Fusion Cross Sections for the Proton Drip Line Nucleus ^{17}F at Energies below the Coulomb Barrier

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The fusion-fission cross section for the system ^{17}F + ^{208}Pb involving the drip line nucleus ^{17}F has been measured at energies in the vicinity of the Coulomb barrier. No enhancement of the fusion-fission yields due to breakup or to a large interaction radius was observed. [S0031-9007(98)07400-6]

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The production of beams of short-lived, radioactive nuclei is currently being pursued at many laboratories around the world. With these exotic beams one can for the first time study nuclear reactions using projectiles with properties drastically different from those found along the valley of stability. In particular, nuclei located near the drip lines, where the neutrons or protons are very weakly bound, are expected to give rise to new phenomena [1]. In a semiclassical picture, the low binding energies result in larger radii and, thus, in increased probabilities for specific reaction channels such as neutron transfer(s) and fusion (see, e.g., [2] and references therein). On the other hand, these exotic systems also exhibit large excitation probabilities for low-lying dipole modes which, due to the small binding energies, result in an increased breakup probability. At high bombarding energies the "halo" structure manifests itself through an increase of the total reaction cross section [3].

At lower beam energies, the influence of the large interaction radius and the breakup probability on, e.g., the fusion channel has been discussed extensively in the literature [4–6], but the question of whether fusion is enhanced or reduced has not yet been answered experimentally. In fact, fusion reactions involving nuclei at the drip lines have been investigated only recently [2] and have in some cases led to contradicting results [7–9]. This is due, at least in part, to experimental difficulties. Thus far, most halo nuclei have been produced by fragmentation, a process where the projectiles of interest emerge from the production target with high kinetic energies. They then have to be slowed down in degrader foils, and a relatively poor energy resolution follows. Furthermore, the achievable intensities in these secondary beams are also quite low, and in most cases the smallest cross sections measured are in the 10–100 mb range, where possible differences between halo and stable projectiles are difficult to discern. Since the halo effects have first been detected in the nucleus ^{11}Li, most of the early investigations dealt with nuclei involving weakly bound neutrons. Proton halo nuclei have only recently received increased attention [10–13].

The first measurement of a fusion cross section involving the proton drip line nucleus ^{17}F with incident energies at and below the Coulomb barrier is presented here. ^{17}F is the lightest particle-stable fluorine isotope, with a proton binding energy of 0.6 MeV. Its only excited level $(1/2^+)$ has a binding energy of only 0.1 MeV and is connected to the $5/2^+$ ground state through a transition with a noticeably large $B(E2)$ value: 66.4 $e^2\,\mathrm{fm}^2$ [14]. While the $d_{5/2}$ structure of the ground state suppresses the halo character [15], the $l = 0$ structure and the small binding energy of the excited $1/2^+$ level make it a good proton halo candidate. The larger spatial extension of the excited state can be inferred from recent measurements of the $^{16}\mathrm{O}(p,\gamma)$ reaction [16], where rms radii of 5.33 fm for the $1/2^+$ level and 3.7 fm for the $5/2^+$ ground state have been reported. Thus, if ^{17}F can be prepared in its first excited state with a sufficiently high probability (e.g., via Coulomb excitation taking advantage of the large $B(E2)$ value), the larger radius for the $1/2^+$ state should lead to a lowering of the Coulomb barrier and to an increased fusion probability. Breakup effects for a proton-halo nucleus should also lead to an increase of the fusion cross section. If the breakup occurs at sufficiently large distances, the remaining core (^{16}O in this case) experiences a reduced Coulomb barrier which should lead to an increased fusion probability. As a result, ^{17}F offers an excellent opportunity to study possible changes in fusion in the vicinity of the Coulomb barrier over what would be expected for a stable beam, e.g., ^{19}F.

