NEW EVIDENCE FOR PARITY INVERSION IN $^{10}$Li FROM $^9$Li-$\gamma$ COINCIDENCES

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The structure of neutron-unbound $^{10}$Li remains an open question and thus also the complete understanding of the two-neutron halo nucleus $^{11}$Li. The knowledge of the $(n+^{9}$Li) interaction is of essential importance to theoretical calculations of the three-body Borromean system $^{11}$Li ($n+n+^{9}$Li) for which the two sub-systems $^2n$ and $^{10}$Li are unbound.

Simple shell-models predict a $\frac{1}{2}^-$ state as the ground state of $^{10}$Li, however the appearance of the $\frac{1}{2}^+$ state from the sd-shell as the ground state of $^{11}$Be instead of the $\frac{1}{2}^-$ was the first case of an intruder state in the shell structure of nuclei. This parity inversion has long ago been clearly observed experimentally where the non-normal parity state ($\frac{1}{2}^+$) is 320 keV below the normal parity state which is the first excited state. Theoretical predictions [1] presented on Figure 1 show that the energy of the lowest non-normal parity state with respect to the lowest normal parity state increases systematically with Z for isotones with $N=7$ and $Z>4$. It is expected that this trend should continue in the other direction towards the lighter p-shell $N=7$ isotones, and therefore the ground state of $^{11}$Li is predicted to be a neutron s-state, i.e. a non-normal parity state (several calculations [2-4] agree that this $\frac{1}{2}^+$ neutron couples with the $\frac{3}{2}^-$ proton to a $2^-\ $ state).

Experimentally, the situation so far has been much more unclear. Several experiments using transfer reactions have shown evidence for a p-state around 240-540 keV, see Bohlen [5], Young [6], Caggiano [7] et al. The first experimental evidence for a neutron s-state at very low energy has been provided by the work of Kryger et al [8] using the method of sequential neutron decay spectroscopy at 0.

![Figure 1: N = 7 isotope shell-model predictions for the lowest normal and non-normal parity states. Parity inversion is expected in neutron-unbound $^{10}$Li and $^9$He.](image-url)
A virtual s-state at ~ 50 keV was extracted corresponding to a scattering length of ~ -20 fm. However the s-state could represent a decay to the first excited state in ³Li and would then not be the ground state. The observation by Zinser et al [9] of a narrow momentum distribution of the neutrons in coincidence with ³Li nuclei from the single neutron stripping of ¹¹Li has been interpreted as final state interactions [10] and strongly suggested that the s-state couples to the ground state of ³Li (the removal of a halo neutron is not expected to excite the ¹Li core).

An experiment was recently performed at the National Superconducting Cyclotron Laboratory of Michigan State University to investigate the possibility that the low decay energy s-state is not the ground state of ¹⁰Li and feeds into the first excited state of ³Li with the subsequent emission of a 2.7 MeV γ-ray.

A secondary beam of ¹¹Be (46 MeV/nucleon) produced and separated in the A1200 spectrometer bombarded a 300 mg/cm² ⁹Be target located in the N4 vault. A double-sided silicon strip detector located just after the target measured the energy loss (ΔE) and position of the charged fragments. Their residual energy (E) was measured in 8 vertical plastic scintillator bars located at the exit of a deflecting magnet. Particle identification was achieved from the ΔE-E matrix, showing a clear Z separation. The mass number identification required a Monte Carlo simulation to determine the shape of the contours to apply onto the ΔE-E matrix. Neutron and γ-ray coincidences from the breakup of ¹¹Be into the channels of ¹⁰Li and ¹¹Be were measured using the MSU neutron walls at 0° and the BaF₂ array of ORNL-NSCL-TAMU at 90°. The two liquid scintillator filled neutron walls covered an area of 2 x 2 m² with a total efficiency of about 20 %. The 144 BaF₂ crystals covered a solid angle of approximately 1.5 sr with a total efficiency of about 5 % for γ-rays of 2.615 MeV (²⁸Th).

The γ-ray and charged fragment coincidence analysis required an event-by-event reconstruction of the γ showers to add back the pair production escape peaks located in the nearest neighbouring crystals. Moreover, since the γ-rays are emitted by a fast moving source (β ≈ 0.3) Doppler shift correction was necessary.

The analysis of these coincidences was optimized for the ¹¹Be-γ data which could be easily interpreted using the known level scheme of ¹¹Be. Clear evidence was obtained (see Figure 2-a). for a 3.37 MeV γ-ray from the 2⁺ state and for a 2.90 MeV γ-ray from the decay of the 2⁻ state at 6.26 MeV onto the first excited state (2⁺). A weaker indication of a ~ 6 MeV γ-ray which had not been previously observed has been attributed to the decay of the 1⁻ state at 5.96 MeV onto the ground state (0⁺). The study of the ¹¹Be-γ coincidences from the single-neutron stripping from ¹¹Be should shed light on the wave function of the ground state of ¹¹Be, the dominant part of which is known to be a 1s₀, Sagawa et al [1] have suggested that the parity inversion in ¹¹Be can only be explained if more complex contributions, such as the coupling of Δₚ to the 2⁺ of ¹¹Be, are considered. Our data, as well as those from M. Fauerbach et al [11], show that not only the core excitation to its first excited state should contribute, but also higher states such as the 2⁻ and the 1⁻. Relative intensities for these γ-rays have been preliminary determined and their final interpretation for the structure of ¹¹Be is on the way.

The number of ³Li-γ coincidences (see Figure 2-b) correspond to a feeding of ³Li⁺ (2.7 MeV) in the single-proton stripping reaction from ¹¹Be of 4 ± 1 %, the dominant uncertainty coming from the poor fragment mass identification (a contamination of about 25 % from ⁸Li was determined with the Monte Carlo simulation mentioned above). This branching ratio compares very well with a recent shell-model calculation [12] which leads to the formation of ³Li⁺ in the single-proton stripping from ¹⁸Be of 5.2 %. As expected the number of 2.7 MeV γ-rays is small, therefore the triple γ-neutron-fragment coincidences did not provide sufficient statistics to be analyzed. Although, the angular neutron distributions showed,
Similarly to the GSI and GANIL data, a dependence of the width with respect to the selected fragment: a narrower distribution in the case of $^9$Li resulting from final state interactions when a resonant intermediate state is formed in $^{10}$Li than in the case of $^{10}$Be corresponding to the diffraction dissociation of the neutron (this observation also supports the mass identification of the fragments).

Both, the weak population of the first excited state in $^9$Li and the narrow momentum distribution of the neutrons in coincidence with $^9$Li fragments indicating the formation of $^{10}$Li lead to the conclusion that the ground state of $^{10}$Li is an s-state which decays on the ground state of $^9$Li. Thus we observe, like in the case of $^{11}$Be, a parity inversion in neutron-unbound $^{10}$Li.

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