Astrophysics with Solenoids

• \((\alpha,p)\) reactions – XRB and the \(\alpha p\) process
• Spectroscopy of resonances
  – Neutron-unbound states via \((d,p)\) for \((n,\gamma)\), resonant capture and the \(s\)- or \(r\)- processes
  – Proton spectroscopic factors and states from proton transfer: \((^3\text{He},d)\)
  – Neutron spectroscopic factors of bound states for \((n,\gamma)\) direct capture

• gamma-ray strength functions and testing of HF calculations for \((n,\gamma)\)

• HI Fusion reactions for Carbon burning
(α,p) and x-ray bursts

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(p,γ)

(α,p)
Examples of \((\alpha, p)\) measurements

\[ ^{14}\text{O}(\alpha, p)^{17}\text{F} \] measured at RIKEN

M. Notani et al., NP A738, 411 (2004)

\[ ^{18}\text{Ne}(\alpha, p)^{21}\text{Na} \] from \[ ^{21}\text{Na}(p, \alpha)^{18}\text{Ne} \]: \((p, \alpha)\) only samples g.s. branch

P. Mohr, et al., PRC 90, 065806 (2014),

P. S. Salter et al., PRL 108, 242701 (2012),

S. Sinha et al., (ANL unpublished)
Direct Studies: \((\alpha,p)\) reaction measurements

- HELIOS-type device is complementary to extended gas target techniques (e.g. ANASEN)
  - measure specific energies/resonances

- Advantages:
  - high geometrical efficiency
  - proven method
    - \(^{20}\text{Ne}(\alpha,p)^{23}\text{Na}\) successfully measured December 2014 with HELIOS

- Challenges
  - high RIB intensities needed due to low cross sections

C. Deibel, J. Lai, LSU
Indirect Studies: transfer reactions

- Populate resonances through transfer reactions with RIBs:
  - \((^3\text{He},d) \to (p,\gamma)\)
  - \((d,p) \to (n,\gamma)\)
  - \((^6\text{Li},d) \to (\alpha,\gamma)\)

- Advantages:
  - yields structure information needed to calculate reaction rates:
    - angular distributions, excitations energies, branching ratios
  - good resolution compared to other inverse kinematics techniques
  - high geometrical efficiency \(\to\) angular distribution obtained in single measurement
  - RIB intensities needed are less than required for direct studies

- Challenges:
  - resolution limits feasible studies
    - help from \(\gamma\)-ray coincidences (e.g. using APOOLO)
  - beam contaminants
    - requires heavy recoil coincidences
Indirect II: $(d, p\gamma)$ as a surrogate for $(n, \gamma)$

$$^{232}\text{Th}(d, p\gamma)$$


$$^{171,173}\text{Yb}(d, p\gamma)$$

$$\sigma(n, \gamma) / \sigma^{173}\text{Yb}$$

Neutron Energy (keV)

Cross section ratio

Final Nucleus Excitation Energy (MeV)

Number of Events

$^{232}\text{Th}(d, p\gamma)$

This work

ENDFB7.0

Corrected data

Aerts et al. (gTOF)
Solenoid Spectrometer for Nuclear Astrophysics (SSNAP)

- Second TWINSOL solenoid used as a helical spectrometer
- Reaction products spiral in characteristic trajectories
- Particle identification from cyclotron period
- Large angular range covered simultaneously
- Improved kinematic compression and resolution
- Funded by NSF and JINA
- Currently testing detector concepts.

D. Bardayan
Will be used for studies of \( (^3\text{He},t) \), \( (^3\text{He},d) \), \( (d,t) \), and \( (d,p) \) reactions on stable targets.

Angular distribution of reaction products measured in a single setting. Particle decay branching ratios can also be measured.

D. Bardayan
Summary

• Many opportunities for astrophysics with a solenoidal spectrometer
• Gains in efficiency, resolution for variety of different reactions that produce light charged particles
• Active program is underway now at ANL
• Other efforts are beginning or are contemplated (UND, FRIB/ReA)
• Thanks to Dan Bardayan, Catherine Deibel and Ernst Rehm!
Targets beyond CD$_2$

- $^6$LiF + C backing
  - For ($^6$Li,$d$) $\alpha$-transfer, has been used in HELIOS

- Cryogenic gas target:
  - For ($^3$He,$d$), ($^3$He,$p$), ($\alpha$,$p$), ($\alpha$,$d$), ($\alpha$,$t$)
    Has been built and tested in HELIOS

- $^3$H/Ti foil targets:
  - For ($t$,$p$), ($t$,$\alpha$): Have been used at CERN/ISOLDE and tested in HELIOS. New target is finished and delivered to ANL
HELical Orbit Spectrometer - HELIOS

$B_{\text{MAX}} = 2.85 \, \text{T}$

2.35 m

0.9 m

Beam

Silicon Array

Laser rangefinder

X-Y-\(\theta\) positioning stage

Target

J. P. Schiffer, RIA equipment workshop 1999, NIMPRA 580, 1290 (2007),
J. C. Lighthall et al, NIMPRA 622, 97 (2010)
Particle transport in a solenoid

Measured: $E_{lab}$, $z$, $TOF$
Deduced: $E_{CM}$, $\theta_{CM}$

$T(cyc) = \frac{2\pi m}{qB}$

For a given state:

$z \propto \cos \theta_{CM}$

$E_{lab} = E_{CM} - A + Bz$

$\Delta E_{lab} = \Delta E_{CM}$

For two states at fixed $z$
Solenoid acceptance

- B = 2T
- R (bore) = 0.5m
- Z (fid) = 1.0m
(\(d,p\)) with Stable beams

J. C. Lighthall et al., PRC 111, 123 (2010)


B. P. Kay et al., PRC 111, 123 (2010)
with in-flight ATLAS RIBs

$^{15}\text{C}(d,p)^{16}\text{C}$

$^{19}\text{O}(d,p)^{20}\text{O}$

$^{17}\text{N}(d,p)^{18}\text{N}$

$^{12}\text{B}(d,p)^{13}\text{B}$

$^{13}\text{B}(d,p)^{14}\text{B}$

AHW et al., PRL 111, 123 (2010)

C. R. Hoffman et al., PRC 111, 123 (2010)

C. R. Hoffman et al., PRC 111, 123 (2010)

B. B. Back et al., PRL 111, 123 (2010)

S. Bedoer et al., PRC 111, 123 (2010)
Other reactions

\[ ^{15}\text{C}(d, ^3\text{He})^{14}\text{B} \]

S. Bedoor

\[ ^{14}\text{C}(d, ^3\text{He})^{13}\text{B} \]

S. Bedoor

\[ ^{28}\text{Si}(d, t)^{27}\text{Si} \]

B. Kay

\[ ^{28}\text{Si}(d, ^3\text{He})^{27}\text{Al} \]

B. Kay

AHW et al., PRC 111, 123 (2014)