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Study of Nuclear Reactions with Radioactive ^{17}F at HRIBF

J. F. Liang[1,a]

[1] Physics Division, Oak Ridge National Laboratory,
Oak Ridge, TN 37830, U.S.A.

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Abstract. Radioactive ^{17}F beams were produced at the Holifield Radioactive Ion Beam Facility (HRIBF) using the Isotope Separator On-Line (ISOL) technique. Two of the experiments using accelerated ^{17}F beams to study reaction mechanisms are presented: the simultaneous emission of two protons from a resonance in ^{18}Ne and the breakup of ^{17}F by ^{208}Pb.

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1. Introduction

Experimental research using radioactive beams is a topic of current interest in low energy nuclear physics[1]. There are several laboratories around the world actively engaging in research using radioactive beams while many others will be operational in the near future[2]. The Holifield Radioactive Ion Beam Facility (HRIBF)[3] at the Oak Ridge National Laboratory provides a variety of unstable proton rich and neutron rich beams for studying properties of nuclei far from stability, dynamics of reactions induced by nuclei with large neutron or proton excess, and nuclear reaction rates in astrophysical environments. One of the unique capabilities of the HRIBF is the ability to accelerate beams to energies above the Coulomb barrier. This has broadened the area of research and enables researchers to make important discoveries.

In this report, results of two experiments using beams of ^{17}F will be presented. A description of the production of ^{17}F is given in Sect. 2. Sect. 3 describes the simultaneous emission of two protons from ^{18}Ne populated by the ^{17}F+^{1}H reaction. The breakup of ^{17}F by incidence on a ^{208}Pb target is described in Sect. 4 and followed by the conclusions in Sect. 5.

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2. Production of ^{17}F

The HRIBF employs the Isotope Separator On-Line (ISOL) technique to produce radioactive ion beams. The Oak Ridge Isochronous Cyclotron (K=105) is used as the driver accelerator by which light ion beams are accelerated to bombard a solid target. The ^{17}F was produced by the ^{16}O(d,n) reaction where a 42 MeV deuteron beam was incident on a highly refractory fibrous hafnium oxide target[4]. Heat was applied to the target to reduce the diffusion time and allow for a fast release of the reaction products which were ionized in the kinetic ejection negative ion source (KENIS) [5]and mass analyzed by a magnetic separator on the 160 kV platform. After leaving the high voltage platform, the low energy ions went through the high resolution (m/Am = 20,000) sector field isobar separator to clean up isobar contaminants. The beam was subsequently accelerated by the 25 MV tandem accelerator. Due to the intrinsic large emittance of the KENIS, not all the ^{17}O contamination was removed by the isobar separator. A poststripper foil was inserted at the exit of the tandem and a 9^+ ion beam was selected by the analyzing magnet. Thus, only the fully stripped $^{17}F^{9+}$ ion beam was delivered to the experiment. The intensity of pure ^{17}F used in the two-proton decay experiment was 1.2×10^5 ions/s. The breakup experiments were performed at higher energies where the charge state fraction for the 9^+ ion was larger. Therefore, the beam intensity was higher, 7x 10^5 ions/s. Recently, an intensity of 10^7 ions/s of pure ^{17}F was achieved for the new ^{17}F breakup measurement performed at 120 MeV.

3. Two-Proton Decay

Simultaneous emission of two protons from a nucleus was predicted four decades ago[6]. Much effort has been devoted to the search for such an exotic decay mode. The two protons can be emitted as a ^{2}He nucleus (correlated) then separate[6] or emitted in a direct three-body process (uncorrelated) [7]. However, all the data are consistent with sequential one-proton emission through an intermediate state[8].

As shown in Fig. 1, states in ^{18}Ne at energies between 4.5 and 6.5 MeV can decay by two-proton emission and the sequential one-proton emission is energetically forbidden. We have performed experiments to populate the excited states of ^{18}Ne by the $^{17}F+^{1}H$ reaction in inverse kinematics at two beam energies, 33 and 44 MeV, using a thick $(CH_2)_n$ target. The beam was degraded as it went through the target and eventually stopped in the target. Nevertheless, the target was thin enough for the recoiling protons to escape. Using this technique, an excitation function can be obtained with one bombarding energy. A detailed description of this thick target technique can be found in Ref. [9, 10]. The scattered protons were detected by a 300 μm double sided Si strip detector (DSSD) and backed by a 100 μm Si surface barrier detector (SBD) placed at 0°. The DSSD has an area of 5x5 cm^2 subtending $\pm 15°$. There are 16 horizontal and 16 vertical strips on the DSSD yielding an angular resolution of 1.9". The area of the SBD is 900 mm^2 and the angular range is $\pm 10°$. A beam tagging detector[ll], consisting of a carbon foil and a microchannel plate detector measuring scattered secondary electrons, was used to veto positron events that originated from ^{17}F decay.

