Measuring neutron-unbound states with MoNA-LISA

Neutron decay measurements of $^{11}$Li and $^{12}$Be

Jenna Smith
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Neutron unbound states

$A^2Z + n \rightarrow A - 1 Z + n$

neutron separation energy
Neutron unbound nuclei

unbound nucleus

daughter nucleus

neutron
What is a resonance?

![Graph showing amplitude vs. frequency with a peak at a specific frequency]

- Frequency
- Amplitude
What is a resonance?

Breit-Wigner distribution

\[ \sigma(E; E_0, \Gamma) \propto \frac{\Gamma^2}{(E - E_0)^2 + \Gamma^2} \]
Why study unbound nuclei?

bound nucleus

unbound nucleus
Dripline nuclei

Experimental measurements

\[ E_d = \sqrt{(P_f^\mu + P_n^\mu)^2 - M_n - M_f} \]
$^{11}\text{Li}$: An overview

Background on $^{11}\text{Li}$

$^{11}\text{Li}(p, p)$

$^{14}\text{C}(\pi^-, \text{pd})X$

$^{11}\text{B}(\pi^-, \pi^+)^{11}\text{Li}$

Korsheninnikov et al., PRC, 53, R537 (1996)
Kobayashi et al., NPA, 538, 343 (1992)
Beam production at NSCL
Projectile fragmentation
Beam production at NSCL
Experimental layout
Experimental set-up: fragments

Charged Particle Detectors

- CsI(Na) array
- Timing scintillator
- Ion chamber

CRDC2

CRDC1

Sweeper Magnet

Reaction Target
Experimental set-up: neutrons
Interpretation through simulation

Physical reality + Experimental limitations = Data

Data - Experimental limitations = Physics
Interpretation through simulation

Physical reality + Experimental limitations = Data

Physics + Simulation = Simulated data
Simulation

- Beam profile
- Reaction dynamics
- Fragment tracking
- Detector acceptances and resolutions
- Neutron interactions in MoNA-LISA
  - Cross-talk
- Decay energy distribution
$^{12}{\text{Be}}^* \rightarrow ^{11}\text{Be} + n$ decay energy

Smith et al., PRC, 90, 024309 (2014)
$^{12}\text{Be}^* \rightarrow ^{11}\text{Be} + \text{n}$ decay energy

$E_d = 1243 \pm 20$ keV

$\Gamma = 634 \pm 50$ keV

Smith et al., PRC, 90, 024309 (2014)
$^{12}\text{Be}^* \rightarrow ^{10}\text{Be} + 2n$ decay energy

Smith et al., PRC, 90, 024309 (2014)
Spin and parity in $^{12}$Be

- Requires $L=1$ decay to $1/2^+, 1/2^-$
- Population: 1p knockout from $^{13}$B ground state of $3/2^-$
- Very little 2n decay

- Spin: 0, 1, 2
- Eliminates 0-
- Negative parity

Probable spin and parity: $1^-, 2^-$

Smith et al., PRC, 90, 024309 (2014)
Garrido et al., PRC, 86, 024310 (2012)
From 1n decay to 2n decay

\[ E_d = \sqrt{(P_f^\mu + P_n^\mu)^2} - M_n - M_f \]

\[ \sigma(E; E_0, \Gamma) \propto \frac{\Gamma^2}{(E - E_0)^2 + \Gamma^2} \]
From 1n decay to 2n decay

\[ E_d = \sqrt{(P_f^\mu + P_{n1}^\mu + P_{n2}^\mu)^2 - M_f - 2M_n} \]

\[ \sigma(E; E_0, \Gamma_0, E_1, \Gamma_1) = \text{??} \]
Two neutron correlations

Sequential:
- $^{11}\text{Li}$
- $^{10}\text{Li} + \text{n}$
- $^{9}\text{Li} + \text{n} + \text{n}$

Simultaneous:
- $^{11}\text{Li}$
- $^{10}\text{Li} + \text{n}$
- Dineutron
- 3-Body

no intermediate step
Two neutron correlations

- **Sequential model**
  - continuum shell model formalism
  - input: central energies and widths
  - output: neutron energy distributions
  - neutrons: same orbital, paired to $J=0^+$

- **Dineutron model**
  - input: central energy and width
  - output: total energy and dineutron energy
  - assumes two $L=0$ decays

- **3-body model**
  - phase space decay
  - input: central energy and width
  - output: energies and angles of particles
$^{11}\text{Li}^* \rightarrow ^9\text{Li} + 2n$ decay energy

Smith et al., PLB, in review
Potential decay paths – 2n

Diagram showing energy levels and decay paths for different isotopes of lithium, including \(^{11}\text{Li}\), \(^{10}\text{Li} + n\), and \(^{9}\text{Li} + 2n\). The diagram illustrates energy levels in MeV and phase space relationships between the isotopes.
Potential decay paths – 1n
$^{11}\text{Li}^* \rightarrow ^9\text{Li} + 2\text{n}$ decay energy

Smith et al., PLB, in review
Jacobi plot definitions

T-system

Y-system
Jacobi plots
$^{11}\text{Li}$ Jacobi plots
Jacobi plots

Smith et al., PLB, in review
Jacobi plots

Smith et al., PLB, in review
Pushing particle decay farther
Future directions

• Combining neutron detectors with gamma, beta detectors

• Identification of unique particles (neutrons)

• Better models that track the entire decay

• Neutron-rich beams needed to reach the neutron drip line at higher Z
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