Title	Prevalence of Direct-Reaction Mechanism in a Deeply Inelastic ^<197>Au(^<19>F,^<12>B)
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Note	

Prevalence of Direct-Reaction Mechanism in a Deeply Inelastic Reaction, ^{197}Au(^{19}F,^{12}B)

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Continuum cross sections and spin polarizations of ^{12}B produced in the reaction ^{197}Au(^{19}F,^{12}B) induced by 186-MeV ^{19}F were measured. The observed data were reproduced very well in terms of a distorted-wave Born-approximation theory, indicating that this reaction transferring as many as seven nucleons proceeds as a direct process.

Recent measurement[1] of the spin polarization of the ejectile ^{12}B produced in the reaction ^{100}Mo(^{14}N,^{12}B) added a new dimension to the understanding of the mechanism of heavy-ion reactions leading to continuum excited states. The polarization (P) measured as a function of the energy (E_b) of ^{12}B revealed a unique feature characterized by a large positive P at the highest E_b, followed by a rapid decrease to negative values of P with decreasing E_b. It was recognized[2] that such behavior of P is completely opposite to the prediction made by a classical macroscopic model based on the frictional force.[3] A theoretical analysis[4] using an exact-finite-range distorted-wave Born approximation (EFR-DWBA) achieved a successful fit to the data and provided a quantitative explanation. Two ingredients inherent in the EFR-DWBA were crucial in reproducing the experimental observation: The transverse recoil effect yields large positive P values for high E_b; the l-window effect causes the decrease of P towards lower E_b. This theoretical finding suggests that such behavior of P may generally be considered as a "signature" of a one-step direct reaction. We recently studied a one-proton transfer reaction ^{232}Th(^{13}C,^{12}B) to corroborate this argument, and found that the observed P indeed exhibited the same behavior.[5]

The study was then extended in order to see whether the direct-reaction mechanism persists even in reactions involving much larger mass, charge, and energy transfers. The reaction ^{197}Au(^{19}F,^{12}B) at 186 MeV was chosen as an example of such a deeply inelastic reaction. Surprisingly enough, the same feature was found to prevail in this reaction. The discussion below is concerned with this unexpected result.

The experimental procedure was similar to that of the previous study[1]; several improvements, however, were made to cope with complexities involved in the ^{19}F-induced reaction. The spin polarization of ^{12}B is determined from the asymmetry of the β rays in the decay of ^{12}B(g.s.) to ^{12}C(g.s.), measuring the intensities in the directions of 0° and 180° with respect to the polarization axis [defined parallel to the ($\vec{k}_i \times \vec{k}_f$) axis]. The 190-MeV $^{19}F^{5+}$ beam from the Texas A&M cyclotron was used to bombard a gold target of 5.6 mg/cm^2 thickness placed at 45° to the beam (the effective incident energy is estimated to be 186 MeV as a result of the energy loss in the target). The beam was pulsed with 40-ms duration and 130-ms repetition period; the β rays were counted during the beam-off intervals. The ^{12}B ejectiles scattered at the laboratory angle 25° were implanted into a platinum stopper foil which was placed in the vertical external magnetic field. An aluminum energy-degrading foil, whose thickness was varied, was inserted to select the ^{12}B energy bin. The β rays from the stopper foil were detected with a pair of threefold plastic counter telescopes placed above and below the stopper. To compensate for possible asymmetry in the counting efficiencies of the two telescopes, the spin orientation of the implanted ^{12}B was externally reversed in every second counting period using the NMR technique of the fast adiabatic method. For each thickness of the absorber the measurement was made both with a 15-μm and with a 5-μm platinum stopper. This, in turn, provided the correction for the depolarization effect due to the hyperfine interaction.

