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Direct reaction analysis of $^{19}F(p,\alpha)^{16}O$ below the Coulomb barrier

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The reaction $^{19}F(p,\alpha)^{16}O$ (g.s.) is analyzed in terms of the distorted-wave Born approximation at energies below the Coulomb barrier. We calculate differential cross sections at 250, 350, and 450 keV as well as excitation functions between 150 and 850 keV and compare with experimental data. The astrophysical S factor is determined. We conclude that a direct reaction mechanism alone can account for the observed sub-Coulomb cross section below about 500 keV.

For the general description of nuclear reactions, two extreme models are available. The first is the compound nucleus model, developed by Niels Bohr more than 50 years ago; the second is the direct reaction model, formulated about 20 years later. These reaction models, together with experimental cross-section data in a wide range of energies lead to predictions of nuclear reaction rates in astrophysical scenarios.

It is commonly accepted that nuclear reactions for energies above about 20 MeV mainly proceed via a direct mechanism. For intermediate projectile energies ($\lesssim$20 MeV), however, distinct levels of the compound system are populated, resulting in pronounced resonances in the excitation functions. Also for astrophysically relevant reactions which typically proceed at sub-Coulomb energies of a few keV or tens of keV, compound mechanisms have frequently been suggested. It has been a long-standing question whether direct mechanisms could also give substantial contributions to light-ion induced reactions at thermonuclear energies. While sub-Coulomb transfer reactions involving heavy ions were a hot topic during the last decade (e.g., [1]), no comparable effort has been made yet for light-ion collisions, i.e., for astrophysical scenarios.

Recent analysis of experimental data for $^{7}Li(p,\alpha)^{4}He$ suggest the presence of a direct reaction mechanism at sub-Coulomb energies [2,3]. This mechanism can also be important for other astrophysically relevant three-nucleon transfer reactions with an α particle in the entrance or exit channel, i.e., (p,α) and (α,n) reactions on light nuclei. It is well known that (p,α) reactions play an important role in primordial nucleosynthesis as well as in hydrogen burning in stars, while (α,n) reactions are neutron sources for the s process. In this work, we focus on the reaction $^{19}F(p,\alpha)^{16}O$ (g.s.) (Q=8.115 MeV), which is responsible for the burning of ^{19}F in the fourth branch of the carbon-nitrogen-oxygen (CNO) cycle. We calculate the direct contribution to this reaction in zero-range distorted-wave Born approximation (DWBA) for thermonuclear energies.

In Fig. 1, the experimental excitation functions for the transitions to the ground state and to excited states of ^{16}O for projectile energies between 150 and 900 keV are shown [4]. The reaction scheme including these transitions is shown in Fig. 2. On top of Fig. 1, the level scheme of the compound nucleus ^{20}Ne is indicated. While the transitions to excited states show marked resonance peaks, no resonant behavior is observed for the ground-state transition up to about 500 keV. This indicates that the excited ^{20}Ne states in this energy range have only a small $\alpha+^{16}O$ (g.s.) component, meaning that the decay of the compound nucleus into the ground state of the exit channel is suppressed. As a consequence, the ground-state transition may be dominated by a direct mechanism.

The reaction $^{19}F(p,\alpha)^{16}O$ (g.s.) was already investigated at projectile energies greater than 18 MeV. This energy range is the domain of the direct reaction mechanism, and the angular distributions and the absolute magnitude of the cross sections could be well reproduced by microscopic finite-range DWBA [5,6]. An essential improvement in the calculation of the absolute cross sections for (p,α) reactions was obtained by using the double-folding procedure for the α-optical potential [7].

The present calculations were done with the DWBA code TETRA [8], which is designed for all energies, but with special emphasis on correct analytical and numerical behavior for extremely low energies. Presently, this code works in zero-range approximation. Finite range is currently being implemented.

In the entrance channel we used a Saxon-Woods optical potential with parameters given in Table I. We did not include a spin-orbit term, which is negligible at these low energies. We needed, however, an energy dependent small volume absorption term.