The inverse $p(^{17}\mathrm{O},^{17}\mathrm{F})n$ reaction was used to produce the radioactive ^{17}F beam. The ATLAS superconducting linear accelerator provided a high-intensity, primary ^{17}O beam (≤ 250 particle nA) which bombarded a 7.5 cm long gas cell, filled with hydrogen at a pressure of $\sim$600 Torr [17]. The windows of the gas cell consisted of 1.9 mg/cm^2 thick HAVAR foils. Because of the large center-of-mass momentum, the ^{17}F ions produced in the reaction are emitted at forward angles within a cone of $\sim 2°–4°$ with energies that depend on the incident ^{17}O energy, the Q value of the $p(^{17}\mathrm{O},^{17}\mathrm{F})n$ reaction and the

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energy loss in the hydrogen target and the entrance and exit foils. The ^{17}F energies necessary for the present study [$87 \leq E(^{17}\mathrm{F}) \leq 99$ MeV] were obtained by varying the primary-beam energy between 95 and 120 MeV. The gas cell was located in front of a 22° bending magnet. By selecting the magnetic field to transport fully stripped $^{17}\mathrm{F}^{9+}$ ions to the target, a good suppression of the intense primary ^{17}O beam was achieved. The energy of the secondary $^{17}\mathrm{F}^{9+}$ beam was measured with an Enge split pole magnetic spectrograph positioned at 0° after having reduced the primary ^{17}O beam incident on the gas cell to a suitably low intensity. The spectrograph was calibrated with a ^{228}Th α source and with the primary ^{17}O beam scattered from a thin Au target at $\theta = 5°$. The ^{17}F intensity measured at the ^{208}Pb target was $(1-2) \times 10^5$ ^{17}F/sec with an energy resolution of $\sim 2.5\%$. The main contaminant in the secondary beam consisted of energy degraded $^{17}\mathrm{O}^{8+}$ ions with the same magnetic rigidity, i.e., with an energy of $64/81 \times E(^{17}\mathrm{F})$. The ratio of the beam intensities between ^{17}F and ^{17}O depended on the energy, but was generally better than 1:1.

The $^{17}\mathrm{F} + {}^{208}\mathrm{Pb}$ fusion-fission reaction was studied with a high-efficiency Si surface barrier detection system surrounding the 500 μg/cm^2 ^{208}Pb target located at the center of the spectrograph scattering chamber. In these heavy systems the fusion cross section is dominated by the fission channel which is stronger than the evaporation residue production by factors of 5–10 [18]. The fission fragments were measured in coincidence using four large 5×5 cm^2 Si detectors at a distance of 5 cm from the target. The front side of each detector was subdivided into 4 quadrants each covering an angular range of $\Delta\Theta \sim 25°$. The coincidence requirement between the two fission fragments resulted in very clean, background-free signals. The total efficiency of the detection system for fission fragments was calculated in a Monte Carlo simulation to be 7.8%. It was also tested directly through a measurement of the fusion-fission cross sections for the system $^{19}\mathrm{F} + {}^{208}\mathrm{Pb}$ in the energy range $E(^{19}\mathrm{F}) = 85-109$ MeV (see below). The quality and isobaric purity of the incident secondary beam was monitored continuously by detecting elastically scattered particles at $\theta = 5°$ in the magnetic spectrograph, where the ions were identified with respect to mass and nuclear charge Z in a hybrid-type focal plane detector. It should be noted that contributions to the cross section from fission induced by the isobaric beam components of ^{17}O are smaller than 3%. This is due to the $\sim 20\%$ lower energy of the ^{17}O ions discussed above. For the energy range of interest ($87 \leq E(^{17}\mathrm{F}) \leq 99$ MeV), the corresponding ^{17}O energy is 69–78 MeV, i.e., 63.5–72 MeV in the center of mass, where fusion-fission cross sections of only 0.1–9 mb have been reported for the neighboring system $^{16}\mathrm{O} + {}^{208}\mathrm{Pb}$ [18]. These cross sections are considerably smaller than those expected in the $^{17}\mathrm{F} + {}^{208}\mathrm{Pb}$ case.

The experimental results for the fusion-fission cross sections obtained with ^{17,19}F beams on ^{208}Pb are presented in Fig. 1. The data points have been corrected for the energy width of the incident beam, by taking the energy dependence of the experimental fusion cross section into account. In Fig. 1a the cross sections are given as a function of the center-of-mass energy E_{cm}, while in Fig. 1b they are plotted as a function of E/V_c, where V_c is the Coulomb barrier calculated according to Ref. [19]. The open circles are the results obtained in the present work for the $^{19}\mathrm{F} + {}^{208}\mathrm{Pb}$ reaction: they are in good agreement with the cross sections measured in small energy steps in Ref. [20] for the same system (see solid line in Fig. 1).