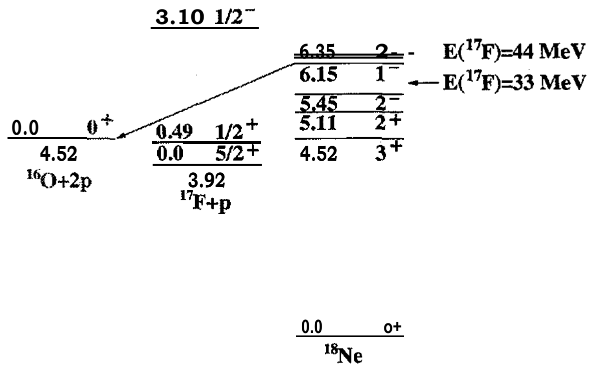

Fig. 1. Level scheme of ^{18}Ne and its one-proton and two-proton decay daughters.

Fig. 2 displays the excitation function constructed from single proton events. The astrophysically important 3^+ state at E_{cm} = 0.6 MeV was observed in a separate measurement using the conventional thin target method[12]. Our results are consistent with those of Ref. [12]. Shown by the solid curve is the R-matrix calculation performed by the code MULTI[13]. It reproduces the data very well.

Candidates of two-proton (2p) decay without contributions from sequential one-proton decay are the states shown in Fig. 2 with E_{cm} = 1.18 MeV (2^+), 2.22 MeV (1^-), and 2.42 MeV (2^-). Because ^{2}He emission from the 2^+ state has a very small phase space available and ^{2}He emission from the 2^- state is forbidden, it leads us to search for 2p events in the 1^- state[14]. The absence of 2p events in the data for E(^{17}F) = 33 MeV also excludes the E_{cm} = 1.18 MeV state as a viable candidate. Shown in Fig. 3 are the angular correlation and the, relative kinetic energy distribution of two coincident protons from the E_{cm} = 2.22 MeV (E_{ex} = 6.15 MeV) 1^- state. The solid curves are the results of Monte Carlo simulations assuming ^{2}He emission and the dashed curves are for direct S-body decay. The mechanism responsible for the 2p emission cannot be distinguished with the present data.

One potential source of background in the 2p data is proton evaporation from the fusion of ^{17}F with ^{12}C in the target. Monte Carlo statistical model calculations were carried out to examine the proton spectra. The calculations show that the summed 2p energy for ^{17}F+^{12}C is higher than that for ^{18}Ne 2p decay and there is no overlap between the two energy distributions. The 5.0 MeV state in ^{17}F, corresponding to 8.9 MeV in ^{18}Ne, has a width of 1.5 MeV[15]. It is conceivable that sequential one-proton decay through the tail of this state could take place. In this case, the energies for the two protons will be asymmetric since the first will have very small energy. However, this is not observed in the data and it can be

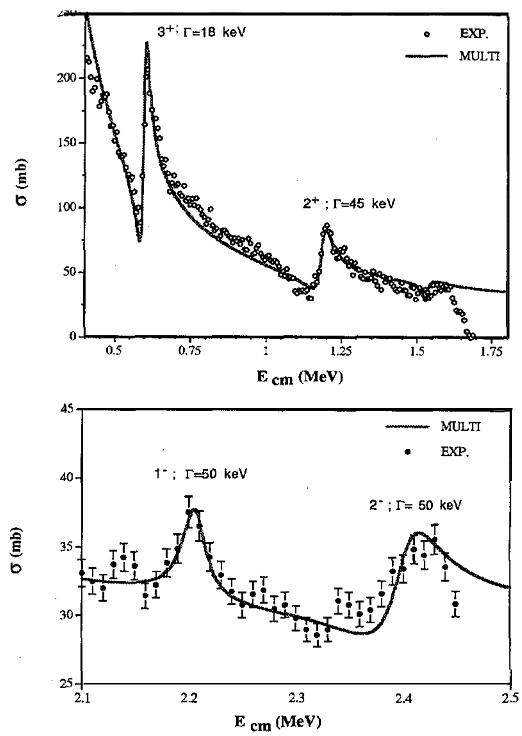

Fig. 2. Experimental excitation function obtained from the recoil proton spectra for the reaction $^{1}H(^{17}F,^{1}H)$ at $E(^{17}F) = 44$ MeV. The solid curve is the R-matrix fit using the code MULTI.

ruled out.