In the exit channel, we applied a double-folding procedure for the real part of the optical potential [9], with a normalization factor of λ=1.312, which reproduced the elastic α-^{16}O data [10] near 5 MeV. For the imaginary part, a volume absorption term was used (Table I). The volume integral for this imaginary part fits well into an

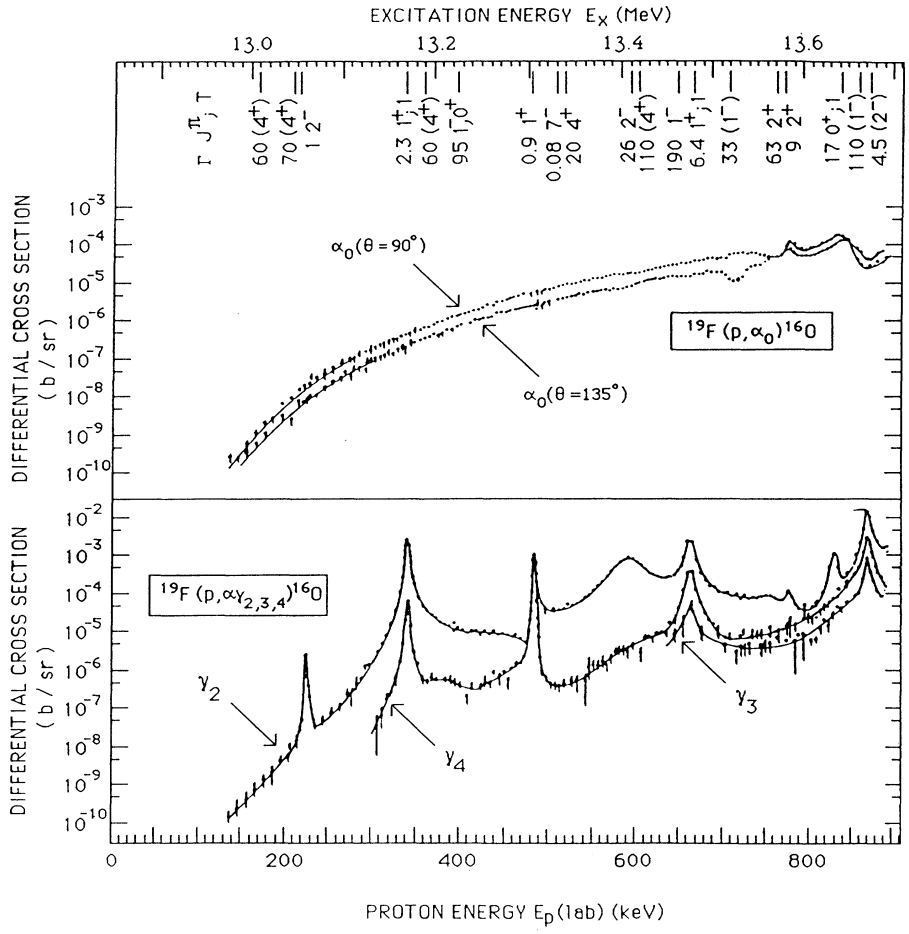

FIG. 1. Excitation functions of $^{19}F(p,\alpha)^{16}O$ (g.s.) for $\theta_\alpha = 90°$ and 135° (upper part) and $^{19}F(p,\alpha\gamma_{2,3,4})^{16}O^*$ for $\theta_\gamma = 45°$ (lower part) [4]. The solid lines are guides to the eye only. The levels of ^{20}Ne together with their spins, parity assignments, and widths are indicated on top of the figure.

