Open Nuclear Systems in Structure and Astrophysics

Ingo Wiedenhöver

John D. Fox Laboratory, Department of Physics, Florida State University

Research supported by the US National Science Foundation
and the US Department of Energy

Working Title: Robert made me do it !

1) Erice Conference
September 1996

Topic:
“4Π high resolution gamma ray spectroscopy and nuclear structure"

2) IW visits ANL, March 7, 1997 RVFJ: “Don’t do anything, give me a week”

3) An early-morning phone call from Robert, March 14, 1997 :

- RVFJ: You are experienced in Gamma-spectroscopy, but before we continue: Are interested in radioactive-beam experiments ?
- IW: (Enthusiastically) YES, that is one of the reasons I would love to come to Argonne ! (Translate: *I have no idea what you are talking about...*)
- RVFJ: Congratulations, we are offering you a postdoc position.

The Atlas in-flight radioactive beam facility, early days

Experiments with Radioactive Beams at ATLAS

K. E. Rehm[a], I. Ahmad[a], J. Blackmon[b], F. Borasi[c], J. Caggiano[a], A. Chen[d], C. N. Davids[a], J. Greene[a], B. Harss[a], A. Heinz[a], D. Henderson[a], R. V. F. Janssens[a], C. L. Jiang[a], J. Nolen[a], R. C. Pardo[a], P. Parker[d], M. Paul[e], J. P. Schiffer[a], R. E. Segel[c], D. Seweryniak[a], R. H. Siemssen[a], M. S. Smith[b], J. Uusitalo[a], T. F. Wang[f], I. Wiedenhöver[a]

