Above-barrier narrow resonances in ^{15}F

I. Physics Motivations

Recently, a narrow resonance was observed in the unbound nucleus ^{15}F located two neutrons beyond the proton drip line [deGrancey]. It was shown that the second excited state, a 1/2- resonance, is very narrow, with a width of Γ=36(19) keV, despite the fact that it is located above the Coulomb plus centrifugal barriers at E_R = 4.757(16) keV, see Figure 1. It was shown that this property is due to the peculiar structure of the state. This state is mainly described as a ^{13}N core and 2 quasi-bound protons in the 2s1/2 shell. The two proton emission is mostly hindered by the very low Q_{2p} = 129 keV.

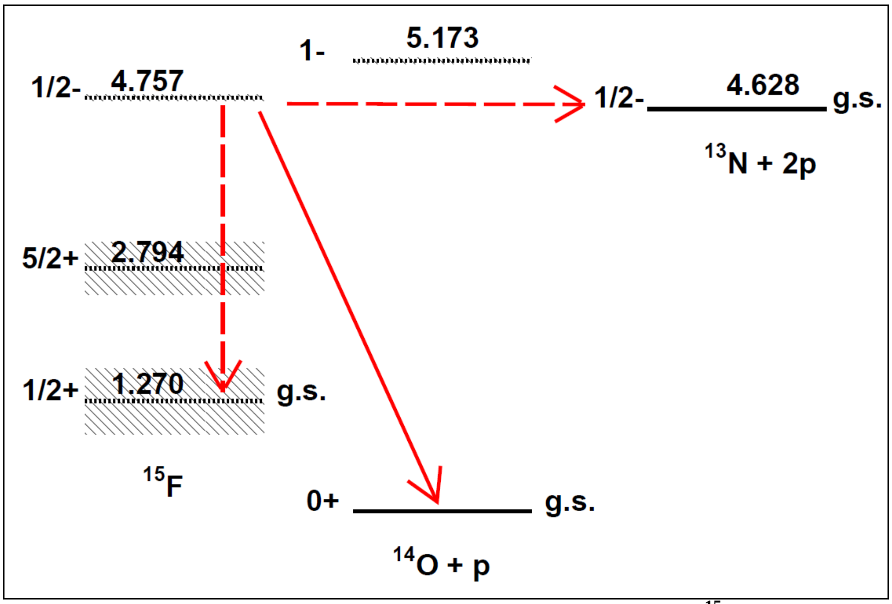

Figure 1 Level scheme showing the newly observed state in ^{15}F. Three decay channels are open and might compete: the one proton emission (Γ=36(19) keV), the two protons emission, and the gamma emission to the ground state of the unbound nucleus ^{15}F.

Theory predicts the existence of another narrow state in ^{15}F. This state is located at E_R~6 MeV with J^π =5/2-, see Table 1 for predictions.

J^π	E_R (keV)	Ex in ^{15}F (keV)	Γ in ^{15}F (keV)	Ref
1/2-	4757(16) 4630 5490	3487(16) 3360 4220	36(19) 38 5	[deGrancey] Fortune 11 Canton06
5/2-	5920 6880	4650 5610	6 keV 2 keV	Fortune 11 Canton06

Table 1: Measured and predicted properties for the second and third excited state of ^{15}F

This proposal is motivated by two different questions:

1. What is the decay mechanism of the 5/2- state? This state is predicted to decay mostly by two protons since the one proton emission is hindered (width predicted to be less than 6 keV). Different 2p-emission mechanisms are possible. The direct 2p-emission to the ground state of ^{13}N is favored since the structure of the 5/2- state is probably very similar to the one of the ^{15}F(1/2-) state, that is mainly described as a ^{13}N core and 2 protons in the 1d5/2 shell. This fact makes it is an ideal case to observe direct two-proton emission. The sequential emission through the 1- excited state in ^{14}O is also possible, but with a very different kinematics.

