Investigation of the nuclear structure of ^{17}O at high excitation energy with five-particle transfer reactions

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Recently, there has been renewed interest in multi-particle transfer reactions as a way to populate highly-excited states of light nuclei. Studies of multi-particle transfer on various light targets have suggested the possible presence of molecular cluster configurations in light nuclei [1], which were predicted more than 30 years ago by the theoretical work of Ikeda *et al.* [2]. For example, Milin and von Oertzen [3], and von Oertzen *et al*. [4] have made extensive studies of the $^{13\text{-}14}$C isotopes using four- and five-particle transfer reactions on ^{9}Be. Through measurements with several different reactions, they have obtained an almost complete spectroscopy of ^{14}C up to 18 MeV excitation. In their works, they remark that the (^{7}Li,d) reaction in general selectively populated different excitation states than other reactions where fewer particles were transferred. Also, Crisp *et al.* [5] measured the ^{12}C(^{7}Li,d)^{17}O and ^{12}C(^{6}Li,p)^{17}O reactions and suggested that the ^{17}O states between 11.82 MeV-12.42 MeV excitation were populated by direct transfer of five particles. This result indicated that states with five-particle – four-hole (5p-4h) structure were present in ^{17}O, as had been suggested previously by the theoretical work of Brown and Green [6]. Following the work of Crisp *et al.*, next Milin *et al.*[7] measured ^{13}C + ^{9}Be → ^{13}C+2α+n and were able to reconstruct levels in ^{17}O through ^{13}C+α coincidences. Although their reconstruction of ^{17}O excited states has relatively poor resolution, their experiment suggests that the states with an undetected particle of mass A=5 are from 10.8 MeV to 14.9 MeV excitation, and includes a strongly populated level at 13.6 MeV excitation. Further, they show that another group of states exist around ~19 MeV excitation, but the resolution was too poor to isolate any individual states.

We propose to make new, high-resolution measurements of the ^{12}C(^{7}Li,d)^{17}O and ^{12}C(^{6}Li,p)^{17}O reactions in order to confirm the 5p-4h structure of the ^{17}O states above 11 MeV excitation. While the measurement of either reaction could be used to identify the states of interest, the true 5p-4h states should be simultaneously populated in both reactions. Thus, the measurement of the two reactions is needed. In addition, improved resolution would allow the detailed investigation of other states above 12.42 MeV excitation which were observed to be selectively populated by these reactions in the previous work of Crisp *et al.* [5], but were not cleanly separated from nearby levels and continuum background. In particular, high-resolution data for levels between 12.5 MeV to 15.6 MeV excitation in ^{17}O would allow extraction of angular distributions for DWBA analysis and provide insight into the possible 5p-4h structure of these levels.

The data will be collected with the Pelletron-Enge-Split-Pole facility at the University of São Paulo using the nuclear emulsion technique. The use of the spectrograph will dramatically improve the experimental resolution of the ^{12}C(^{6}Li,p)^{17}O and ^{12}C(^{7}Li,d)^{17}O reactions for ^{17}O excitation energies above 11 MeV. As an example of the possibilities of improvement versus previous experiments in this area, consider the previous work of the "Light Ion Spectroscopy" group at the University of São Paulo with this device. M.R.D. Rodrigues *et al*. measured the ^{12}C(^{6}Li,d)^{16}O alpha-particle transfer reaction with a ^{6}Li beam energy of 25.5 MeV. While the low-energy excited states of ^{16}O have been extensively studied [8], the states of ^{16}O above ~11 MeV excitation have proven difficult to populate and to resolve due to

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background and resolution issues. Using the excellent beam properties of the Pelletron accelerator, a thin ^{12}C target, the Enge Split-pole spectrograph, and the nuclear emulsion detection technique, a resolution of approximately 15 keV in energy for the detected deuterons in the focal plane was obtained [9]. Depending on the detection angle in the experiment, this energy resolution is much better than the resolution from previous experiments after other limitations, such as reaction kinematics and energy straggling from the target are taken into account. This excellent resolution led to the measurement of cross sections and angular distributions for ^{16}O excited states up to ~17 MeV. For comparison, the $^{12}C(^{7}Li,d)^{17}O$ reaction in the work of Crisp *et al.* [5] measured states in ^{17}O up to 15.6 MeV excitation with a resolution about 7-times worse than this (~110 keV) using the ΔE-E silicon detector telescope method. The resolution in the Crisp *et al.* experiment was limited in part by the width of the collimator (~0.5° in lab angle), but was also limited because of the thickness of the ΔE detector in the silicon telescope and the electronic noise of the detector setup. The Enge split-pole spectrograph and the nuclear emulsion technique do not have these limitations since the resolution in that case is determined mainly by the position resolution on the emulsion plates, about 0.2 mm, and the target thickness. Further, the selection of the outgoing light-particle from the reaction is chosen with the magnetic field of the spectrograph, so the ΔE-E silicon telescope is unnecessary. Assuming that resolution similar to that obtained for the $^{12}C(^{6}Li,d)^{16}O$ reaction is possible for the proposed measurement of the $^{12}C(^{7}Li,d)^{17}O$ and $^{12}C(^{6}Li,p)^{17}O$ at the Pelletron-Enge-Split-Pole facility, clean separation of the many ^{17}O levels between 11 and 16 MeV excitation should be possible. In addition, a high-resolution investigation of the ^{17}O levels up to 20 MeV excitation will be attempted. According to the level compilation for ^{17}O of Tilley *et al.*[8], most of the previously reported excitation levels in this region should be separated if the resolution is around ~30 keV or better, not taking into account the continuum background. Very little information about the levels above 12.5 MeV excitation is currently known, other than their energies.

