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Two-Neutron–Transfer Reaction Mechanism with Heavy Ions at Sub-Coulomb Energies

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The reaction ^{208}Pb(^{16}O,^{18}O)^{206}Pb has been measured at incident energies of 69, 71, and 73 MeV. Calculations free of optical-potential ambiguities and utilizing spectroscopic information derived from extensive sub-Coulomb single-neutron–transfer experiments show that, even at these low energies, the sequential transfer of two neutrons is the dominant process.

Although the two-neutron–transfer (2NT) reaction has been studied extensively over a wide range of target-projectile combinations, a detailed understanding of the way the reaction proceeds is far from having been achieved. For both both light- and heavy-ion–induced reactions one-step distorted-wave Born-approximation (DWBA) analyses have consistently been unable to reproduce the observed absolute cross section.[1-6] For heavy-ion reactions, inclusion of inelastic excitations in the reaction channels goes some way towards resolving the problem,[7,8] but the predicted cross sections typically remain too low by about an order of magnitude. Agreement is more noticeably improved if two-step processes corresponding to sequential neutron transfers are taken into account in the calculations.[9-11] However, while few doubt that sequential transfer and other multistep processes can and do occur, especially when the binding of the neutrons to the core is greater than the cluster binding, their relative importance is still an open question.

Even within the framework of an accepted reaction mechanism there are a number of sources of uncertainty which can greatly affect the predicted 2NT cross sections, such as the use of wave functions which provide an inadequate description of neutron clustering or which have an incorrect radial form in the nuclear surface. The situation is in general further clouded by ambiguities in the description of the distorted waves in the various channels. In DWBA the transfer form factor falls off more steeply in the nuclear surface as the mass transferred increases. This tends to make the transfer calculation sensitive to a region of the optical potential inside that which is determined by elastic scattering. For example, the use of weakly or strongly absorbing potentials, each of which predicts similar elastic scattering, can give 2NT yields differing by factors of 4 or 5.[12] Our purpose in this work is to explore the heavy-ion 2NT reaction mechanism in a situation free from optical-potential ambiguities.

We have measured cross sections for the (^{16}O, ^{18}O) and (^{18}O, ^{16}O) reactions connecting states in ^{206}Pb and ^{208}Pb at bombarding energies near the Coulomb barrier (see Table I). We have also measured cross sections for the (^{16}O, ^{17}O) and (^{18}O, ^{17}O) reactions connecting the ^{206}Pb and ^{208}Pb ground states to various states of ^{17}O and ^{207}Pb. These one-neutron–transfer (1NT) data will be reported elswhere.[13] They are used below to determine successive neutron-transfer amplitudes important to the two-neutron–transfer cross section.

Targets of approximately 60 μg/cm^2 (isotopically enriched) ^{208}PbS or ^{206}PbS vacuum deposited onto 10–20-μg/cm^2 carbon backings were bombarded using the University of Minnesota MP

TABLE I. Cross sections (μb/sr) for ^{208}Pb(^{16}O, ^{18}O)^{206}Pb and ^{206}Pb(^{18}O, ^{16}O)^{208}Pb. Column *A* identifies the final levels, column *B* the incident lab energy (MeV), and column *C* the cross section and center-of-mass angle.

A	*B*	*C*
206(g.s.)×18(g.s.)	69	1.8±0.4 (157)
	71	4.1±0.8 (157)
	73[a]	11.5±1.1 (157)
206(2_1^+)×18(g.s.)	69	2.0±0.4 (157)
	71	4.1±0.8 (157)
	73	12.8±1.6 (157)
208(3_1^-)×16(g.s.)	71.6	3.4±1.2 (134)
	71.6	9.4±1.5 (157)
208(5_1^-)×16(g.s.)	71.6	2.6±1.0 (134)
	71.6	9.7±1.5 (157)

[a]Includes ^{206}Pb(^{18}O, ^{16}O)^{208}Pb(g.s.) data.

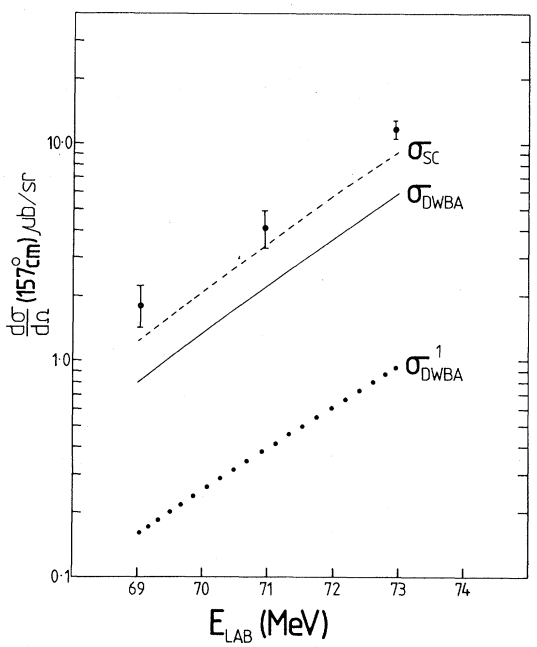

FIG. 1. The differential cross section for the reaction ^{208}Pb(^{16}O, ^{18}O)^{206}Pb to the ground state in the exit channel observed at 157° (c.m.) and at three ^{16}O bombarding energies. The point at 73 MeV includes the data from the reaction ^{206}Pb(^{18}O, ^{16}O)^{208}Pb taken at 71.62-MeV ^{18}O energy. The lines with the various labels correspond to the different theoretical predictions described in the text.

