Resonance scattering to study exotic nuclei at the limits of stability

V.Z. Goldberg, B.T. Roeder, G.G. Chubarian, A.A. Alharbi, A. Banu, M. McCleskey, E. Simmons, G. Tabacaru, L. Trache, R.E. Tribble, G.V. Rogachev,[1] E.D. Johnson,[1] C. Fu,[2] M.L. Avila,[1] and J.P. Mitchell[1]
[1]*Department of Physics, Florida State University, Tallahassee, Florida*
[2]*Indiana University, Bloomington, Indiana*

1. Introduction

Examining nuclear matter under extreme conditions makes the most demanding test of our understanding of nuclear structure. A perfect opportunity is provided by the study of exotic nuclei which are far from the valley of stability. This is because the addition of a single nucleon can change the properties of a light nucleus, and because theoretical calculations, such as *ab-initio* calculations, can only be made for light nuclei at present. ^{14}F and ^{9}He, two exotic nuclei beyond the limits of stability, provide good systems to test the parameters of the nucleon-nucleon (NN) interactions used in these theoretical calculations. In the present work we consider application of the resonance scattering induced by rare isotope beams to obtain experimental data on both borders of nuclear stability.

2. ^{14}F

Fig. 1 illustrates the typical experimental setup for the Thick Target Inverse Kinematics (TTIK) method [1]. In this method, a beam of heavy ions is stopped in the target material and the light recoil

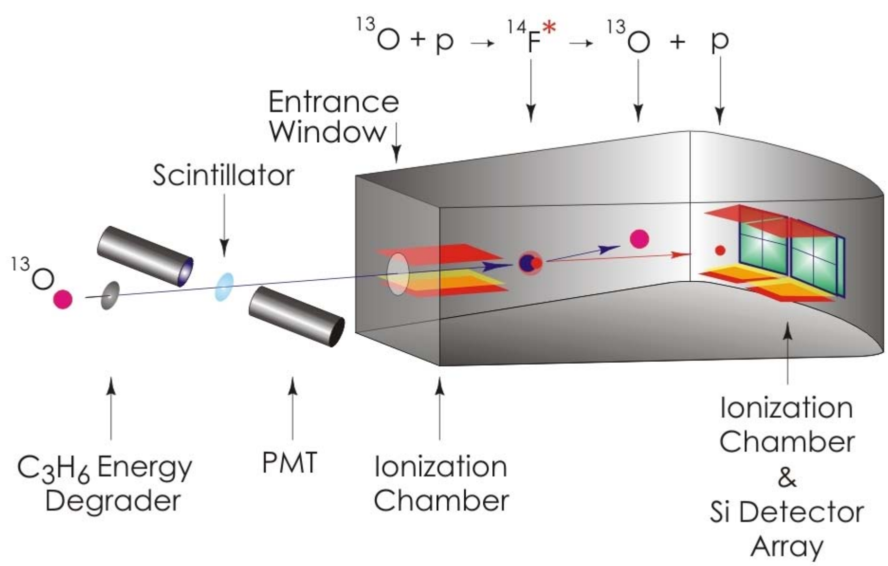

FIG. 1. The setup for the ^{14}F experiment. The "gray box" is the scattering chamber. See explanation in the text and Ref. [5].

product of the elastic scattering reactions (protons in our case) comes out of the target due to much smaller specific energy loss and is detected.

