-defined lines are found and an upper limit of about 10% of the $2^+ \to 0^+$ intensity is placed on the intensities of any higher-energy transitions in this region. We have also examined these data for evidence that the transfer reaction proceeds in part by producing ^{12}C* in its 4.4-MeV excited state.[5] The spectrum of all γ rays in true coincidence with the heavy particles was summed with background subtrac-

TABLE I. Intensity of γ transitions in ^{94}Mo populated in the reaction ^{90}Zr(^{16}O, ^{12}C). The intensities are given relative to the intensity of the 2^+ (870 keV) to ground state transition. Spin assignments are taken from Refs. 3 and 4.

γ energy (keV)	Excitation energy (keV)	Transition	Relative intensity
870	870	$2^+ \to 0^+$	100
702	1537	$4^+ \to 2^+$	31.8 ± 3.8
849	2423	$6^+ \to 4^+$	1.3 ± 1.0
993	1864	$2^+ \to 2^+$	12.1 ± 3.4
1196	2067	$(1^+, 2^+) \to 2^+$	23.4 ± 4.8
1522	2393	$(1^+, 2^+) \to 2^+$	2.3 ± 2.0
1868	2740	$(1^+, 2^+) \to 2^+$	26.1 ± 9.2

tion in the energy region from 3.67 to 5.19 MeV where one would expect the Doppler-broadened 4.4-MeV γ-ray full-energy peak to appear. An upper limit of 5% is assigned to $^{12}C^*(4.4\text{ MeV})$ production relative to the production of ground-state ^{12}C in the transfer reaction. γ rays characteristic of $^{90}Zr^*$ are found to be in coincidence with the upper half of the broad peak, while in coincidence with the lower peak in the particle spectrum are found γ rays characteristic of $^{98}Ru^*$, $^{100}Pd^*$, and $^{102}Pd^*$, indicating that the reactions (^{16}O, 2α), (^{16}O, $\alpha 2n$), and (^{16}O, α) have some strength, particularly at the higher bombarding energies.

The ^{12}C energy spectrum shown in Fig. 1(c), as measured in coincidence with the 0.870-MeV line from $^{94}Mo^*(2^+ \rightarrow 0^+)$, shows that a relatively narrow band of states in ^{94}Mo is actually populated by the reaction. Calibration with elastic ^{12}C scattering from ^{90}Zr indicates that these states have an average excitation energy in ^{94}Mo which depends on bombarding energy and is about 6.5 MeV at $E_b = 51$ MeV (lab). Most of the linewidth in Fig. 1(c) can be accounted for by target thickness and energy straggling in the nickel absorber foil placed before the annular detector.

From analysis of the γ-ray and particle coincident spectra described above, we conclude that the band of states populated by the reaction decays mainly through a number of intermediate states to the lowest 4^+ and 2^+ states of ^{94}Mo. The primary transitions to these intermediate states are distributed among very many γ-ray lines and thus do not appear as individual peaks above background in the γ-ray spectra. There have been some theoretical and experimental indications that the 4^+ and 2^+ states of ^{94}Mo have mainly the configuration[3] $(\nu d_{5/2})^2(\pi g_{9/2})^2$ and that the intermediate states which we have observed have the configurations $(\nu d_{5/2})(\nu g_{7/2})(\pi g_{9/2})^2$.[6] It would therefore be consistent with the experimental observations described above if the band of states populated by the α-transfer reaction have a four-particle structure $(\nu g_{7/2})^2(\pi g_{9/2})^2$.