The experimental angular distributions of the levels measured will be analyzed using with DWBA calculations using the code FRESCO [11]. Overall, the method of calculation will be similar to that used in the previous work [5]. However, the expected high-resolution of the data for this experiment will allow the separation of levels that were previously analyzed as doublet or triplet levels. Perhaps this will allow more detailed analyses using coupled reaction channels (CRC) or similar techniques that are also possible with FRESCO.

The $^{12}C(^{7}Li,d)$ and $^{12}C(^{6}Li,p)$ measurements are considered to be complimentary measurements to those currently being performed with the "Nuclear Spectroscopy with Light Ions Group" at the University of São Paulo. In fact, T. Borello-Lewin, M.R.D. Rodrigues *et al.* already have proposed a measurement of $^{13}C(^{6}Li,d)^{17}O$, an α-particle transfer reaction, and this measurement has already been approved [12]. The results of their work, in addition to those obtained in this work, will provide a complete spectroscopy of the ^{17}O nucleus up to 20 MeV excitation. The $^{12}C(^{7}Li,d)$ and $^{12}C(^{6}Li,p)$ measurements will be conducted in collaboration with their research group.

The Comitê Avaliador de Projetos (CAP) of 18 October 2013 gave ten days to complete this experiment.

Status of Experiment E-118

A preliminary measurement of the $^{12}C(^{6}Li,p)^{17}O$ reaction with ^{6}Li beam energy of 28.5 MeV was conducted with the University of São Paulo Pelletron-Enge-Split-Pole facility in July 2014 during a five day experiment. Even though the ^{6}Li beam intensity was relatively low with an average intensity of less than 10 nA, spectra for ^{17}O were obtained with the nuclear emulsion technique for excitation energies above 11 MeV. A 380 μm thick aluminum degrader was mounted in front of the nuclear emulsion plates

at the Enge Split-Pole focal plane to ensure that heavier particles from other reaction channels were stopped and only protons were recorded. Data were measured at six angles: 6°, 8°, 10°, 13°, 16° and 19°.

While analysis of the measured data is ongoing, it has been observed that the statistics obtained at all six angles were extremely low due to a combination of lower ^{6}Li beam intensity than expected and a thinner ^{12}C target than expected (28 μg/cm^2 at 45°). The first issue, the low beam intensity, has already been addressed by the staff of the USP Pelletron lab. ^{6}Li beam intensities between 100 nA and 300 nA were available on target for an experiment conducted at the Enge Split-Pole facility in November 2014. Also, since the preliminary experiment, Monte-Carlo simulations with GEANT4 [13] have been conducted to determine the optimum ^{12}C target thickness. These simulations determined that a 50 μg/cm^2 thick target at 45° with respect to the beam axis (effective thickness 70.7 μg/cm^2) could be used while still preserving the experimental resolution needed for the identification of the ^{17}O states. Thus, by increasing the beam intensity by a factor ~10 and the target thickness by about a factor of ~2, it is expected that the statistics that could be obtained in a subsequent experiment would increase by a factor of ~20 versus the July 2014 measurement.

The differential cross sections for the ^{17}O levels around 12 MeV were measured to be about 0.1 mb/sr in the previous measurements of Crisp *et al.*[5]. The levels at higher excitation energies are shown to be populated with similar strength to the 12 MeV levels in their spectra, even though the peaks in their spectra may contain several levels together and are on top of continuum background. Nine lab angles between 8°-34° are needed to obtain the forward angle angular distribution where direct transfer should be important for the reaction [5,10]. The ^{7}Li beam energy will be 30 MeV and the ^{6}Li beam energy will be 28.5 MeV such that the two reactions can be measured at approximately the same center-of-mass energy. The ^{7}Li and ^{6}Li beam energies have been chosen so that the Pelletron terminal voltage will be stable during the measurements. Assuming 0.1 mb/sr as a typical differential cross section for a given level, 100 nA of ^{7}Li or ^{6}Li beam, and a ^{12}C target with areal density of 50 μg/cm^2 at 45° (70.7 μg/cm^2) , an estimate of beam time needed for this experiment is given in Table 1. In addition to measurements of the transfer reactions, elastic scattering measurements for ^{6}Li+^{12}C and ^{7}Li+^{12}C should be done with the same target at the same measurement angles in order to obtain the absolute cross sections.