At the Texas A&M University Cyclotron Institute, a 31 MeV/u ^{13}O beam was produced after MARS separation [2] for the ^{14}F experiment. The beam was then slowed down, close to the entrance to the scattering chamber, to minimize the loss of intensity. Stacks of 100 μm polypropylene (C_3H_6) foils (total thickness 1.5 mm) were used to degrade the energy of the beam of ^{13}O from 31 MeV/u to ≈ 11 MeV/u. A scintillating foil was placed before the entrance to the scattering chamber. The light signal from the particles passing through the foil was detected by a pair of photomultiplier tubes (PMTs). The signals from the PMTs were used to monitor the beam, to obtain a "start" signal for time-of-flight (TOF) measurements, and to identify the main beam contaminant, ^{10}C. Our experimental setup was similar to that used in [3,4]. The scattering chamber was filled with methane gas (CH_4) which was used as a safe substitute for hydrogen. The CH_4 was separated from the high vacuum of MARS by a 3 μm Havar foil. However, a few modifications made the target system more "active" than before. A windowless ionization chamber (ICE) was placed in the scattering chamber close to the entrance window (see Fig. 1) to measure the specific energy loss of incoming ions and discriminate protons related with the interaction of the beam with the degrader, which resulted in the destruction of ^{13}O. A pair of quadrant-silicon detector telescopes (QSDs) (the same as in [4]) was also mounted inside smaller windowless ionization chambers 515 mm from the entrance window. Each QSD consisted of four square detectors (12.5 × 12.5 ×1 mm^3) and was followed by a similar veto detector to eliminate high-energy particles that passed through the first QSD. The role of the small ionization chambers was to allow *ΔE–E* analysis for the light ions that are not stopped in the gas and can reach the Si detectors. Further details about the experiment setup and data analysis are given in Ref. [5].

Fig. 2 presents the excitation functions for ^{13}O +p elastic scattering. A code of the complete R-matrix analysis was used [6]. The results of the analysis are summarized in Table I. As seen in Table I, ^{14}F is unstable by 1.56 MeV relative to proton decay, which corresponds to an atomic mass excess of 31 960 ± 50 keV for ^{14}F using the mass tables in [7]. According to the recent *ab-initio* calculations [8], it is expected be unstable by ~3 MeV. While new calculations are needed to specify the necessary corrections

Table I. Levels in ^{14}F.

E_R (MeV)[a]	E_{ex} (MeV)[b]	J^π	Γ	Γ/Γ_{sp}
1.56±0.04	0.00	2-	910±100	0.85
2.1±0.17	0.54	1-	~1000	0.6
3.05±0.06	1.49	3-	210±40	0.55
4.35±0.10	2.79	4-	550±100	0.5

[a] Energy above ^{13}O+p threshold.
[b] Excitation Energy in ^{14}F.

to the theoretical approaches, part of the disagreement between the predictions and the present result should be related with the Thomas–Ehrman shift of levels in mirror nuclei. This shift down toward greater stability in proton rich nuclei is the largest (and therefore famous) for *s*-states. The shift is strongly dependent upon the single particle structure of the state. As reported in Table I, the ground state in ^{14}F has nearly pure shell model structure, and thus the effect of the Thomas–Ehrman shift on the ^{14}F binding energy should be larger than normal.