In the present reaction, the presence of a large number of background β emitters was noted in an independent measurement of charged-particle spectra using solid-state counter telescopes. Taking advantage of the large decay energy of ^{12}B, the low-energy threshold of β rays was set high, typically at 6 MeV, to eliminate a strong contribution from ^{20}F as well as other background. The remaining background from the long-lived activities such as ^{8}Li, ^{15}C, and ^{16}N were clearly distinguished and corrected by observation of the decay curves. This procedure did not allow separation of the contribution from ^{13}B. In the present method, the contamination of ^{13}B simply reduces the magnitude of the observed P in proportion to its relative cross section; thus the correction was made from the energy spectra of the direct charged-particle measurement.

The results for the reaction ^{19}Au(^{19}F, ^{12}B) are shown in Fig. 1. Figure 1(a) shows that the present β-ray measurements are consistent with the

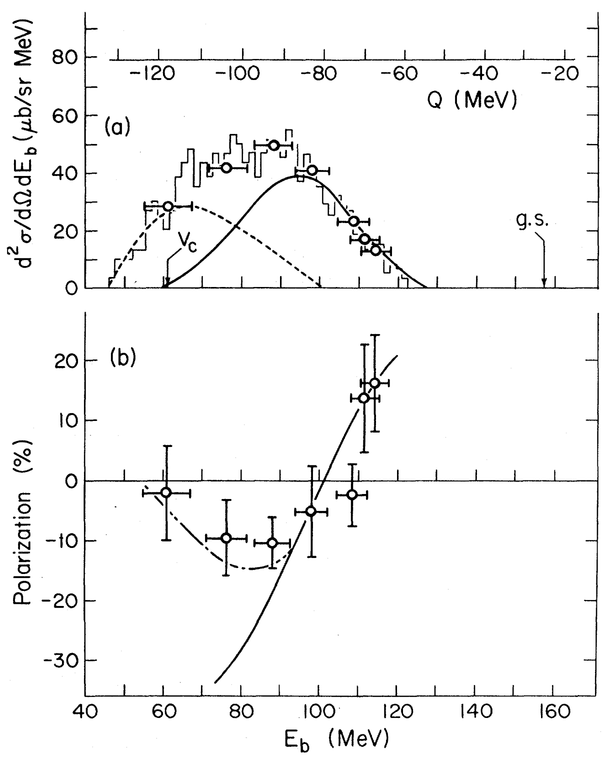

FIG. 1. (a) The cross sections $d^2\sigma/d\Omega\, dE_b$ of the reaction ^{197}Au(^{19}F, ^{12}B) measured at 25° with the incident energy 186 MeV are shown as a function of the energy E_b of ^{12}B and Q value. The experimental points are shown by the open circles, and the widths of the energy bins are indicated by the horizontal bars through these points. The histogram shows the energy spectrum obtained in a separate experiment using solid-state counters. The solid lines show the theoretical results, while the dashed line corresponds to the difference between the theoretical and experimental cross sections. (b) The spin polarization P is also shown in terms of E_b. The errors indicated include the statistics and uncertainties in the corrections. The theoretical fits are shown by the solid lines. The dot-dashed line displays the corrected result of the polarization as discussed in the text.

energy spectrum obtained in the direct charged-particle measurement as shown by the histogram. It is seen that, contrary to the (^{14}N, ^{12}B) reaction where the enhancement appears near the ground-state Q value (Q_{gg}) (cf. Fig. 2 of Ref. 1), the energy spectrum of the (^{19}F, ^{12}B) reaction exhibits a characteristic of a strongly energy-damped collision, showing little strength near Q_{gg} but considerable strength down to the Coulomb barrier (V_C). The optimum Q values of -20 MeV for the (^{14}N, ^{12}B) reaction and -100 MeV for the (^{19}F, ^{12}B) reaction represent a difference of the degree of energy damping. In spite of this sharp contrast in the energy spectra, the behavior of P is surprisingly similar between the two reactions; compare again Fig. 2 of Ref. 1 and Fig. 1 of the present article. This result immediately indicates the direct nature of the (^{19}F, ^{12}B) reaction.