The two processes for simultaneous 2p emission lead to dramatically different energy and angular correlations between the two protons, provided the correlations are studied over a large enough angular range, as shown in Fig. 4. Preparation for a new experiment aiming at identifying the mechanism for 2p emission from the $E_{ex} = 6.15$ MeV state in ^{18}Ne is underway. Detectors with a large angular coverage, ±40°, and fine granularity will be used[16]. A beam tracking detector with position resolution better than 1 mm[ll] will be implemented to obtain good angular resolution, < 0.5”.

4. Breakup of ^{17}F

Breakup is an important reaction channel in the scattering of weakly bound nuclei and can be a rich source of information on reaction mechanisms[17] and the structure

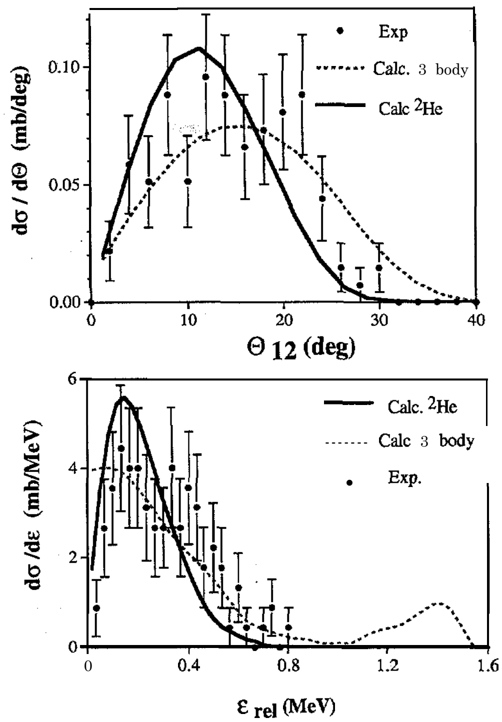

Fig. 3. Top panel: Experimental angular correlation compared to a Monte Carlo simulation assuming a ^{2}He emission (solid curve) and a direct 3-body decay (dotted curve). Bottom panel: Relative kinetic energy distribution.

of such nuclei[18]. How breakup influences fusion near the Coulomb barrier is still an open question[19]. Large subbarrier fusion enhancements were found in the fusion of the neutron skin nucleus, ^{6}He, with ^{209}Bi[20] whereas a large breakup cross section of ^{6}He in the same reaction were observed[21]. In contrast, the fusion of ^{17}F, a proton drip line nucleus, with ^{208}Pb was not enhanced[22]. We have measured the breakup of $^{17}F \rightarrow {}^{16}O+p$ by ^{208}Pb at 170 and 120 MeV to study the reaction mechanism.

The measurements were carried out with a ΔE-E telescope consisting of a DSSD and a 5x5 cm^2 large area Si detector (LASD). The construction of the DSSD is the same as the one used in the 2p decay experiment. The angular distribution of ^{16}O was obtained by placing the 30 μm LASD in front of the 300 μm DSSD to identify the nuclear charge (Z) of reaction products. At E_{lab} = 170 MeV, a separate measurement was performed by detecting the ^{16}O and proton in coincidence[23]. This was achieved by placing the DSSD in front of the 100μm SBD. The coincidence

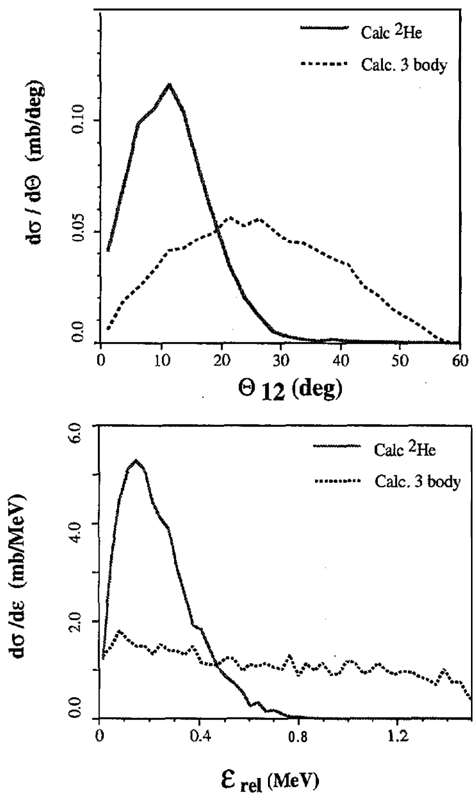

Fig. 4. Top panel: Monte Carlo simulation of angular correlation assuming a ^{2}He emission (solid curve) and a direct 3-body decay (dotted curve). Bottom panel: Monte Carlo simulation of relative kinetic energy distribution.

was established by associating protons in the SBD with the ^{16}O stopped in the DSSD within the same event gate. Two silicon surface barrier detectors located at 10" on either side of the beam were used for monitoring the beam position and for cross section normalization.