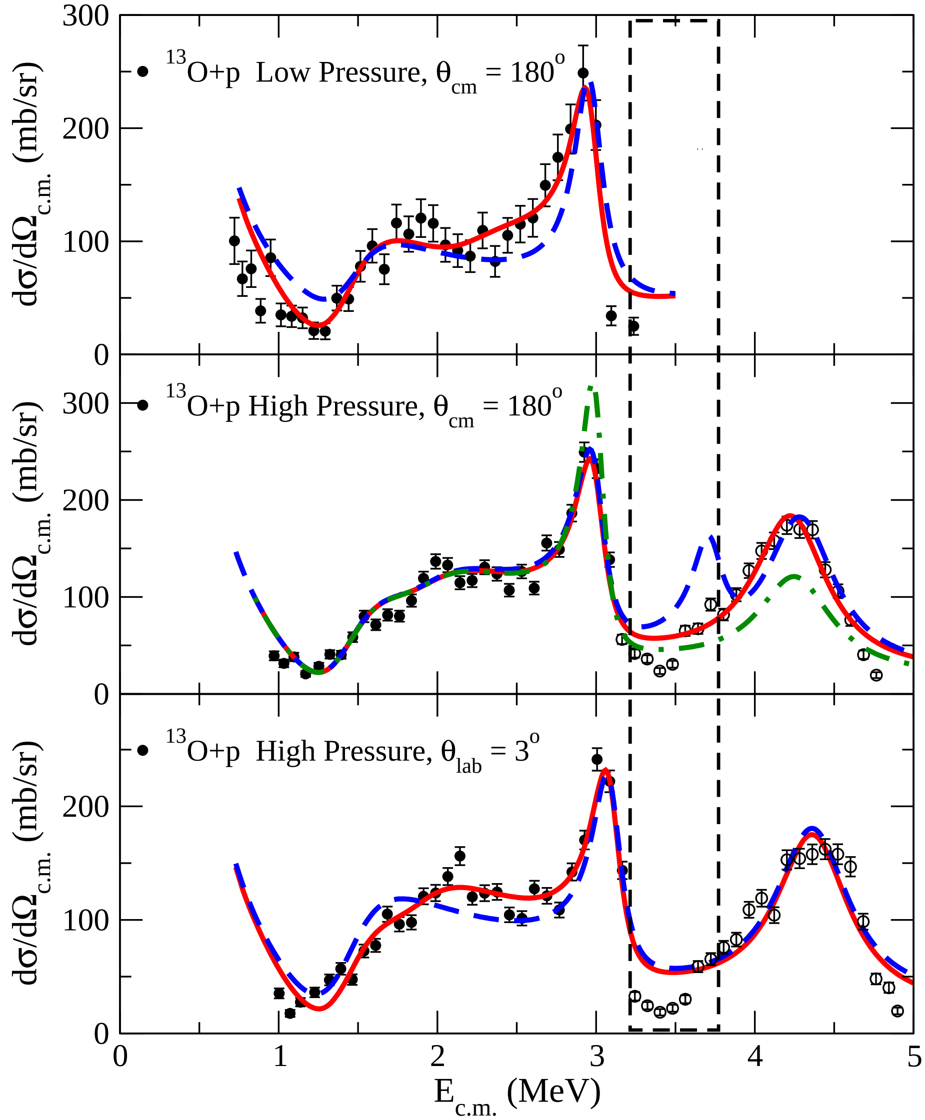

FIG. 2. Excitation functions for ^{13}O+p elastic scattering are given in comparison with R-Matrix calculations. The solid line (red) is the best fit calculation following the ^{14}F level scheme as given in Table 1. The dashed box shows the region where the data are distorted because the QSD detector was not fully depleted. Top Panel. The dashed line (blue) is a fit with 1^- as the ground state (instead of 2^-). Middle Panel. The dashed line (blue) is a calculation with a second hypothetical 2^- state at high energy. The dashed-dot line (green) is a calculation with a 4^- state at 3 MeV (instead of 3^-) and a 3^- state at 4.35 MeV (instead of 4^-). Bottom Panel. The dashed line (blue) is the fit without the 1^- first excited state. See text for further discussion.

It is easy to note looking at Fig. 3 that the shell model calculations produce a much more compressed level scheme than the *ab-initio* calculations. The latter are in better agreement with the experimental data. We suppose that this indicates that the residual interactions should be modified in the shell model for a better description of these exotic nuclei.