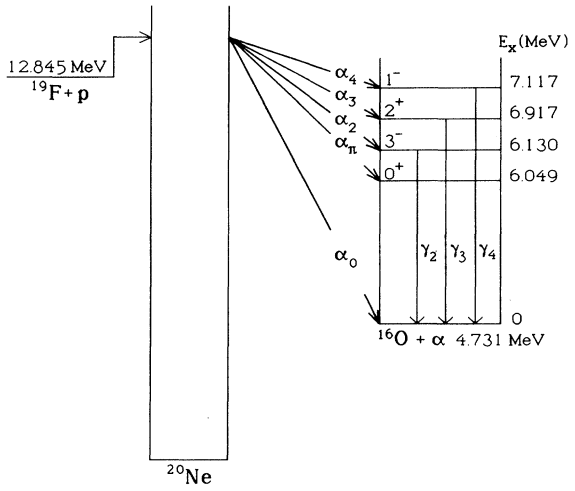

FIG. 2. The energy scheme for the reactions $^{19}F(p,\alpha)^{16}O$ (g.s.), $^{19}F(p,\alpha_\pi)^{16}O$, and $^{19}F(p,\alpha\gamma_{2,3,4})^{16}O^*$.

TABLE I. Parameters of the optical potentials and the potentials of the bound states of the single particles for the reaction $^{19}F(p,\alpha)^{16}O$ (g.s.) in the energy range of 100 to 900 keV.

$p+^{19}F$	Real and imaginary part: Saxon-Woods potentials $V = V_0 + V_1 E_{lab}$; $V_0 = 56.5$ MeV, $V_1 = -2$ $r_0 = 1.12$ fm, $a = 0.48$ fm $W = W_0 + W_1 E_{lab}$; $W_0 = 0.625$ MeV, $W_1 = 1.5$ $r_0 = 1.25$ fm, $a = 0.55$ fm $r_c = 1.20$ fm
$\alpha+^{16}O$	Real part: double-folding potential Imaginary part: Saxon-Woods potential $W = 2$ MeV, $r_0 = 1.25$ fm, $a = 0.6$ fm $r_c = 1.25$ fm
Bound states	Saxon-Woods potentials V_0 [a] $r_0 = 1.31$ fm, $a = 0.65$ fm, $r_c = 1.25$ fm $V_{so} = 6.25$ MeV, $r_{so} = 1.31$ fm, $a_{so} = 0.65$ fm

[a]Calculated from the separation energy $S = 3.5$ MeV.

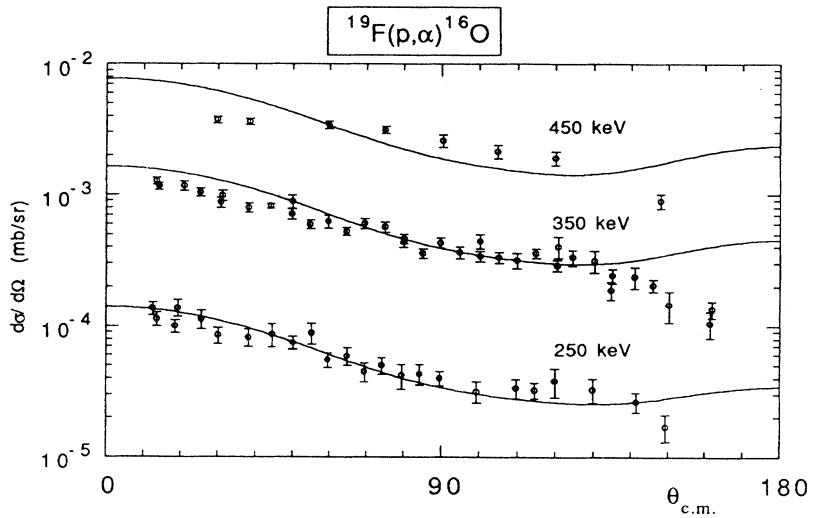

FIG. 3. Differential cross sections of $^{19}F(p,\alpha)^{16}O$ (g.s.) at projectile energies of 250, 350, and 450 keV. The experimental data are taken from [4]. The solid lines are the results of the present calculation.

energy dependent analysis of the α-^{16}O optical potential [11].

