Study of $^{11}$N by Elastic Resonance Scattering in Inverse Kinematics

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In some nuclei along the drip-line, for example the exotic nuclei $^{11}$Be, an energy level inversion between the $2s_{1/2}$ and $1p_{1/2}$ states occurs. Interest in the mirror state of $^{11}$Be on the proton rich side, $^{11}$N, resulted in a continuation of an earlier study searching for resonances in this nucleus. The experiment involved the resonance scattering reaction $^{10}$C + $p$ in inverse kinematics performed at the NSCL at MSU. Preliminary analysis of the data shows evidence for three energy states above the $^{10}$C + $p$ threshold with energies 1.3, 2.1, and 3.1 MeV. Using a potential-model analysis, these states can be interpreted as the ground and first two excited states of the $^{11}$N system.

Introduction

Since knowledge of the structural and physical properties of matter is derived from the studies of atomic, nuclear, and particle physics, a great scientific interest in studying and understanding atomic nuclei results. Through experimentation and analysis, the nature of interactions between the nuclear particles of protons and neutrons, can be explored resulting in a proton-neutron model of the nucleus based on the laws of nuclear physics.\(^1\) According to Marmier and Sheldon though, the main contribution of nuclear physics to other sciences is the diverse applications of its techniques and influence of its scientific methods.\(^2\) The following study of the $^{11}$N nuclear resonances results in both gaining information on nuclear particle interaction and developing a new technique which can be used to explore other nuclear systems.

Previous studies have made information available on the exotic nuclides $^{11}$Be and $^{11}$Li, their interest focused on the neutron halo structural characteristic. Also observed in the bound $^{11}$Be is an energy level inversion between the $2s_{1/2}$ and $1p_{1/2}$ states. Since mirror nuclei, nuclei with reversed numbers of protons and neutrons, exhibit similar
characteristics, a study by Axelsson\textsuperscript{3} was performed to identify the resonance states, the ground and excited states, of $^{11}\text{N}$. Interest on this unbound mirror nucleus of $^{11}\text{Be}$ on the proton rich side was focused toward looking for a similar parity inversion. Yet, difficulties arose with the experimental data. Since only a silicon energy detector was employed to locate the desired protons an accumulation of other particles, such as alphas, were also detected in the detectors, affecting the energy data analysis. Therefore, no particle identification could be made and energy spectra contained both proton and other particle energies. Because of this, resonances of $^{11}\text{N}$ were again studied with a slightly different approach, which included particle identification.

**Theory**

Prior studies of the $^{11}\text{N}$ system by other physicists used complicated reactions to investigate the unstable exotic nuclei. These findings resulted in contradictory conclusions. Therefore, to study $^{11}\text{N}$ although at lower intensities but more directly, a new method of elastic scattering measurements using inverse kinematics was employed in both the Axelsson experiment in 1996 and our current experiment. In this method, a cyclotron accelerated heavy ion beam passes through a scattering chamber filled with a light gas (eg., helium, methane). The incident and target nuclei unite for a long period of time compared to the time it would take the incident nuclei to travel the diameter of the target nucleus. Energy is shared and redistributed between the nucleons until all or a large part of the energy is concentrated on one particle. A resonance can then occur in the reaction when the total energy in the center of mass system is enough to create an excitation energy equal to an energy level of the compound nucleus. At this point, there is enough energy to remove a proton from the nucleus and the proton is emitted.\textsuperscript{4} The recoil
proton spectra are then detected and measured by detectors located on the opposite wall of the chamber. As the beam decelerates in the gas, reactions can take place at any energy. Therefore with this arrangement, the whole spectrum is recorded at once. The gas pressure is also selected so that the beam is stopped prior to reaching the detectors.