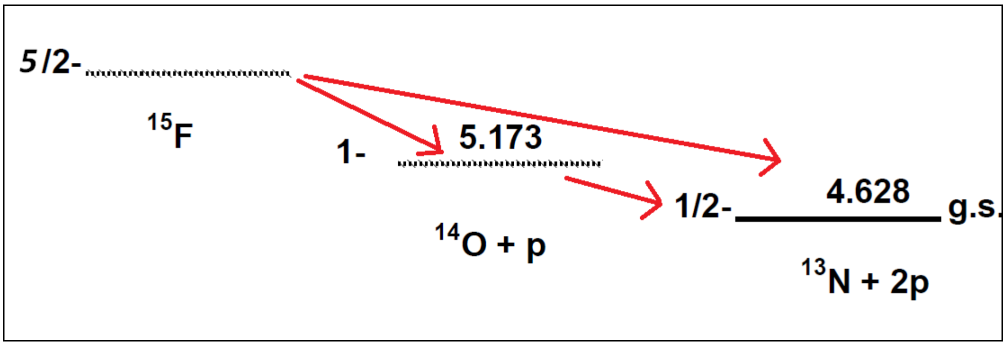

Figure 2. A very narrow state is predicted in 15F at Er~6 MeV with J=5/2-. This state is predicted with a structure of 13N core plus 2 protons.

2. Is it possible to observe a gamma transition within an unbound nucleus? A first case was observed in 8Be [Datar]. Our aim is to observe, for the first time, a gamma transition between the 1/2- excited state and the ground state of ^{15}F. The 1/2- state is an ideal case since this state is narrow and since the 1/2- => 1/2+ gamma transition is a very fast electric dipole transition (E1).

Both ground state and excited state are unbound and have an extended wave function, see Figure 3. Since the gamma decay probability is proportional to the square of:

$$\langle r^L \rangle = \int u_f \, r^L u_i \, dr$$

(L=1), it results in an increased probability for γ emission. We calculated $\langle r \rangle^2$= 27 fm2, a value similar to the one obtained for the halo nucleus ^{11}Be, the fastest known E1 transition, and we predicted a gamma width of Γ_γ = 116 eV and σ(p,γ) ~ 1 mb.

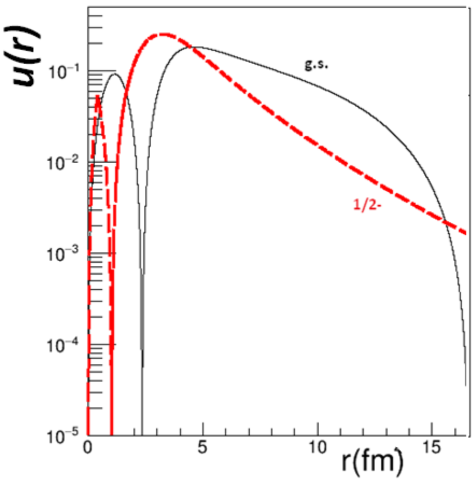

Figure 3 Wave functions of the 1/2- state and the 1/2+ ground state of ^{15}F.

In the future using much more intense ^{14}O beam, we will be able to measure the shape of the ground state "peak" when populated by gamma transitions.

This peak is called the strength function [Stefan1] and its shape is defined by quantum mechanics. The shape of the ground state peak is a subject of debate. The shape of the peak could be a “usual Breit-Wigner” shape, since it is the universal shape due to the fact that the decay fellows an exponential law. It might be a modified shape, mainly because this decay should not follow an exponential law [Rothe]. In particular, it will be extremely interesting to study the gamma transitions populating the low energy tail of the ^{15}F ground state resonance. There, the penetrability for the proton to escape the ^{15}F nucleus is strongly reduced by the Coulomb barrier, making the proton “trapped” inside the Coulomb field [Stefan1]

II. Method

A SPIRAL radioactive beam of ^{14}O accelerated to 7.5MeV/u and two targets will be used.