The measured fusion-fission cross sections for the $^{17}\mathrm{F} + {}^{208}\mathrm{Pb}$ reaction are represented by the solid points in Fig. 1. The values vary smoothly with energy from 310 mb at $E_{\mathrm{cm}} = 91$ MeV to 1.5 mb at $E_{\mathrm{cm}} = 80.4$ MeV. A close inspection of Fig. 1 indicates the most important result from the present study: fusion with the drip line nucleus ^{17}F is *not* enhanced relative to that measured with the stable ^{19}F projectile. To the contrary, at the lowest beam

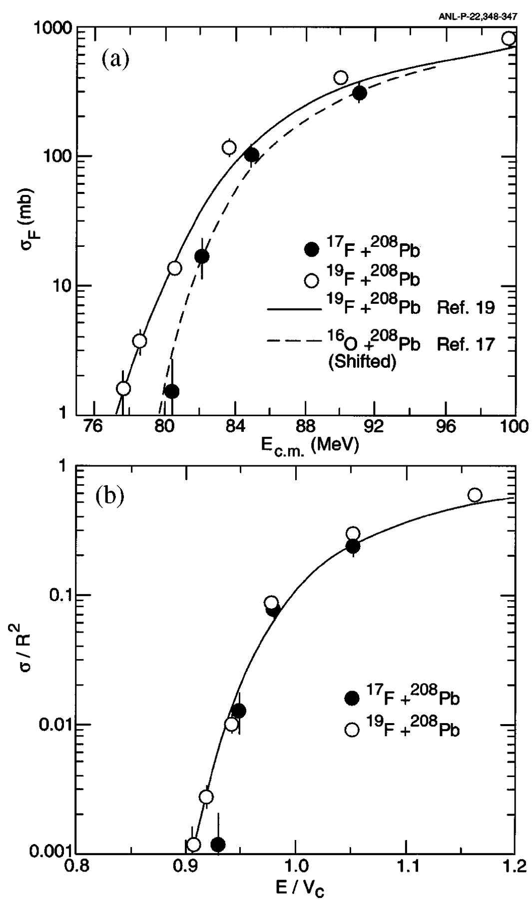

FIG. 1. (a) Fusion-fission cross sections as a function of the center-of-mass energy for the systems $^{19}\mathrm{F} + {}^{208}\mathrm{Pb}$ (open circles) and $^{17}\mathrm{F} + {}^{208}\mathrm{Pb}$ (solid points) measured in this experiment. The solid line represents the cross sections measured for $^{19}\mathrm{F} + {}^{208}\mathrm{Pb}$ in Ref. [19]. The dashed line gives the fusion-fission cross section measured for $^{16}\mathrm{O} + {}^{208}\mathrm{Pb}$ shifted in energy by 9/8, i.e., the factor of the nuclear charges. (b) Same as (a), but plotted as a function of E/V_c, where V_c is the Coulomb barrier calculated from Ref. [18].

energy a reduction by a factor of ~ 4 is observed. Another conclusion can also be drawn from Fig. 1. The dashed line (Fig. 1a) presents the fusion-fission cross section for the $^{16}O + ^{208}Pb$ reaction [18] shifted by the ratio $9/8$ of the nuclear charges (F vs O). The agreement between the dashed curve and the solid points indicates that the systems $^{17}F + ^{208}Pb$ and $^{16}O + ^{208}Pb$ have essentially the same behavior.

In order to study the possible influence of Coulomb excitation and dissociation on the fusion-fission process, the probabilities for exciting the $1/2^+$ state of ^{17}F and for dissociating ^{17}F into its $^{16}O + p$ constituents in the $E1$ and $E2$ fields of the target nucleus have been calculated to all orders in a consistent way. These calculations were performed as described in Ref. [21] for the case of ^8B breakup, with the only difference that Coulomb trajectories instead of straight line trajectories were used for the ^{17}F case. Thus, the dynamical evolution of the single-particle wave function of the valence proton (initially bound in a d wave) was followed in the time-dependent $E1$ and $E2$ fields of the target nucleus. The single-particle Hamiltonian was adjusted so that the known binding energies of the $5/2^+$ ground state and the $1/2^+$ excited level are reproduced. This was achieved by using a Woods-Saxon well, with a slightly larger radius parameter for d waves. This Hamiltonian reproduces fairly well the measured low-energy radiative capture cross sections [16] of protons on ^{16}O to the ground state and to the excited $1/2^+$ level.