For the inclusive measurements, products from two breakup processes, diffraction and stripping, can contribute to the data[24]. In diffraction dissociation, the projectile breaks up, leaving the valence nucleon in the continuum and the core intact. Stripping occurs when the valence nucleon or the core is absorbed by the target. Fig. 5a displays the angular distribution of ^{16}O measured at E_{lab} = 170 MeV. The predicted stripping, diffraction and the sum of the two breakup angular distributions are shown by the dashed, dotted and solid curves, respectively. The measurement was performed at backward angles and a large stripping contribution was observed. The agreement between the data and predictions is fairly good.

The diffraction breakup was measured in the coincidence experiment. The result is shown in Fig. 5b along with predictions from a semiclassical calculation (dashed curve) and a coupled discretized-continuum channels (CDCC) calculation (dotted curve). Both calculations agree with the data fairly well. The solid curve is for the semiclassical calculation without considering target-core absorption.

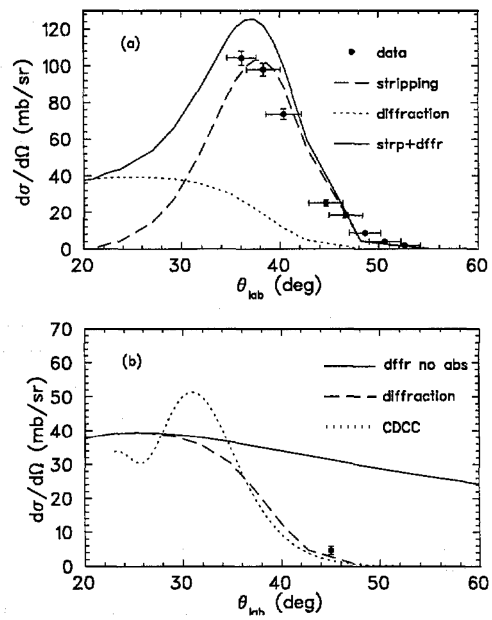

Fig. 5. a: Angular distribution of ^{16}O produced in ^{17}F breakup at 170 MeV. The dashed and dotted curves are for contributions of stripping and diffraction breakup, respectively. The solid curve represents the sum of stripping and diffraction breakup. b: Data and predictions of diffraction breakup. The solid curve is for the semiclassical calculation without considering target-core absorption and the dashed curve includes core absorption. The CDCC calculation is shown by the dash-dotted curve.

The preliminary results of the ^{16}O angular distribution measured at E_{lab} = 120 MeV are shown in Fig. 6. The shape of the angular distribution is similar to that of the 170 MeV measurement. The peak at θ_{lab} = 58" is predominantly due to the contribution from stripping breakup. Although the ^{16}O and proton coincidence was not measured at E_{lab} = 120 MeV, the forward angle data may have significant contributions from the diffraction process.

Further analysis of the experimental data and theoretical calculations are in progress. The eikonal approximation used for calculations at 170 MeV may not be valid at 120 MeV. Recoil effects and excitation of the final nuclei were ignored

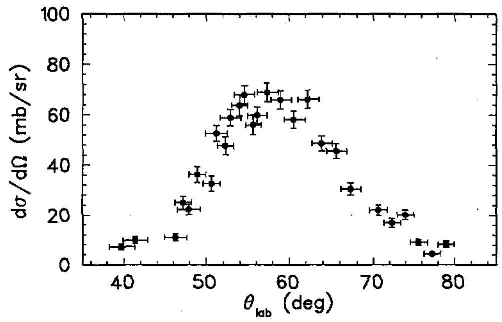

Fig. 6. Preliminary data of ^{16}O angular distribution produced in ^{17}F breakup at 120 MeV.

in the 170 MeV calculations. Taking those effects into account may improve the agreement between the data and calculations. It is very desirable to be able to reproduce the 120 MeV data by calculation. This can give more reliable predictions of breakup reactions and will help in planning experiments at the Coulomb barrier.

5. Conclusions

The HRIBF has diverse research programs using radioactive beams. Simultaneous two-proton emission was discovered in the 6.15 MeV (1^-) state of ^{18}Ne populated in the ^{17}F+p reaction. The present experiment is not able to distinguish between ^{2}He emission and direct 3-body decay. Future experiments will utilize detectors of larger solid angle and finer angular resolution to identify the mechanism. Breakup of ^{17}F by ^{208}Pb was measured at 170 and 120 MeV. A large stripping breakup yield was observed in the angular distribution of ^{16}O. Theoretical calculations reproduce fairly well the 170 MeV measurement. Further analysis of the 120 MeV data is in progress.

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Notes

a. E-mail: liang@mail.phy.ornl.gov

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