Nuclear structure studies along the proton dripline with Gammasphere and the Fragment Mass Analyzer

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Nuclear structure along the proton dripline at ATLAS
Proton drip-line

exotic nuclei

doubly-magic $^{100}$Sn

The rp-process nuclei
All stable beams from H to U with energies up to ~10 MeV/nucleon

Recent addition: CARIBU
^{252}_{\text{Cf}}

Argonne Tandem Linac Accelerator System
Argonne ~30 miles west of Chicago
GAMMASPHERE
4\pi array of Compton suppressed $\gamma$-ray detectors

Up to 110 HPGe detectors in BGO shields $\gamma$-ray detection efficiency at 1.3MeV $\approx$10%
The world’s largest
GAMMASPHERE in the movie “Hulk”
250 M$ gross
Fragment Mass Analyzer
Argonne Fragment Mass Analyzer

Mass resolution: $\delta M/M \sim 1/350$
Angular acceptance: $\Delta \Omega = 8 \text{ msr}(2 \text{ msr})$
Energy acceptance: $\Delta E/E = +/- 20\%$
M/Q acceptance: $\Delta (M/Q)/(M/Q) = 10\%$
Flight path 8.2m
Max($B_\rho$) = 1.1Tm
Max($E_\rho$) = 20MV
Can be rotated off 0 degrees
Can be moved along the axis
Different focusing modes

Separates reaction products from beam and disperses them according to $M/Q$
Implantation-decay station at the FMA focal plane isomer, p-γ, α-γ, βγ studies

- Ge clovers
- 160X160 DSSD
- Large area Si
- Si/PiN box
- Plastic β dets
FMA Implantation-Decay array

160X160 64mmX64mm
Double Sided Si Strip Detector

X-Array
5 Ge clover detectors in box geometry
GAMMASPHERE combined with FMA and its auxiliary detectors allows detection and assignment of $\gamma$ rays associated with weak reaction channels.

Recoil-Decay Tagging techniques, i.e. selection of prompt gamma rays using characteristic decay properties.
Doubly magic $^{100}$Sn
100\text{Sn} physics

- Super allowed \(\alpha\)-decay
- \(\beta\)-decay
- \(\alpha\)-decay
- RP process end point
- Double-magic
- GT \(\beta\)-decay
- spe
- n-n interactions
- \(\beta\)p

\(100\text{Sn}\)
100Sn region experimental status

N=50

Z=50

β-delayed protons with sizeable branch
Observed/expected

Excited states
Fusion-evaporation

Decay properties
Fusion-evaporation

Decay properties
Existence
Fragmentation
$^{101}\text{Sn} \beta$-delayed protons

\[ \gamma \xrightarrow{\beta^-} \beta^-p \xrightarrow{\gamma^-} \text{growing} \]

$^{101}\text{Sn} \rightarrow ^{100}\text{Cd}$

$E_p = 1.5$-$5$ MeV
$T_{1/2} = 1.9(3)$ s
$b_{\beta^-p} \sim 15\%$

GSI online mass separator
$^{101}$Sn prompt $\gamma$ rays

1 out of $\sim 10^8$ $\gamma$ rays emitted
### Light Sn isotopes

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N=51 isotones

\[ ^{101}\text{Sn} \rightarrow ^{99}\text{Cd} \rightarrow ^{97}\text{Pd} \rightarrow ^{95}\text{Ru} \rightarrow ^{93}\text{Mo} \]

\[ \nu g_{7/2} \rightarrow \nu d_{5/2} \rightarrow 5/2^+ \rightarrow 5/2^+ \rightarrow 5/2^+ \rightarrow 5/2^+ \]

\[ 172 \rightarrow 1363 \rightarrow 1363 \rightarrow 942 \rightarrow 942 \rightarrow 686 \rightarrow 686 \rightarrow 441 \rightarrow 441 \]

\[ 9/2^+ \quad 9/2^+ \quad 9/2^+ \quad 7/2^+ \quad 7/2^+ \quad 7/2^+ \]

99Cd and 97Pd are doubly magic.
$^{101}$Sn level scheme

Yrast state
Systematics of the N=51 isotones
Shell Model
Previous assignment based on $^{101}$Sn $\beta p$
Shell-model calculation of light Sn isotopes

Odd Sn
Even Sn

$E(7/2^+)-E(5/2^+)$

$(g_{7/2})^2 \quad 0^+_2$ TBME decreased by 20% - very good agreement
CD-Bonn nucleon-nucleon interaction ($^{100}$Sn core)
$^{107}$Te $\alpha$ decay fine structure