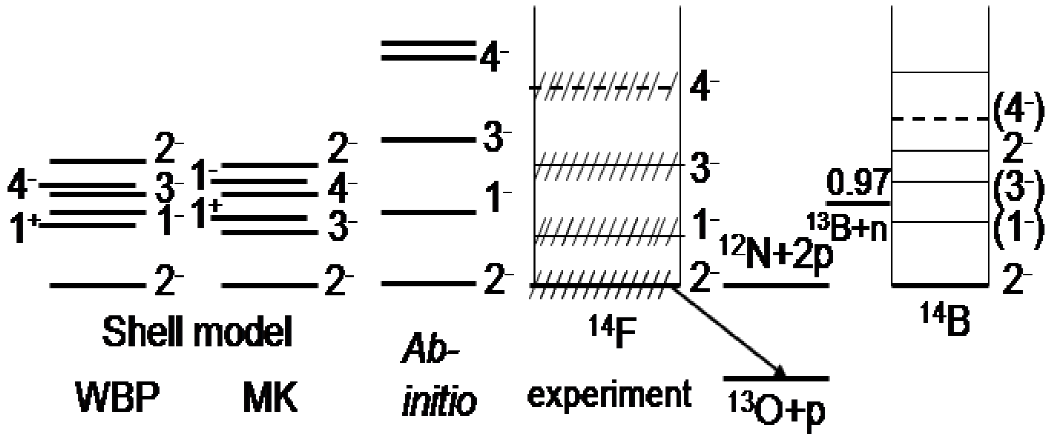

FIG. 3. ^{14}F level scheme from this work compared with shell-model calculations, ab-initio calculations [8] and the ^{14}B level scheme. See Ref. [5] for further explanation about these calculations.

3. A mystery in the structure of ^{9}He

The structure of ^{9}He, with its two protons and seven neutrons, could be expected to be simple: two protons fill the *s*-shell, while six neutrons fill the $p_{3/2}$ sub shell and the extra neutron should be in the $p_{1/2}$ shell. Since the time of its first observation in the ^{9}Be(π^+,π^-) reaction [9], a ($1/2^-$) state, unstable by 1.1 MeV to neutron emission, was considered to be the ground state of ^{9}He. The authors compared the excitation energies of the observed levels with theoretical predictions of Ref. [10] and noted that these predictions, based on calculations for nuclei on the line of stability, “appear to be remarkably good for ^{9}He”[9]. Then several high resolution measurements with heavy ion mass transfer reactions [11, 12] brought more exact data. A state of ^{9}He at 1.27 ± 0.10 MeV above the ^{8}He + n threshold with $\Gamma = 0.10 \pm 0.06$ MeV was found. It is remarkable that the width appeared to be more than ten times smaller than what could be expected from “naïve” shell model considerations. The narrow width of the $½^-$ state is direct evidence for its complicated, non shell-model structure, and could be a sign of unusual nuclear structure beyond the neutron dripline.

Then, a surprising result was obtained from neutron-fragment velocity difference measurements in the two-proton knockout reaction ^{9}Be(^{11}Be, ^{8}He + n)X [13]. The MSU group [13] found that the ground-state of ^{9}He was a virtual s-wave state within 0.2 MeV of the ^{8}He + n threshold. Evidently, this result is also in contradiction to the conventional shell structure, and can again be considered as a manifestation of unusual structure near the dripline. Additionally, this result is confusing when one considers the ground state in ^{10}He [14]. New predictions for the ground state of ^{10}He on the basis of new results for ^{9}He gave a much more tightly bound ^{10}He. Finally, the recent availability of a more intense, rare beam of ^{8}He made the long waited ^{2}H(^{8}He,p)^{9}He experiment feasible [15]. The energy resolution and the counting statistics were poor in [15] due to evident experimental difficulties. Still, the authors claimed that their data exclude existence of the narrow $½^-$ resonances which have been previously observed [11, 12]. Simultaneously, Ref. [15] supported finding an *s*-state near the threshold for the ^{9}He decay into ^{8}He+n on the basis of the interference pattern between broad l=0 and l=1 structures, but it was noted that "the energy resolution and the quality of measured angular distributions are not sufficient to draw solid conclusions about the exact properties of the *s*-wave contributions".

Probably the very confusing situation around ^{9,10}He should also be combined with the similar situation for the heavy hydrogen isotope, ^{7}H. The possibility of observing ^{7}H as a sharp resonance was first stimulated by the unusual stability of ^{8}He [16]. The discovery of ^{7}H as a resonance in the ^{12}C(^{8}He,^{13}N)^{7}H reaction was claimed in Ref [17]. However, several more recent attempts to observe ^{7}H in the ^{2}H(^{8}He,^{3}He)^{7}H reaction with an expected higher yield were not successful [18].

Thus, there remain many problems to be resolved in the structure of ^{9}He, and all evident nuclear reactions involving direct measurement of ^{9}He have been tried. However, resonance reactions again can be useful, but this time the study should be related with population of the ^{9}He analog states in ^{9}Li.

