Investigation of the structure of nuclear cluster states at the University of São Paulo, Brazil

B. T. Roeder, M. R. D. Rodrigues,[1] T. Borello-Lewin,[1] L. B. Horodynski-Matsushigue,[1] J. L. M. Duarte,[1] C. L. Rodrigues,[1] H. Miyake,[1] X. X. Zhang,[1] and G. M. Ukita[2]
[1]Instituto de Física, Universidade de São Paulo, São Paulo-SP, Brasil
[2]Faculdade de Psicologia, Universidade de Santo Amaro, São Paulo-SP, Brasil

This year, we have started a collaboration with the Light-Ion Spectroscopy group at the University of São Paulo in Brazil. For many years, the Light-Ion Spectroscopy group has been measuring transfer reactions with the Pelletron-Enge-Split-Pole facility at the University of São Paulo. Recently, this group has become interested in measuring α-particle transfer reactions, such as the (^{6}Li,d) reaction, in order to investigate the cluster structure in highly-excited states of light nuclei [1]. Their experimental setup has several advantages for making these measurements. First, the beam produced by their Tandem Van de Graff Accelerator (Pelletron) has high energy resolution and be tuned to an extremely small beam spot size. Second, the Enge Split-Pole spectrograph [2] can select and separate specific reaction products and focus them at the exit of the spectrograph. Finally, the particles are detected with the nuclear emulsion technique which allowed them to obtain an excellent detection resolution of 15 keV in their most recent measurement of the ^{12}C(^{6}Li,d)^{16}O reaction [3].

In the near future, the Light-Ion Spectroscopy group is planning to build a new focal plane detector for the Enge Split-Pole spectrograph in collaboration with the University of Orsay, France and the Laboratori Nazionali del Sud in Catania, Italy that will allow for coincidence measurements and the measurement of heavier ions with the spectrograph. In preparation for this new detector, a simulation of the Enge Split-Pole spectrograph has been developed with the GEANT4 toolkit [4]. A diagram of the Enge Split-Pole spectrograph and a figure showing the GEANT4 simulation are shown in Fig. 1. The

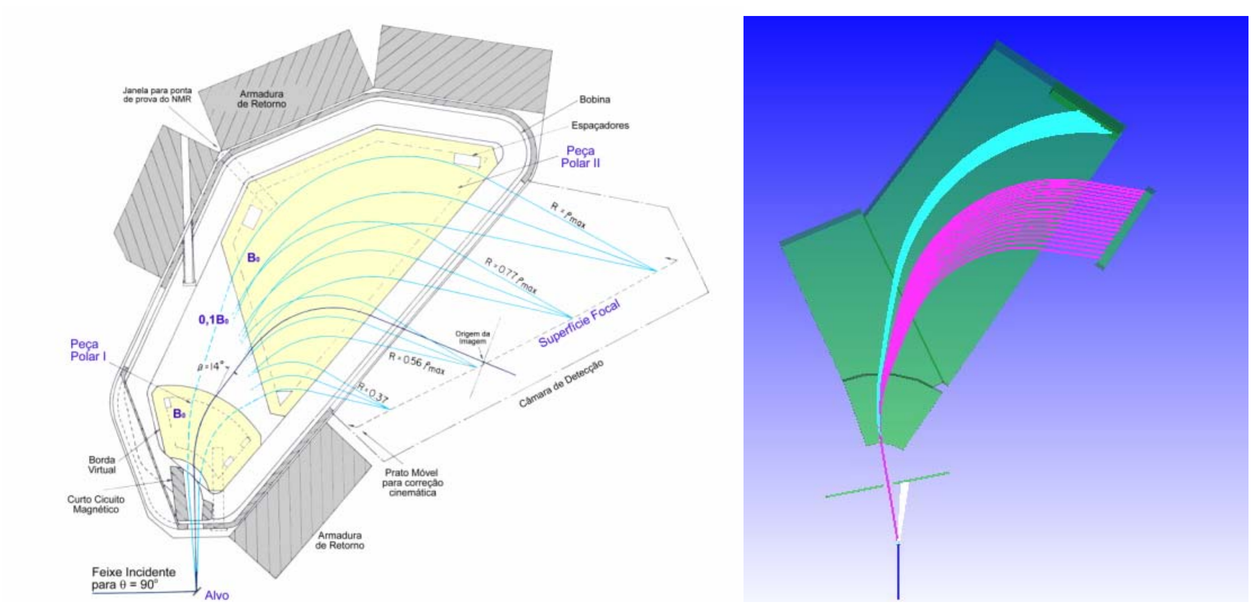

FIG. 1. (Left) Schematic representation of the Enge split-pole magnetic spectrograph with lines showing the paths of particles with different magnetic rigidities. (Right) GEANT4 simulation of the Enge split-pole magnetic spectrograph showing the separation between protons (magenta tracks) and deuterons (light-blue tracks) from different reactions.

reactions $^{12}C(^{6}Li,d)^{16}O$ and $^{12}C(^{6}Li,p)^{17}O$ are simulated with the magnetic field of the spectrograph set for the protons. In the simulation, the particles from the two reactions are well-separated.