Reaction	Tandem Terminal Potential (MV)	E_{ex} (MeV)	Effective Target Thickness (μg/cm^2)	Solid Angle (msr)	Approx. counts/ peak	Average cross section (mb/sr)	Number of Angles	Time per angle (h)	Total Time (h)
^{12}C(^{7}Li,d)^{17}O	7.5	10-20	70.7	1.24	1000	0.1	9	2	33
^{12}C(^{6}Li,p)^{17}O	7.11	10-20	70.7	1.24	1000	0.1	9	3	42
Elastic ^{6}Li									36
Elastic ^{7}Li									36
Experimental set-up time for each period								36	72
							Total		219

Table 1: Time required per angle assuming a beam intensity of 100 nA. The total time listed includes the time required to change the emulsion plates.

So far, five of the ten days given by the October 2013 CAP have been used for the experiment. However, a ^{6}Li beam intensity of 100 nA was expected for the experiment in the original proposal. Since only 10 nA were available at the time of the measurement, most of the angles for the ^{12}C(^{6}Li,p)^{17}O reaction will need to be remeasured in the future experiment to obtain the needed statistics for identification of the ^{17}O states and the angular distributions. In addition, data for the ^{12}C(^{7}Li,d)^{17}O reaction and elastic scattering measurements for ^{6}Li+^{12}C and ^{7}Li+^{12}C have not been measured yet.

To complete these measurements, we are requesting about 4 days to measure $^{12}C(^{7}Li,d)^{17}O$ and about 5 days to complete the $^{12}C(^{6}Li,p)^{17}O$ measurement. The time requested includes the set-up time and the time required to change the nuclear emulsion plates ~3 times (~ 5 hours / plate change) for each reaction measurement. While the predicted cross sections are similar for the two reactions, the reaction kinematics of the $^{12}C(^{6}Li,p)$ reaction account for the extra time to collect the needed statistics.

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Previous Information on Project

Proposal approved	N **E118**
Period of beam time (date)	July 2014 – 5 days

Results or problems:

The last proposal approved considered the measurement for $^{12}C(^{6}Li,p)^{17}O$ and $^{12}C(^{7}Li,d)^{17}O$ to search for five-particle, four-hole (5p-4h) states in ^{17}O at high excitation energy. Preliminary data with low statistics were collected and analysis of these data is ongoing. Due to a long strike in the university, problems with the ions source in 2014 resulting in low ^{6}Li beam intensity, and problems with the vacuum system of the spectrograph in 2015, the measurement of $^{12}C(^{6}Li,p)^{17}O$ was not able to be completed and the measurement of $^{12}C(^{7}Li,d)^{17}O$ was not yet performed.

Since the July 2014 measurement, a new turbo pump was installed on the Enge Split-Pole spectrograph. There remains a vacuum leak in a dynamic bellows on the spectrograph. Repair of this vacuum leak is in progress.

The problem with low beam intensity for 6Li and 7Li has been addressed and more than 100 nA of beam intensity is expected for the requested measurements.

LABORATÓRIO ABERTO DE FÍSICA NUCLEAR

PAC 2016

Proposal	N° E-118
Title: Investigation of the nuclear structure of ^{17}O at high excitation energy with five-particle transfer reactions	
Responsable: Brian Thomas Roeder	e-mail: broeder@comp.tamu.edu
Participants: M.R.D. Rodrigues, T. Borello-Lewin, L.B. Horodynski-Matsushigue, J. L. M. Duarte, C.L. Rodrigues, M.A. Souza, H. Miyake, G.M. Ukita *Instituto de Física, Universidade de São Paulo, São Paulo-SP, Brasil*	
Spokeperson: Brian Thomas Roeder	e-mail: broeder@comp.tamu.edu
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Number of days for experiment: 9	
Period planned for the experiment (are the setup ready for beam time?): July 2016 if vacuum leak in spectrometer is fixed.	

Technical information

Ion source			Accelerator			Experimental Area	
Beam	Cathode	$I_{mínima}$	V_{min}	V_{max}	Bunched beam?	Beam line	Target
^{6}Li		100 nA	7.12	7.13	No	Enge	12C-50μg/cm^2
^{7}Li		100 nA	7.5	7.5	No	Enge	12C-50μg/cm^2

Other relevant/needed information: Experiment requires at least 100 nA of 6Li and 7Li beam on target in order to measure the relatively small reaction cross sections within the requested time.