1. A 100 µm thick polypropylene target will be used to measure the 5/2- state and the 1/2- state simultaneously.

   The 5/2- state. The position, spin, parity, and the width of the state will be determined by measuring the resonant elastic scattering reaction H(^{14}O,p)^{14}O. This kind of measurement was performed with stable and radioactive beams [DeGrancey, Axelsson, Assié, Stefan2]. **Figure 4** shows the excitation function that we measured for the H(^{14}O,p)^{14}O reaction. If this resonance is too narrow to be observed, the two protons emitted from this state will be used to determine the excitation energy of the state.

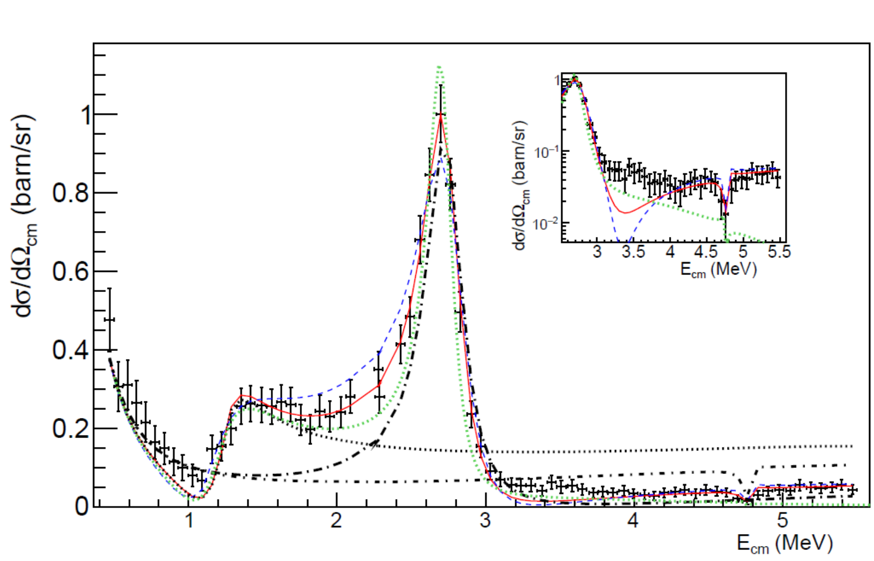

Figure 4 : Measured excitation function of the resonant elastic scattering reaction H(14O,p)14O, [DeGrancey]. The 1/2- narrow state is clearly visible at 4.7 MeV (negative interference peak)

The 1/2- state. Gamma rays emitted from this state $^{14}O(p,\gamma)^{15}F_{gs}(p)^{14}O$ will be measured with 2 LaBr3 detectors, and the emitted proton will be measured in coincidence using MUST2.

2. A 70µm polypropylene target will be used to measure the 5/2- state only. This measurement will also be used to compare the on-resonance (previous target) with the off-resonance (this target) data.

III. Experimental Set-up

The experimental setup called "LISE2017" will be used, see Figure 5. The beam is stopped in a foil of Ta.

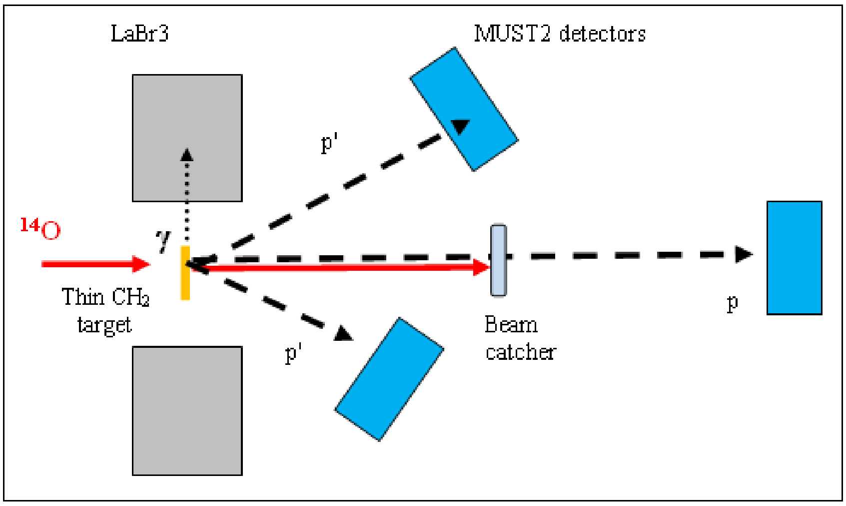

Figure 5 : Experimental setup.