In the ^{8}He+p resonance elastic scattering, excitations of ^{9}Li levels (see Fig.4) with T=3/2 or T=5/2 are allowed in accordance with isobaric spin conservation. Strong resonance population of (unknown) T=3/2 resonances at high excitation energy in ^{9}Li is not expected due to the small ratio of the proton width of the initial channel to the total width of the hypothetical T=3/2 resonances. However, only two decay channels are allowed by T conservation for the lowest states with T=5/2. These are the initial channel ^{8}He+p, and its isobaric conjugate, ^{8}Li(T=2)+n (Fig.4). The analog of the "sharp" ½$^{-}$ state in ^{9}He with T=5/2 [11,12] should be present at an excitation energy of 16.1 MeV in ^{9}Li [19]. As can be seen in Fig. 4, more than 2 MeV of energy interval below the ½$^{-}$ (T=5/2) state in ^{9}Li are open for the investigation

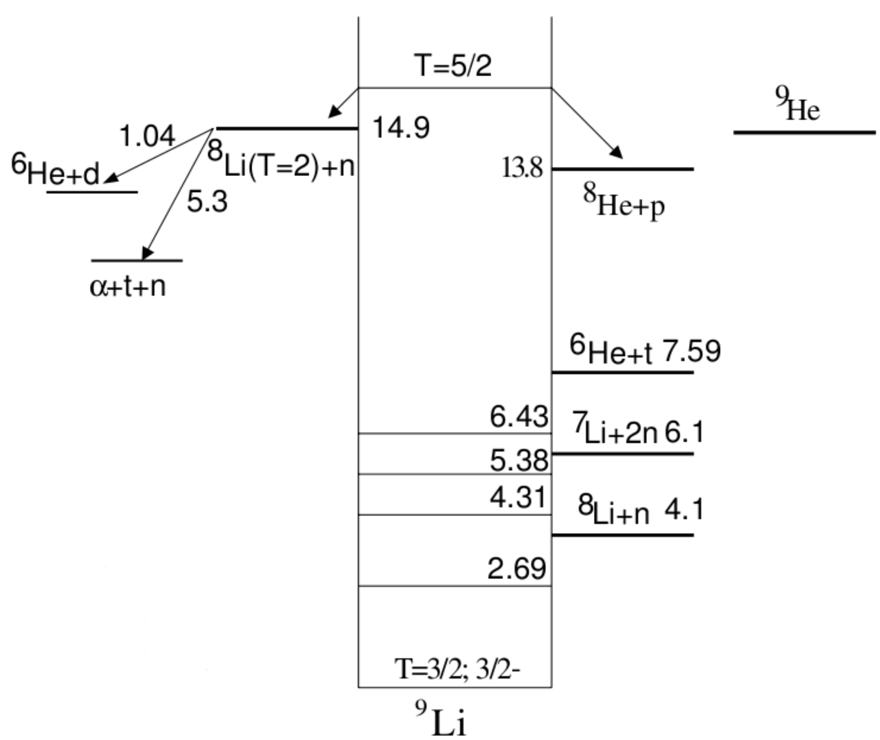

FIG. 4. Level scheme of ^{9}Li showing various possible decay channels for excited states.

in ^8He+p resonance scattering as a result of the Coulomb interaction and the *p-n* mass difference. Also the Coulomb interaction turns the virtual $½^+$ ground state in ^9He [13] into a quasi- stationary state in ^9Li.