tandem with 0.5–1.0 μA of oxygen 6^+ ions at energies which ranged between 69 and 73 MeV. 2NT and 1NT events were distinguished from other reaction products using position-sensitive silicon detectors appropriately placed along the focal plane of a split-pole magnetic spectrometer. Transfer cross sections were determined relative to elastic-scattering cross sections which were independently established to be within a few percent of the Rutherford-scattering values, even at 73 MeV, which was the highest energy used.

The remainder of this Letter describes our attempt to understand the magnitude of the g.s. → g.s. transition. A one-step finite-range full-recoil calculation was performed, with the ^{208}Pb and ^{16}O ground states taken to be doubly closed shells, and the ^{206}Pb and ^{18}O wave functions taken from True[14] and Engeland and Ellis.[15] The bound-state well geometries used to calculate the radial parts of the single-particle orbitals were those determined from studies of sub-Coulomb 1NT on ^{208}Pb (Ref. 13) and the half-separation energy procedure[16] was used to fix the well depths. Figure 1 shows that this calculation underestimates the cross section by an order of magnitude. This discrepancy is especially noteworthy, since the optical-model wave functions at these sub-Coulomb energies are essentially pure Coulomb waves. This removes a major source of ambiguity that usually obscures comparison of DWBA with experiment. Furthermore, the bound-state wave functions in this case are fairly well known. We conclude that the actual g.s. → g.s. transition receives important contributions from multistep processes.

We have estimated the contribution of two-step processes using the semiclassical model of Broglia and Winther.[17] The probability for transfer of the two neutrons between ^{208}Pb and ^{16}O is calculated along a classical Coulomb trajectory. The treatment of the neutrons and holes in the Pb and O wells is fully microscopic and quantum mechanical. The only approximation is the requirement that the nuclei move along classical orbits, with no recoil when the transfer takes place. Since the Sommerfeld parameter is large (~53), the use of classical orbits for the relative motion is reasonable. We assess the reliability of the semiclassical procedure below.

Some results of the semiclassical calculation are summarized in Fig. 1 and Table II. The calculated total cross section σ_{sc} includes both one-step and two-step transfers, with the latter playing the greater role. The two-step cross section includes contributions from the six sequential transfer paths 2 to 7 shown in Fig. 2. The cross

TABLE II. Semiclassical (s.c.) and DWBA reaction amplitudes for the 2NT paths shown in Fig. 2. Calculations are for 73 MeV and $\theta_{c.m.} = 157°$.

Path	Magnitude $[(\mu b/sr)^{1/2}]$		Phase (rad)	
	S.C.	DWBA	S. C.	DWBA
1	1.48	0.96	0.00	0.16
NO	0.97	0.63[a]	π	3.30[a]
2	0.76	0.63	0.70	0.70
3	0.35	0.28	0.57	0.54
4	0.37	0.33	0.43	0.46
5	0.51	0.40	0.42	0.47
6	0.12	0.09	0.32	0.36
7	0.40	0.34	0.24	0.30
8		0.22		
9		0.32		
10		< 0.04		
2→7	2.5	2.1	0.49	0.52
1→7+NO	3.0	2.4	0.41	0.47

[a]Assuming the same relative NO amplitude as given by the semiclassical calculation.

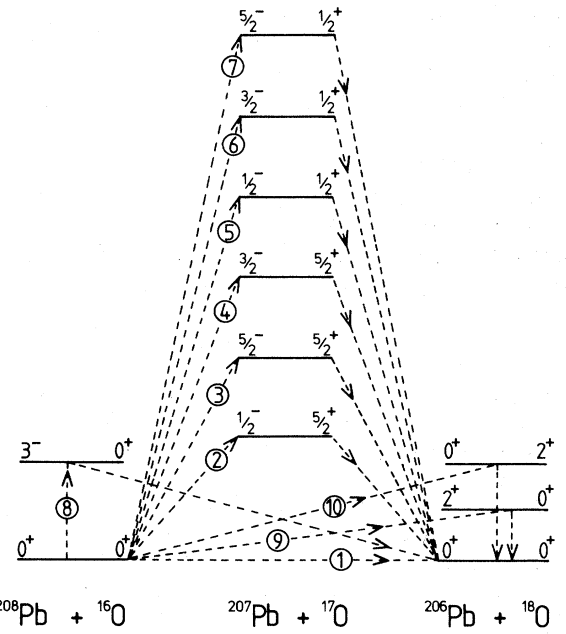

FIG. 2. The direct and two-step paths considered in the predictions of the cross section for the reaction ^{208}Pb(^{16}O, ^{18}O)^{206}Pb. The levels in ^{207}Pb and ^{17}O concerned in the sequential transfer paths are the $p_{1/2}$, $f_{5/2}$, and $p_{3/2}$ single-hole states and the $d_{5/2}$ and $s_{1/2}$ single-particle states, respectively.