D. Seweryniak et al., PRC (2002)051307(R)

$^{105}$Te $\alpha$ decay fine structure

I. Darby et al., PRL 105, 162502 (2010)

Digital electronics $^{109}$Xe-$^{105}$Te pileup events

Confirmed the 172 keV transition but proposed to reverse the $d_{5/2}$ and $g_{7/2}$ and reported agreement with SM calculations

However, one could have inversion in $^{105}$Te!
Shell-model calculations

- CD-Bonn ($^{88}\text{Sr}$ core) meson exchange potential
- N3LO Chiral perturbation theory to next-to-next-to-next-to-leading order
- AV18 Phenomenological high-precision potential

I. Darby et al., PRL 105, 162502 (2010)
• ANL calculations with the $d_{5/2}$ gs better than two of the calcs with the $g_{7/2}$ gs
• ANL calcs with the adjusted $(g_{7/2})^2$ tbme fits best
\( ^{105}\text{Te}, \ ^{107}\text{Te} \) SM calculations

Proton SPE and T=0 TBME not known very well!

- 7/2\(^+\) always lower except w/o s\(_{1/2}\) and d\(_{3/2}\)
- 7/2\(^+\)-5/2\(^+\) separation sensitive to s\(_{1/2}\) and d\(_{3/2}\)
- g\(_{7/2}\) lower pushes 7/2\(^+\) higher!
- reducing \((g_{7/2})^2\) pushes 7/2\(^+\) lower

- 5/2\(^+\) always lower
- 7/2\(^+\)-5/2\(^+\) separation not sensitive to s\(_{1/2}\) and d\(_{3/2}\)

109\(^{\text{Xe}}\)
- Calcs for 109\(^{\text{Xe}}\) produce 5/2\(^+\) gs!
Tensor interaction

- Tensor interaction 300 keV
  
  T. Otsuka et al., PRL 95, 232502 (2005)

- Monopole & tensor interaction -500 keV
  
  T. Otsuka et al., PRL 104, 012501 (2010)
Core excited states in $^{101}\text{Sn}$
original and follow-up experiment

172-kev gate 1st exp

172-kev gate 2nd exp

172-kev gate 1st and 2nd exp

$^{101}\text{Sn} \beta p$ gate 1st exp

$^{101}\text{Sn} \beta p$ gate 2nd exp

$^{101}\text{Sn} \beta p$ gate 1st and 2nd exp

Random $\gamma$ rays

A candidate ~2.5 MeV with 2 counts feeding the 172-keV state

C. Fahlander et al., PR C63(2001)021307(R)
$^{100}$In beta delayed gamma tagging
proton hole - neutron interactions

$^{58}$Ni+$^{45}$Sc->$^{100}$In+3n
$T_{1/2}\sim 7s$, $b_{\beta p}\sim 4\%$

$\mu$Ball as a proton/alpha veto detector
FMA mass tag
Betas in the DSSD
Gamma rays in Ge clovers

Recoil-Beta tagging with fast beta emitters:
$^{40}$Ca+$^{24}$Mg->$^{62}$Ga(pn)/$^{50}$Mn(on $^{16}$O)

Data analysis in progress
C.J. Chiara, H.David, ..
**100Sn region - perspectives**

- More statistics for $^{101}\text{Sn}$: core excitations, neutron $h_{11/2}$ state
- $\pi-\nu$ multiplets in $^{100}\text{In}$ (7s, 4%) using $\beta\gamma$ tagging
- Proton hole states in $^{99}\text{In}$ (3s, 4%) using $\beta p$ tagging
- Excited states in $^{100}\text{Sn}$ using $\beta\gamma$ as a tag?
- Excited states in $^{105}\text{Te}$
Proton drip line
Proton emission

✓ Analogous to $\alpha$ decay
✓ No pre-formation factor
✓ Decay rates sensitive to $E_p$ and $I_p$
✓ Unique laboratory to study tunneling through a 3D barrier
✓ Source of information on shapes, single-particle nuclear structure and masses far from stability
✓ Relevant to $(p,\gamma)$ cross sections which depend on $\Gamma_\alpha$
Proton Decay Observables

\[ \Gamma_{l_p j_p}^{\text{sph}} = \frac{\hbar}{\tau} = \frac{\hbar^2 k}{\mu} \left| N_{l_p j_p} \right|^2 \]

\[ \psi_{K_p}^{\text{inside}}(r) = \sum_{l_p j_p} c_{l_p j_p}^{K_p} \frac{u_{l_p j_p}(r)}{r} \]

\[ \Gamma_{K_p}^{\text{def}} = \frac{\hbar}{\tau} = \frac{2(2R + 1)}{2I + 1} \sum_{l_p j_p} \left| \langle j_p K_p R0 | IK_p \rangle \right|^2 \left| c_{l_p j_p}^{K_p} \right|^2 \Gamma_{l_p j_p}^{\text{sph}} \]
Proton emitter landscape