Due to the large differences in bremsstrahlung losses between the heavy ions and the protons with the light gas nuclei, the protons lose only a small fraction of their energy in the gas even though the primary beam is completely stopped. Therefore, it is possible to carry out measurements at an angle $0^\circ$ from the beam direction. This angle relates to measurements of elastic scattering in inverse geometry through an angle of $180^\circ$ in the center of mass frame. Calculations for the center of mass energies in relation to the detected proton energies can be made using the equations:

$$E_{p^{\text{cm}}} = \frac{1}{4} E_p \quad 1)$$
$$E_{c^{\text{cm}}} = \frac{1}{40} E_p \quad 2)$$
$$E^{\text{cm}} = \frac{11}{40} E_p \quad 3)$$

where $E_{p^{\text{cm}}}$ is the energy of the proton in the c.m. frame, $E_{c^{\text{cm}}}$ is the energy of the $^{10}$C beam in the c.m. frame, $E^{\text{cm}}$ is the total energy of the system in the c.m. frame, and $E_p$ is the detected energy of the proton from the lab frame. Using this method, the resonances of $^{11}$N were selected and analyzed through a resonance scattering reaction $^{10}$C + $p$ in inverse geometry.

**Experiment**

The experiment was carried out at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. A $^{12}$C primary beam with energy
75 MeV/nucleon was directed onto a 1.46 g/cm² thick Be target. Extraction from the fragmentation products resulted in a secondary beam of $^{10}$C with kinetic energy 8.1 MeV/nucleon. Time of flight for each nucleus was calculated using a parallel plate avalanche counter (PPAC) which the $^{10}$C beam passed through, in correlation with the radio frequency (RF) from the cyclotron. The $^{10}$C beam then entered a scattering chamber (Fig. 1) filled with CH₄ gas used as a target, resulting in a $^{10}$C + p reaction. A silicon detector array located along the wall of the chamber detected the scattered protons from the reaction. Gas pressure within the chamber was tuned to 490 mbar to stop the $^{10}$C beam just before the detectors. For particle identification purposes, the initial Axelsson experiment was revised and a thin 500µm silicon $\Delta$E detector was placed in front of the $0^\circ$ energy detector. Since different charged particles lose different amounts of energy as they pass through the thin $\Delta$E detector, this placement became effective in distinguishing protons from other particles (Fig. 3 and Fig. 4).

Earlier, an experimental run using the $^{12}$C beam in a $^{12}$C + p reaction, similar to the $^{10}$C experiment, studied the scattered protons from resonances in $^{13}$N. The data from this run was used to calibrate the instruments and test the set up.

![Figure 1](image) Experimental arrangement used in the resonance scattering experiment.
Results

Preliminary analysis of the experimental data yields three energy peaks with center of mass energies of 1.3, 2.1, and 3.1 MeV. Comparison between the previous experimental data (Fig. 3) and the present data (Fig. 4) result in more clearly defined peaks in the current experimental analysis and a decrease in particles detected past 4 MeV. This is, in part, due to the use of the thin $\Delta E$ detector for particle identification.

*Figure 2* Preliminary analysis of the total energy spectrum. Energies displayed are from all particles collected by the detectors.

*Figure 3* Final analysis of the proton energy spectrum from the initial Axelsson experiment. Of importance is the possibility of an energy peak beyond 4 MeV in the data analysis.

*Figure 4* Preliminary analysis of the proton energy spectrum using the thin $\Delta E$ detector. The use of the $\Delta E$ detector separates the proton energies from the other particle energies. In comparison with the Axelsson experiment, there seems to be little statistical support for an energy peak after 4 MeV.

Although more analysis is necessary, results are in agreement with previous experimentation in identifying the ground and first two excited states of $^{11}$N. These states
also have characteristics similar to the ground and first two excited states of the mirror state, $^{11}$Be, as expected.

**Conclusion**

With interest growing in gaining a detailed understanding of the properties of matter, nuclear physics is becoming increasingly important to not only understand the interactions between nuclear particles, but also to develop new techniques and applications of its scientific methods. Both of these properties of the nuclear physics discipline are established in this study of the $^{11}$N nuclear resonances. The impending findings of the data analysis may hold another key to scientific understanding and the successful implementation of a new scientific technique may be applicable to the studies of other nuclei.

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**References**