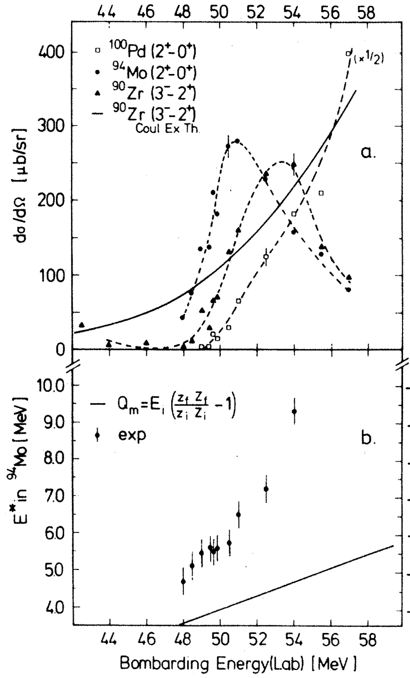

FIG. 2. Experimental and theoretical excitation functions for reactions from $^{90}Zr + ^{16}O$. For details see text.

Figure 2(a) shows the energy dependence of the various back-angle cross sections. All were calculated by assuming that the coincident γ rays were isotropic except the inelastic cross section, where angular correlation effects from Coulomb excitation were included. The cross section for α transfer leading to the 0.870-MeV transition reaches a maximum of 0.28 mb/sr at 51 MeV and falls off essentially linearly beyond that point. It is interesting that 51 MeV (lab) corresponds to a semiclassical distance of closest approach of 10.6 fm, while the empirical relation[7] of $R = 1.16 \times A^{1/3} + 1.2$ fm gives a sum of target and projectile radii of 10.5 fm.

In Fig. 2(a) the inelastic inelastic cross section for exciting the 3^- state of ^{90}Zr at 2.745 MeV is compared with a calculation of the Coulomb excitation cross section of this state,[8] assuming that $B(E_3\uparrow) = 1.08 \times 10^5 e^2\text{ fm}^6$.[9] The Coulomb excitation calculation agrees with the experimental inelastic cross section only at the lowest bombarding energy measured (42.5 MeV) and is qualitatively different in its energy dependence at higher energies. In particular, the experimental cross section shows a minimum at about 46.5 MeV, a steep rise, a maximum at 53.5 MeV, and a steep falloff, which are rather different from the monotonically increasing calculated cross section. These differences we attribute to destructive interference between Coulomb excitation and nuclear inelastic scattering at lower energies[10] and the dominance of the latter at higher energies. The α-transfer reaction sets in near the interference minimum and rises in a similar way to a maximum at 51 MeV, so that the two excitation functions are quite similar but shifted by 1–2 MeV. Figure 2(a) also shows the dramatic rise of the (^{16}O, $\alpha 2n$) cross section above 50 MeV, which we attribute to compound nucleus formation once the Coulomb barrier is reached, removing flux from the direct processes and contributing to their decrease at higher energies.

Figure 2(b) shows the dependence on bombarding energy of Q_m, the centroid of the group of states populated in the α-transfer reaction. The dependence of this "Q window" on energy is predicted by many theories of sub-Coulomb transfer reactions[11-13] to be of the form

$$Q_m = E_i(z_f Z_f / z_i Z_i - 1),$$

where z and Z are the charges of the light and heavy particles, i and f indicate the entrance and exit channels, and E_i is the center-of-mass bombarding energy. It is seen in Fig. 2(b) that the experimental data deviate from this theoretical prediction increasingly with bombarding energy and may have nonlinear energy dependence, in contrast to the theory. The theory of Alder and Trautmann,[14] which predicts a slightly different energy dependence for Q_m, is in even worse agreement with these data.

All of the theories mentioned above are consistent with the dominance of α transfer near the Coulomb barrier, however, for all of the other reaction channels have a predicted Q_m which is more positive than the ground-state Q value of the reaction and will thus be strongly mismatched.

Finally, the present work suggests that the special features of this reaction and of similar ones can be exploited to obtain more information on the properties and structure of selected nuclear levels by using (a) the particular calculational simplicities of sub-Coulomb transfer to make analysis more model independent, (b) the expected alignment of the residual nucleus to determine spins from γ-ray angular distributions, (c) the energy and possible spectroscopic selectivity of the reaction to populate selected states of interest and to study their decay properties, and (d) the very high momentum transfer which is characteristic of this reaction to extend the range of Doppler-shift lifetime measurements.

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