The form factor, identical to the one used for energies greater than 18 MeV [5,6], was calculated in the microscopic model [12], adding the different configurations with the corresponding spectroscopic amplitudes coherently. The bound-state parameters for the single-particle states are listed in Table I. The zero-range normalization constant is given by [5]

$$D_0^2 = 4.53 \times 10^5 \text{ MeV}^2\text{fm}^3. \quad (1)$$

In Fig. 3, the experimental differential cross sections at 250, 350, and 450 keV projectile energy [4] are shown together with the results of our calculations. We found good agreement not only for the angular distributions, but also for the absolute values of the cross section without any normalization factor. Calculations at energies above 20 MeV indicate that finite range effects are not important.

In Fig. 4, the experimental excitation functions [4] for $\theta_{lab}=90°$ and 135° are compared with the calculated DWBA results. The experimentally observed energy dependence is nicely reproduced below about 500 keV. Hauser Feshbach (HF) calculations drastically overestimate the experimental data and result in a different energy dependence of the cross sections (a factor of 20 at 250 keV and a factor of 5 at 850 keV). The reason for this can be found in the HF ansatz, which does not account for the shell-model structures of the nuclei involved: As already discussed above, the ^{20}Ne states have only a small $\alpha + ^{16}O$ (g.s.) component. Therefore the decay of the compound nucleus into the ground state of the ^{16}O nucleus is strongly suppressed.

For astrophysical purposes it is convenient to quote the

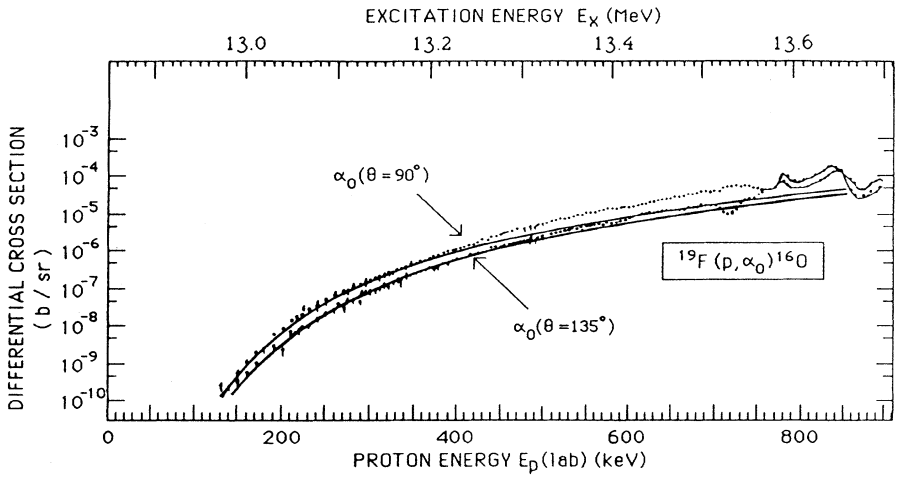

FIG. 4. Excitation functions of $^{19}F(p,\alpha)^{16}O$ (g.s.) at $\theta_{lab}=90°$ and 135° for projectile energies in the range up to 900 keV. The experimental data are taken from [4]. The solid lines are the results of the present calculation.

S factor, which can be parametrized in the analytical form

$$S(E)=S(0)+\dot{S}(0)E+\tfrac{1}{2}\ddot{S}(0)E^2. \quad (2)$$

For $^{19}F(p,\alpha)^{16}O$ (g.s.) the calculated parameters are $S(0)=8.755$ MeV b, $\dot{S}(0)=-3.48$ b, and $\ddot{S}(0)=20.1$ MeV^{-1} b.

Summarizing, the DWBA can reproduce the absolute values of the differential cross section as well as the excitation function for the reaction $^{19}F(p,\alpha)^{16}O$ (g.s.) in the nonresonant range below the Coulomb barrier. Together with the results for the reaction $^{7}Li(p,\alpha)^{4}He$ the present analysis gives strong evidence that (p,α) cross sections at thermonuclear energies may be dominated by a direct mechanism.

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