In order to test the capabilities of the Enge Split-Pole spectrograph, as well as to obtain new data for ^{17}O at high excitation energies, we have proposed an experiment to measure the $^{12}C(^{6}Li,p)^{17}O$ reaction with a ^{6}Li beam energy of 28.4 MeV. This reaction, along with the similar reaction $^{12}C(^{7}Li,d)^{17}O$, was measured previously by Crisp *et al.* [5]. While differential cross sections were obtained in that work for levels in ^{17}O up to 12.5 MeV excitation, in the spectrum from the detector (see Fig. 2) they show that they were able to populate states up to 13.5 MeV excitation and beyond. More recently, Milin et al. [6] measured the $^{13}C + {}^{9}Be \rightarrow {}^{13}C+2\alpha+n$ reaction and were able to reconstruct ^{17}O states with $^{13}C+\alpha$ coincidences. While their detection resolution was relatively poor, they were able to populate ^{17}O levels up to 19 MeV excitation. Clearly, a high-resolution measurement of ^{17}O at these high-excitation energies would help to reveal the structure of ^{17}O in this region, and perhaps indicate the presence of new cluster states.

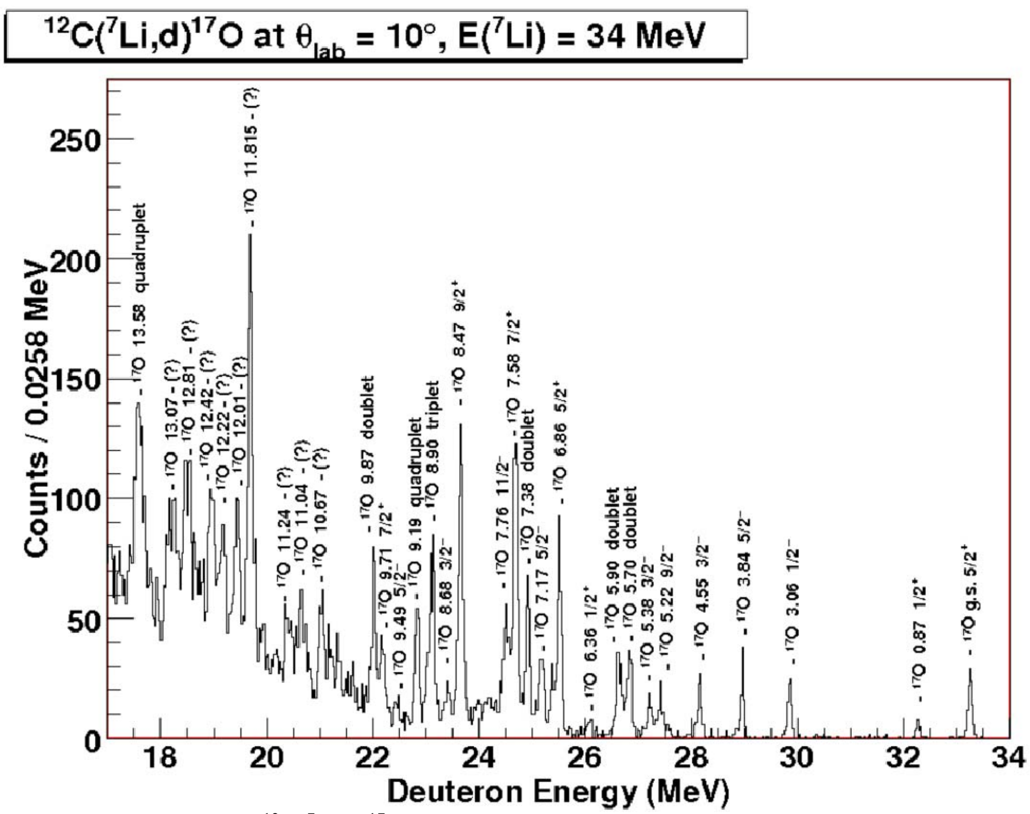

FIG. 2. Spectrum of the $^{12}C(^{7}Li,d)^{17}O$ reaction from Crisp *et al.* [5]. Several strongly-populated states from ^{17}O are shown above 11 MeV excitation.

The $^{12}C(^{6}Li,p)^{17}O$ measurement will be conducted at the Pelletron-Enge-Split-Pole facility at the University of São Paulo this July. The proton tracks, shown in magenta in the simulation of Fig. 1, show that ^{17}O states from 11 MeV to 20 MeV excitation can be measured in the focal plane of the spectrograph with a single magnetic field setting. Assuming that the $^{12}C(^{6}Li,p)^{17}O$ measurement is successful, the

$^{12}C(^{7}Li,d)^{17}O$ might be measured in the future for comparison. However, the $^{12}C(^{7}Li,d)^{17}O$ reaction may require the use of silicon detector telescopes in the focal plane, or perhaps the new focal plane detector, in order to properly identify the deuteron reaction products.

[1] M. Freer, Rep. Prog. Phys. **70**, 2149 (2007).
[2] J.E. Spencer and H.A. Enge, Nucl. Instrum. and Meth. **49** 181 (1967).
[3] M.R.D. Rodrigues *et al.*, Phys. Rev. C **89**, 024306 (2014).
[4] S. Agostinelli *et al.*, Nucl. Instrum. Methods Phys. Res. **A506**, 250 (2003).
[5] A.M. Crisp *et al.*, Phys. Rev. C **77**, 044315 (2008).
[6] M. Milin *et al.*, Eur. Phys. J. A **41**, 335 (2009).