The protons from the elastic scattering reaction $H(^{14}O,p)^{14}O$ are emitted at forward angles and are detected by MUST2 detectors. Protons p' and γ-rays from the reaction $^{14}O(p,\gamma)^{15}F_{gs}(p')^{14}O$, are detected with MUST2 detectors and 2 LaBr3 gamma detectors positioned in a close geometry. We performed simulations of the experiment. The kinematics of the 2 protons emission from the 5/2- state is shown on

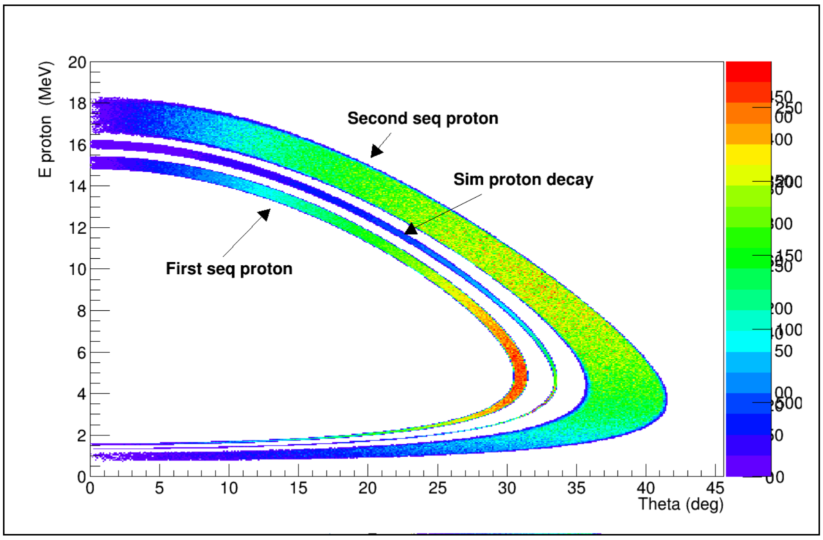

Figure 6 : Simulation of the 2 proton emission from the 5/2- state. The direct two-proton emission (sim proton decay) is separated from the sequential two proton emission (seq).

IV. Beam Time Request

Our beam time request is based on our predicted cross section of $\sigma(p,\gamma)$ ~ 1 mb, which depends on the B(E1) value. Our predicted value B(E1, p 1/2- => 1/2+)= 2.6 e2fm2 is close to the measured B(E1, n 1/2+ => 1/2-)= 0.105 e2fm2 of ^{11}Be corrected for the proton / neutron effective charge difference. Using a beam intensity of 3×10^5 pps (@7.5 AMeV), we predict the (p,γ) reaction rate is 13 h^{-1}. The efficiency to detect the proton p' is 90%, and γ-ray with 2 LaBr3 detectors (2 inches) is 1.6 %, the counting rates will be ~10 protons p' per hour, and ~5 proton-gamma coincidences per day. To answer the first question, i.e. existence of γ-transitions in the unbound nucleus ^{15}F, two days of beam time (6 UT – 480 protons and 10 proton-γ coincidences) are enough to confirm the cross section of the $^{14}O(p,\gamma)^{15}F_{gs}(p')^{14}O$ reaction. To answer the first question, i.e. properties of the 5/2- state, the excitation function of the elastic scattering reaction $H(^{14}O,p)^{14}O$ and the two-proton emission $H(^{14}O,2p)^{13}N$ will be measured with a very good statistics, ~1 count s^{-1} and ~0.1 s^{-1} respectively, in parallel to the first measurement. For the off-resonance measurement we require 4 UT. An additional 4 UT of beam time is required to measure the background induced by a carbon target, + 2 UT for beam purification and alignment with LISE.

In summary, we request a total of **6 + 4 + 4 + 2 UT = 16 UT.**

V. Bibliography

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