We describe a study of the $^{13}$B nucleus done using the $^3$H($^{13}$B,$p$)$^{14}$B reaction in inverse kinematics using HELical Orbit Spectrometer (HELIOS) at the Tandem Linac Accelerator System (ATLAS) at Argonne National Laboratory (ANL). One neutron is transferred from a $^3$H target to the $^{13}$B beam to produce the $^{14}$B nucleus. The excitation energies and the transferred angular momenta are determined for four observed states in $^{14}$B, providing new information to guide models of nuclear structure.

**Motivations**

- Introduction: Nuclei with neutron (N) to proton (Z) ratio (N/Z) $\approx 1$ are typically stable nuclei, nuclei become unstable with extreme neutron-to-proton compositions, which are known as "exotic nuclei." Here, the nuclear start to show phenomena such as "halo", where the last, loosely-bound, neutron orbits far from the tightly bound object that is the core of the nucleus and the usual nuclear-radius relation, $(R = 1.2 \times \text{atomic mass})^{1/3}$, is not valid. $^{13}$B is a halo nucleus with N/Z ratio $\approx 9/5$, and the valence neutron (the last neutron) is loosely bound with binding energy about 1 MeV.

- Purpose of the research: The study of exotic nuclei is important for understanding how the chemical elements were created and synthesized in stars. Very little is known about the $^{14}$B nucleus and most of what is known is tentative and a new study can help us understand not just the structure of $^{14}$B but also other nuclei far from stability. For the first time a nucleon-transfer reaction is used to study $^{14}$B which provides new data, previously unobtainable, about the structure of $^{14}$B. These data will give new guidance for models of nuclear structure that can be used to describe not only $^{14}$B, but also other nuclei that are far from stability.

**Experimental Technics**

- The beam enters the solenoid through a hollow position-sensitive silicon-detector array (PSD-Array) placed inside the solenoid along the magnetic axis. (PSD-Array)
- The beam intercepts a $^3$H target placed inside the solenoid in a position along the magnetic axis. (Target Fan)
- The emitted $^3$H (protons, red lines) are transported in a helical orbit back to the solenoid axis where the energy ($E$), the axial position ($x$), and the time of flight ($t$) are measured in the PSD-Array. We can calculate $E_x$ and $\theta$ from $E$ and $x$.
- The beam-like particles (1-$^{11}$B, blue lines) emitted in the forward direction were detected in the recoil detector to ensure we are looking at the right reaction.
- The beam intensity and purity were monitored using a silicon surface-barrier detector (called Zero-Degree) telescope placed on the solenoid axis.

**Excitation Energy**

Different angular-distribution shapes refer to different angular momentum transitions. The blue curves represent the orbital angular quantum number $\ell=0$, while the red curves represent $\ell=2$. The black dots represent experimental data while the violet curves are the sums of the blue and red curves fitted to the data.

**Valence Neutron Binding Energy**

The neutron binding energy at the $s_{1/2}$ and $d_{5/2}$ orbits of $^{14}$B, $^{13}$C, $^{12}$N, and $^{16}$O nuclei. Where the neutron in $^{13}$B became unbound at $d_{5/2}$ orbit and the $s_{1/2}$-$d_{5/2}$ orbits are inverted.

**The Conclusions**

- 4 negative parity states have been observed; namely $\{1,2,3,4\}$ at energies: 0.00, 0.65, 1.36, and 2.08 MeV respectively.
- The ground and first excited states have a mix of $\ell=0$ and $\ell=2$, dominated by the $\ell=0$ with a loosely bound valence neutron: one neutron halo nucleus.
- The $\ell=0$ and $\ell=2$ orbits are inverted with highest splitting at the region of N=9.

**References**


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