- 15 new proton emitters
- ~20 mass units away from the line of stability
- 5 were studied in-beam
- Often less exotic neighbors not known
Proton emitters at ANL

First deformed proton emitters
Anomalous decay rates explained by introducing deformation

First fine structure

C.N. Davids et al., PRL C55 (1997)2255
A. Sonzogni et al., PRL 83 (1999)1116

✓ Spherical
✓ Axially deformed
✓ Odd-odd axially deformed
✓ Coupling to vibrations
✓ Non-axial deformation

Theory:
ANL
C.N. Davids and H. Esbensen
Padova/Lisbon
E. Maglione/F.Ferreira
ORNL
Rotational bands in the deformed proton emitter $^{141}$Ho

D. Seweryniak et al., PRL C86(2001)1458

Unexpectedly large signature splitting indicates triaxial shape

$\beta=0.25(4)$ from Harris formula

$7/2^-[523]$ $1/2^+[411]$
It was proposed that protons are emitted from the $7/2^-$ state of the $h_{11/2}$ band which partially aligned with the rotational axis.


A. Robinson et al., PRL 95, (2005) 032502
Non-adiabatic quasi-particle model predicts again $\frac{7}{2}^-$ state but the data favors $\frac{3}{2}^+$ however more statistics required!
liGHT rp-process nuclei
Nucleosynthesis

$^{22}\text{Na}$

$^{26}\text{Al}$

$T_{1/2}=2.6\text{yr}, E_\gamma=1275\text{ keV}$

Upper limit for near novae

$T_{1/2}=7.4 \times 10^5\text{yr}, E_\gamma=1809\text{ keV}$

Observed 1-3 $M_\odot$ in Galaxy

... Wolf-Ryet stars

$T=0.5 \times 10^8\text{K}$

Nova

$T=2-3 \times 10^8\text{K}, \rho=10^3-10^4\text{g/cm}^3$

X-ray burster

$T=1-2 \times 10^9\text{K}, \rho=10^6-10^7\text{g/cm}^3$

CCSN

...
$^{26}\text{Al}$ sky image from COMPTEL
Role of narrow resonances in the rp-process

Proton capture proceeds through individual states and cannot be described well by statistical models such as Hauser-Feshbah theory.
**Stellar \((p,\gamma)\) cross sections**

\[
N_A \langle \sigma v \rangle \left[ \frac{\text{reactions}}{\text{cm}^2 \cdot \text{s} \cdot \text{mole}} \right] = 1.540 \times 10^{11} (\mu T_9)^{-3/2} \sum_i \omega \gamma_i e^{-11.605 E_i / T_9}
\]

\(\mu\) – reduced mass; \(\omega \gamma\) – resonance strength

\[
\omega \gamma [\text{MeV}] = \frac{2J + 1}{(2j_p + 1)(2j_T + 1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma_p + \Gamma_\gamma}
\]

\(\Gamma_p\) – proton width; \(\Gamma_\gamma\) – gamma width; \(j_p, j_T, J\) – proton, target, resonance spin

\(\Gamma_\gamma \gg \Gamma_p \Rightarrow \gamma \sim \Gamma_p\)

\[
\Gamma_p [\text{MeV}] = 2 \frac{\hbar^2}{M_e a_c^2} P_l(E_p) C^2 S_p
\]

\(P_l(E_p)\) – transmission through the barriers; \(C^2 S_p\) – spectroscopic factor
In-beam spectroscopy above the proton threshold

Use heavy-ion fusion-evaporation reaction to populate states in light proton-rich nuclei, including proton capture resonances, study their $\gamma$ decay, and deduce their properties

- Precise energies
- Spin can be constrained by $\gamma$-ray angular distributions, $\gamma\gamma$ correlations
- Lifetimes – DSAM method
- Different states populated compared to transfer reactions or $\beta$ decay
Experimental setup
NeNa and MgAl cycles and beyond

Breakout from H(ot)CNO cycles

\[ ^{22}\text{Mg} \rightarrow \text{D. Seweryniak et al. Phys. Rev. Lett. 94 (2005) 032501}\]
\[ ^{24}\text{Al} \rightarrow \text{G. Lotay et al., Phys.Rev. C}\]
\[ ^{26}\text{Si} \rightarrow \text{D. Seweryniak et al., Phys. Rev. C 75 (2007) 062801(R)}\]
\[ ^{27}\text{Si} \rightarrow \text{G. Lotay et al., Phys. Rev. Lett. 102 (2009) 162502}\]
\[ ^{30}\text{Si} \rightarrow \text{G. Lotay et al., Phys. Rev. C 80 (2009) 055802}\]
The $^{21}\text{Ne}(p,\gamma)^{22}\text{Mg}$ reaction