section σ_{sc} also includes the important nonorthogonality (NO) correction which must be made when both one-step and two-step processes are considered. This correction amounts to a 66% reduction (see Table II) of the direct amplitude in the representation which has been used here. As can be seen, all the amplitudes (paths 1–7) are approximately in phase. However, the phase difference between the one-step and two-step amplitudes does depend on the Q values of each successive neutron transfer. If these Q values are taken to be equal this phase difference is close to 90°.

A comparison of the DWBA and semiclassical one-step amplitudes suggests that the constraint of using a fixed trajectory in the semiclassical calculations does not introduce large errors. To study further the effect of this constraint, the sequential paths were calculated in second-order DWBA using the computer code CHUCK,[18] which solves a set of coupled-reaction-channels equations such as formulated by Coker, Udagawa, and Wolter.[19] The two-step predictions of this code were normalized by requiring the predicted 1NT cross sections for each step to be consistent with the measured 1NT cross sections. It was found that the relative magnitudes and phases of the individual two-step amplitudes were in good agreement with the semiclassical calculation (see Table II). The curve labeled σ_{DWBA} in Fig. 1 gives cross section resulting from combining the DWBA one- and two-step amplitudes using the same relative NO correction as obtained in the semiclassical calculation. The essential result of all these calculations is that sequential transfers are responsible for most of the cross section with the direct transfer of a neutron pair accounting for a relatively small fraction of the total yield.

Paths 8 and 9 give the only significant inelastic-plus-transfer amplitudes. CHUCK calculations of the *magnitudes* of these amplitudes are approximately equal, as shown in Table II. These calculations are normalized to experimental Coulomb excitation and 2NT data, but do not yield the phases of the amplitudes since they employ a cluster-transfer approximation. However, a microscopic[14,15,20] semiclassical calculation indicates that these phases are nearly opposite. Thus the net contribution due to paths 8 and 9 is minor, and they have not been included in Fig. 1.

It is clear from this work that even at sub-Coulomb energies a one-step DWBA calculation will usually be inadequate for describing heavy-ion 2NT reactions and that it is particularly important to include the sequential transfer mecha-

nism. If the appropriate individual single-neutron–transfer cross sections can be determined experimentally, as in the present work, one can have greater confidence that the sequential amplitudes have been taken into account properly.

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Fine Structure in the Fusion Cross Section for $^{16}O + ^{12}C$

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γ-ray excitation functions have been measured for several residual nuclei in the $^{12}C + ^{16}O$ system, from $E_{c.m.} = 12.2$ to 15.0 MeV in steps of ~ 27 keV. In addition to three known resonances, a fine correlated structure is found superimposed over a broad resonance, as suggested by the mechanism of a fragmented shape resonance. The data may also be interpreted to indicate that the system decays via two different paths.

During the past two or three years several resonances of the same spin and similar energy have been reported[1,2] in the $^{12}C + ^{12}C$ and $^{12}C + ^{16}O$ systems. This resonance clustering has led Feshbach[2] and Fletcher *et al.*[3] to suggest that we are witnessing a fragmentation of a wide shape resonance via a weak coupling of the incoming partial wave to the excited states of the interacting ions. However, many of the resonances have not been proven[1] to be nonstatistical in nature.

In this Letter, we report on the γ-ray yield measurement for several residual nuclei in the $^{12}C + ^{16}O$ system, from $E_{c.m.} = 12.2$ to 15.0 MeV. In addition to three known[4-6] resonances at 12.8, 13.7, and 14.8 MeV c.m., we find for the first time a fine structure in the fusion cross section. This fine structure, about 70 keV wide, superimposed over a gross structure, approximately 2 MeV wide, presents for the first time a direct visualization of a fragmented wide shape resonance. Furthermore, resonances of different widths are also observed, suggesting that the system decays via two different paths.

The experiment was performed using ^{16}O beams from the Université de Montréal *EN* tandem accelerator. The targets of natural C, having an effective thickness of about 12 $\mu g/cm^2$, were evaporated onto thick Ta backings. They were surrounded by a liquid-nitrogen–cooled shield which effectively limited the carbon buildup, if any, to less than 1% over a period of 96 hours. The mean beam energy loss in the target was of