A theoretical analysis assuming the direct one-step transfer mechanism was carried out in much the same manner as in the previous analysis[4] for the reaction ^{100}Mo(^{14}N, ^{12}B). A major difference in the analysis of the (^{19}F, ^{12}B) reaction lies in the form of the spectroscopic density, $\rho_s(E_x, I)$, derived from Ericson's model[6] with an additional spin cutoff factor

$$\rho_s(E_x, I) = (E_x/T)^6 \exp[-I(I+1)/2\mathscr{G}T)],$$

where E_x and I denote, respectively, the excitation energy and spin of the state in the residual nucleus (^{204}Bi). The moment of inertia of ^{7}Be around ^{197}Au is denoted by $\mathscr{G}$, and the temperature T was set at 10 MeV (corresponding to $E_x = 70$ MeV at the peak of the cross section and seven degrees of freedom in the system).

The calculated results are shown in Fig. 1 by solid lines. Both the energy spectrum and the polarization are reproduced rather well, confirming our premise that the direct-reaction mechanism prevails in the present reaction. More precisely, the agreement with experimental results is particularly good at high E_b, but a noticeable deviation begins to take place as E_b decreases. In fact, the theory predicts too small cross section and too large magnitude of P in low E_b region. In Fig. 1(a), the dashed line displays the difference between the experimental and theoretical cross sections. It was noticed that the shape of this dashed line resembles the energy spectra observed at backward angles (i.e., beyond 50°); thus, it possibly indicates contributions from higher-order processes.[7] Assuming that this extra cross section is to be added to the theoretical cross section obtained above, but with vanishing contribution to the polarization, we obtain new values of P as shown by the dot-dashed line in Fig. 1(b). Although this new P agrees rather well with experiment, of course the fit thus obtained should not be taken too seriously until calculations including higher-order processes are actually performed.

From the results obtained above, we may conclude that even for the reaction (^{19}F, ^{12}B) the prevalence of a one-step transfer mechanism is evident (at least for large E_b), in sharp contrast to the customary understanding of deeply inelastic processes. As emphasized previously, the shape of the energy spectrum of this reaction differs greatly from that of the usual quasielastic-type reactions in that it vanishes near Q_{gg} and is enhanced in the very low-E_b regions. This difference might be regarded as evidence against the interpretation of the (^{19}F, ^{12}B) reaction in terms of the direct-reaction theory. However, it can be readily explained by considering the angular momentum transfer and the spectroscopic density. In this reaction the angular momentum transfer does not cause severe mismatching over the entire energy region considered. For instance, the transferred angular momentum at $Q \simeq -100$ MeV ($E_x \simeq 80$ MeV) is evaluated to be $40\hbar$, for which the spectroscopic density is not much suppressed; that is, many available states are expected at such a high E_x. Thus, even a one-step transfer process can provide considerable cross sections for the region of large energy losses. On the other hand, the strong E_x dependence in $\rho_s(E_x, I)$ suppresses the cross sections in the lower-E_x region, yielding a drastically different energy spectrum from that of fewer-nucleon transfer reactions. As to the assumption of the one-step transfer for these seven nucleons, a direct confirmation of such a clustering phenomena remains an experimental and theoretical question. It is, however, worthwhile to note that in light nuclei such as an sd-shell nucleus ^{19}F the many-body correlation plays a dominant role, resulting in strong clustering phenomena.

In conclusion, we have presented evidence that the direct process prevails in a reaction with large mass, charge, and energy transfers. It is customary to classify such a reaction as a deeply inelastic process, in contrast to the quasielastic process, where the direct-reaction theory is considered to be applicable. Therefore, the present result shows that at least some of the so-called deeply inelastic reactions proceed with a mechanism which is not intrinsically different from that of the quasielastic reactions. This finding is in concurrence with studies of a variety of continuum spectra in reactions transferring α particles.[8]

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