- Relevant to ONe novae
- $^{22}\text{Na}$ synthesis follows 2 reaction paths:
  - $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}(\beta^+\nu)^{21}\text{Ne}(p,\gamma)^{22}\text{Na}$ “cold” NeNa cycle
  - $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}(p,\gamma)^{22}\text{Mg}(\beta^+\nu)^{22}\text{Na}$ “hot” NeNa cycle
- $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$ reaction rate is the main source of uncertainty

J. D’Auria et al., PRC 69, 065803 (2004)
In-beam spectroscopy of $^{22}\text{Mg}$

$E(2^+)=5711.0(1.0) \text{ keV}$

$b(2^+\rightarrow 0^+)=14(4)\%$

All states below and near above the proton threshold were identified.

D. Seweryniak et al., PRL 94, 032501 (2005)
The $2^+$ resonance energy

M. Mukherjee et al., PRL (2004)  
ISOLTRAP at ISOLDE  
$\Delta M^{(22}\text{Mg})=-399.92(27)\text{ keV}$

G. Savard et al., PR C (2004)  
CPT at ANL  
$\Delta M^{(22}\text{Mg})=-399.64(63)\text{ keV}$

S. Bishop et al., PRL 90, 162501 (2003)  
DRAGON at TRIUMF  
direct $p$ capture measurement

$E_R=205.7(5)\text{ keV}$  
however  
$21\text{Na}$ and $22\text{Mg}$ masses and $E^*(2^+)$ gave  
$E_R=212\text{ keV}$???

New $22\text{Mg}$ mass and  
new $E^*(2^+)$ solved the puzzle  
$\sigma$ increased 40%
The \((^{26}\text{Al},\gamma)^{27}\text{Si}\) reaction

- \(^{16}\text{O}+^{12}\text{C}\rightarrow^{27}\text{Si}+\text{n}\)
- Large uncertainties at \(T_\text{g} \sim 0.05\) corresponding to Wolf-Rayet stars (\(\sim >30M_\odot\)) which are along with AGB stars are possible sources of \(^{26}\text{Al}\) in the Galaxy
- GAMMASPHERE only- \(\gamma\gamma\) and \(\gamma\gamma\gamma\)
- Fairly high state density
- Spin assignments for several states near the proton threshold and more precise energies

G. Lotay et al., PRL 102, 162502 (2009)
ATLAS efficiency and intensity upgrade

- More intense beams
  ATLAS intensity upgrade
- Faster detectors
  digital GAMMASPHERE
digital DSSD
- More efficient detectors
  GRETINA
  Gas-filled separator
- Better channel selection
  high-granularity DSSD
Digital Gammasphere and DSSD

Digitizer

TTC module
J.T. Anderson et al., 2007
IEEE Nuclear Science Symposium Conference Record, p. 1751
GRETINA - Ge tracking array
project led by LBNL

Ge shell
Position sensitive, cascade tracking
7 modules – 4 crystals – 36 segments
$1\pi$ array
ready in 2011
Step to GRETA $4\pi$ array ~60% efficiency
Facility for Rare Isotope Beams

Superconducting-RF driver linear accelerator that provides 400 kW for all beams with uranium accelerated to 200 MeV/nucleon and lighter ions with increasing energy

$550M DOE project at MSU, East Lansing to be finished in 2017

- Fragmentation reactions
- Re-accelerated radioactive beams

$^{100}\text{Sn}$ after fragmentation $\sim 10/s$ (reaccelerated $1/s$)
Conclusions

- Transition between the single-neutron $d_{5/2}$ and $g_{7/2}$ states was observed in $^{101}$Sn
- Proton decay studies provide unique experimental information on nuclear structure far away from the line of stability
- In-beam spectroscopy above the proton threshold is a very useful tool to constrain input for the rp-process calculations
- ATLAS upgrade will allow extension of the above studies to even more exotic systems
Thank you!
Excited states in $^{100}$In

Proton-neutron interactions


1st experiment using tagging with $\beta$P like for $^{101}$Sn not sensitive enough

How about tagging with beta delayed gamma rays?

$T_{1/2} \sim 7s$

$\beta/EC ~^{100}$In

$b_{\beta p} \sim 4\%$