The first (and only) study of the ^8He+p resonance scattering found evidence for rather broad *p* and *d* states with *T*=5/2 at excitation energies above 17 MeV in ^9Li [19]. These findings appeared to be in agreement with the recent investigation of ^9He spectrum [7]. However, the most interesting region corresponding to the controversial lowest states in ^9He could not be investigated in [19]. The on-line beam of ^8He [19] separated at FLNR was of high energy and had a large energy spread. The poor parameters of the beam resulted in poor resolution (~400-500 keV) in the region of the possible $½^-$ sharp state. At present, there are reaccelerated low energy ^8He beams at SPIRAL (France) and TRIUMF (Canada), and it is possible to make TTIK measurements at the ^8He initial energy of ~4 MeV/A and energy spread of <0.5%. Under these conditions, the energy resolution in the excitation region of ~16 MeV in ^9Li will be better than 50 keV, and one should easily observe a resonance peak with 100 keV width. It is well know that the elastic scattering cross sections are highly sensitive to the scattering phase. Therefore the parameters of the *s*-wave scattering near the threshold can be fixed. Fig. 5 illustrates the effect of the 2s virtual state in ^9He on the low energy ^8He+p resonance scattering at 180^0 c.m.s. The strong effect of this state is obvious as a result of interference between the nuclear and the Coulomb scattering. We plan to make this measurement in the near future with a setup very similar to that used for the ^{14}F study.

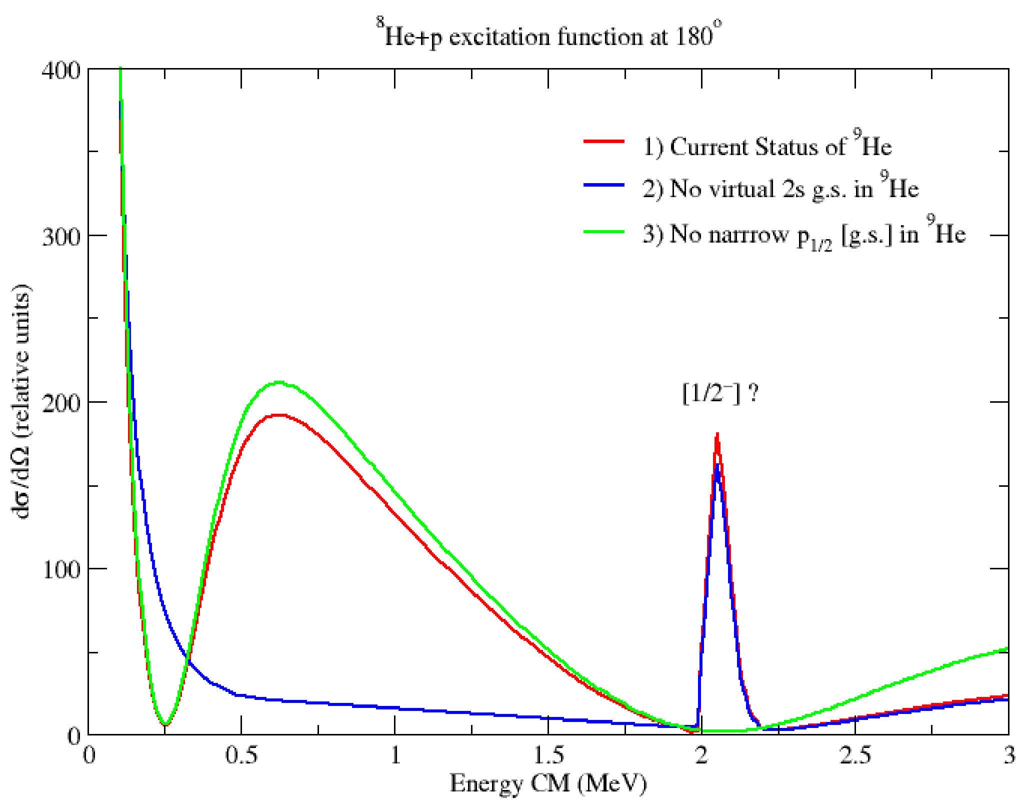

FIG. 5. The effect of a possible 2s resonance (analog of the virtual ground state in ^9He) on the excitation function of the ^8He+p elastic scattering. Also shown is the expectation for a narrow width $p_{1/2}$ first excited state.

4.

Conclusion

In summary, we hope that we have demonstrated using the two examples above the importance of resonance reactions for exciting studies at both borders of nuclear stability.

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