The excitation (dashed line) and breakup (solid line) probabilities obtained at the distance of closest approach in head-on collisions are presented in Fig. 2 as a function of the ^{17}F center-of-mass energy. The probability for exciting the $1/2^+$ level (dashed line) is in good agreement with first-order perturbation theory, based on the known $B(E2)$ value, but it is slightly reduced at the highest energy, most likely because of dissociation from this state. Also shown in Fig. 2 is the fusion probability defined in Ref. [22] as $P_f = \sigma_f/\sigma_r$ measured for the system $^{17}F + ^{208}Pb$ (solid points), where σ_f and σ_r are the fusion-fission and total reaction cross sections, respectively. The total reaction cross section was obtained from an optical model calculation for the system $^{17}F + ^{208}Pb$ with optical potential parameters from the neighboring system $^{16}O + ^{208}Pb$ [23]. A comparison of the various probabilities shows that both the Coulomb excitation and the breakup probabilities at the distance of closest approach are less than 2% for beam energies in the vicinity of the barrier. These are too small to influence the fusion process significantly.

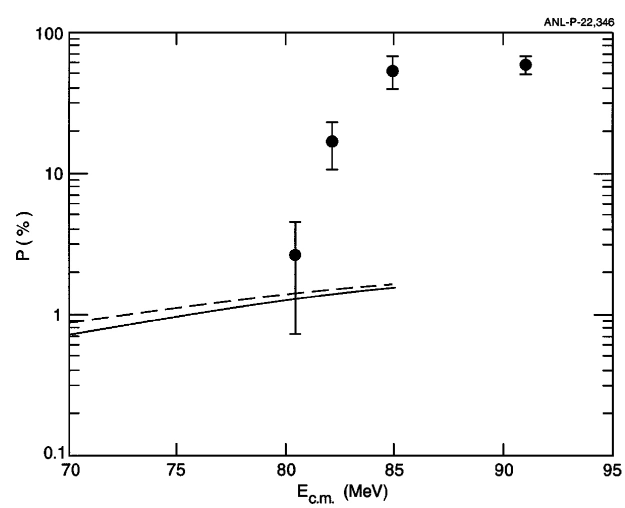

FIG. 2. Probabilities for Coulomb excitation (dashed line) and breakup into $^{16}O + p$ (solid line) calculated for the $^{17}F + ^{208}Pb$ system within a dynamical model described in the text. The solid points represent the fusion probabilities $P_f = \sigma_f/\sigma_r$ from this experiment.

The fusion probabilities for $^{17}F + ^{208}Pb$ shown in Fig. 2 also exhibit an interesting behavior at higher beam energies. In a recent experiment with light, stable nuclei (e.g., $^{6,7}Li$ and ^9Be), a correlation between the nucleon separation energy and the fusion probability at high energies was observed [22]: systems with low separation energies were found to have a small fusion probability at higher energies. For the system $^6Li + ^9Be$, with an effective separation energy (defined in Ref. [22]) of 0.78 MeV, a value $P_f = 0.25$ was reported. From the small effective separation energy of 0.55 MeV for $^{17}F + ^{208}Pb$, a maximum fusion probability $P_f = 0.15$ would be expected based on the systematics of Ref. [22]. From Fig. 2, however, values reaching $P_f = 0.6$ can be observed, indicating that additional effects must play a role for the fusion of the light systems studied in Ref. [22].

In summary, first measurements with the proton drip line nucleus ^{17}F show that in fusion-fission reactions on ^{208}Pb at energies around the Coulomb barrier no enhancement of the fusion cross section is observed. For proton drip line nuclei breakup processes should lead to a lowering of the Coulomb barrier and, thus, to an increase of the fusion probability. Dynamical calculations show, however, that this probability is small for $^{17}F + ^{208}Pb$, in agreement with the data. On the neutron-rich side of the mass valley a comparison of the fusion cross sections induced by ^{32}S and ^{38}S on ^{181}Ta also does not show any increase in the fusion yields [24]. The neutron numbers for these S isotopes, however, are still quite far away from the neutron drip line.

On the neutron-deficient side a more substantial increase of the fusion cross section might be observable for systems where the ground state has a weakly bound proton at low angular momentum, such as ^8B, ^{26}P, or ^{27}S [11].

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