VOLUME 82, NUMBER 20 PHYSICAL REVIEW LETTERS 17 MAY 1999

Stellar Reactions with Short-Lived Nuclei: $^{17}F(p,\alpha)^{14}O$

B. Harss,* J. P. Greene, D. Henderson, R. V. F. Janssens, C. L. Jiang, J. Nolen, R. C. Pardo, K. E. Rehm, J. P. R. H. Siemssen, A. A. Sonzogni, J. Uusitalo, and I. Wiedenhöver
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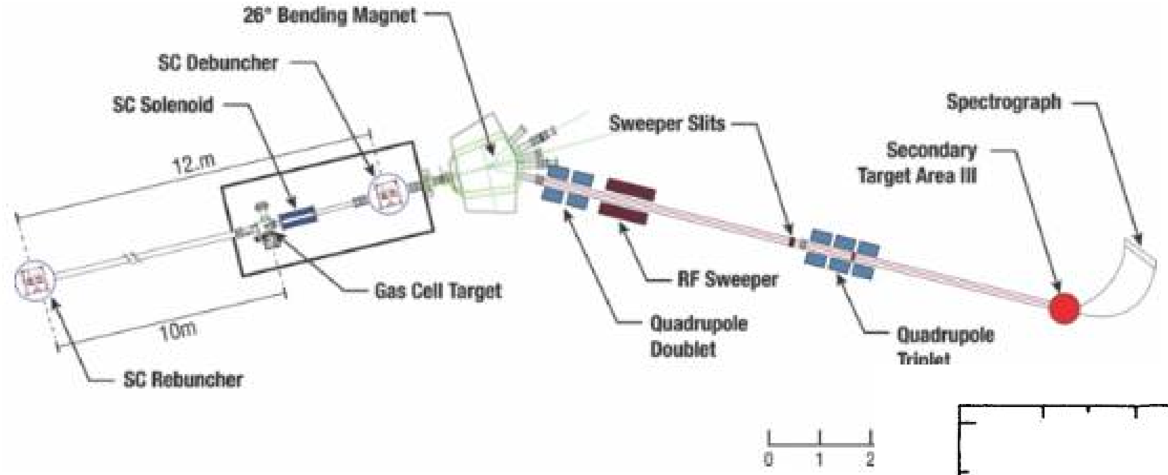
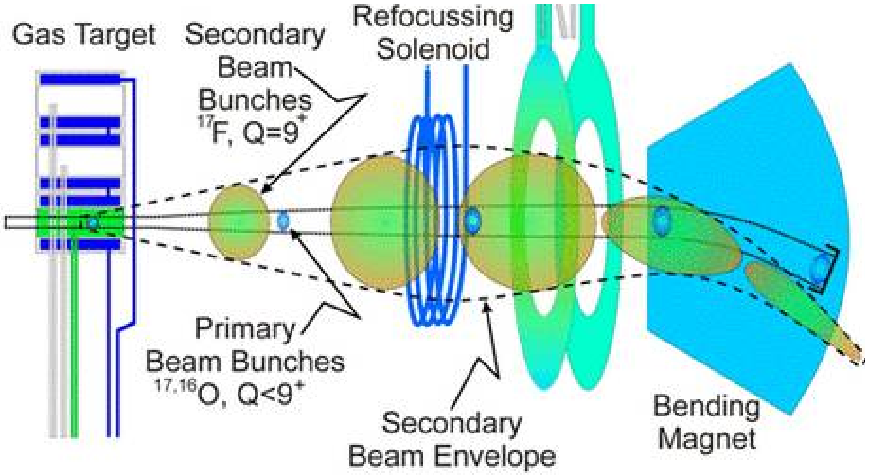
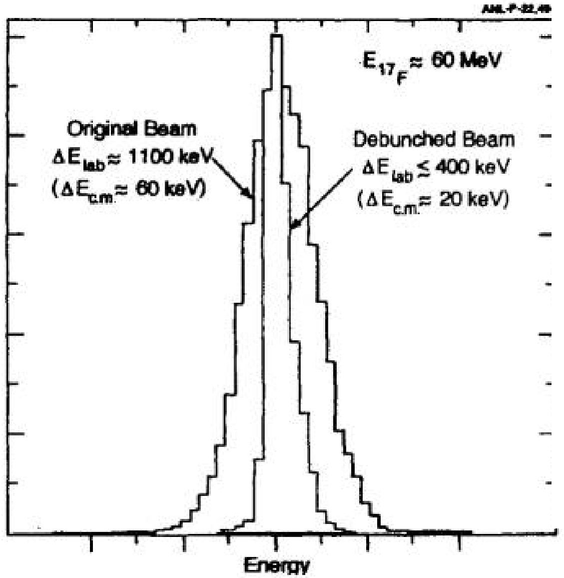
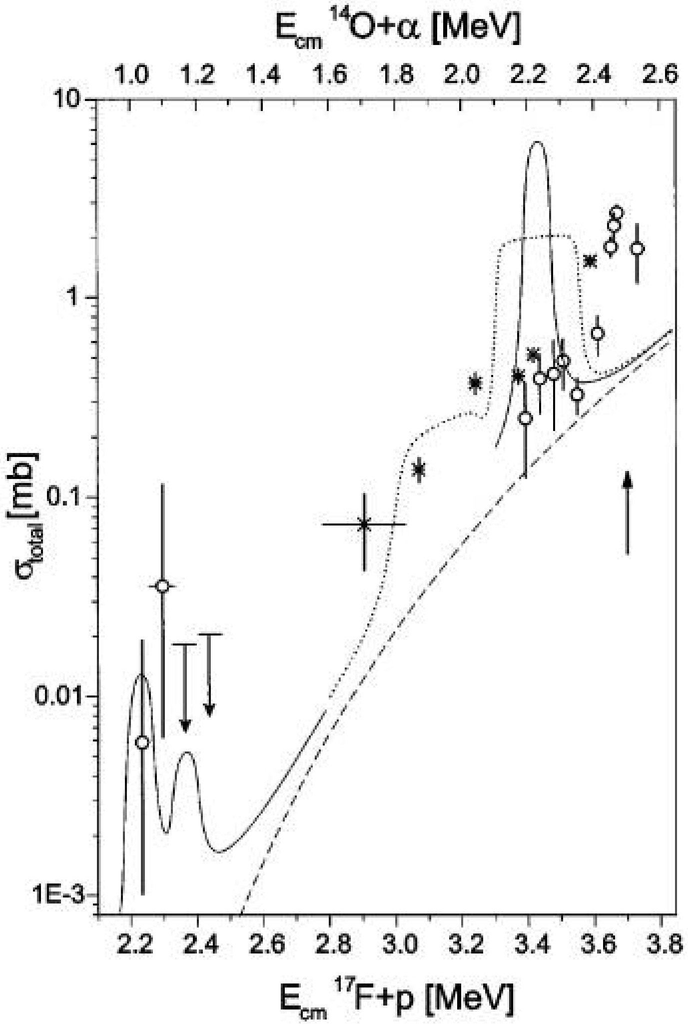
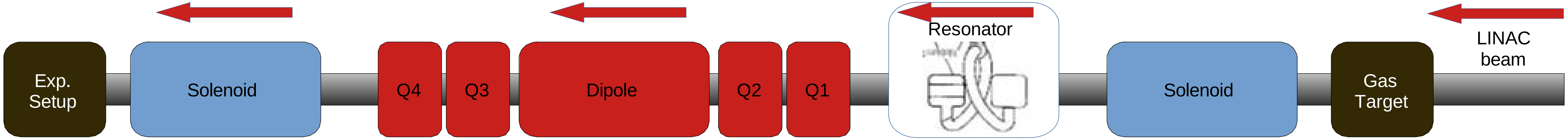


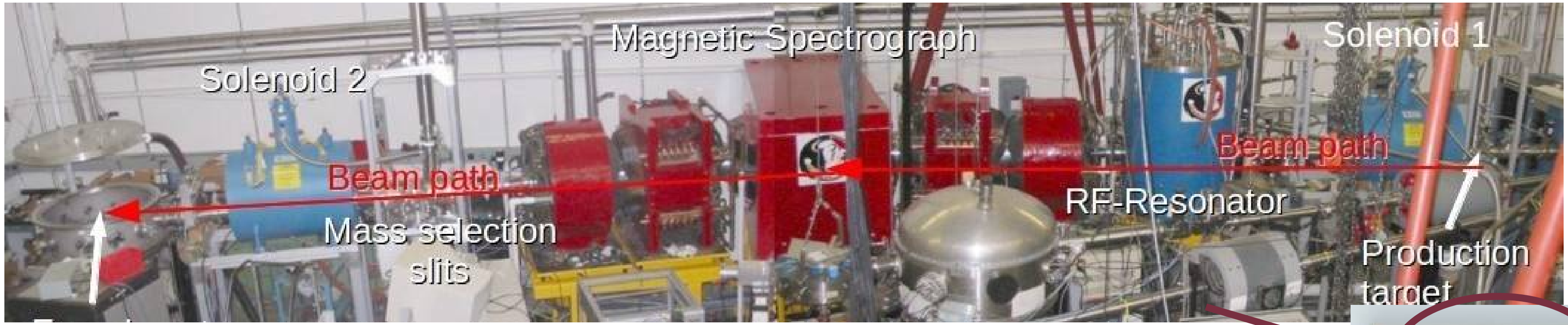


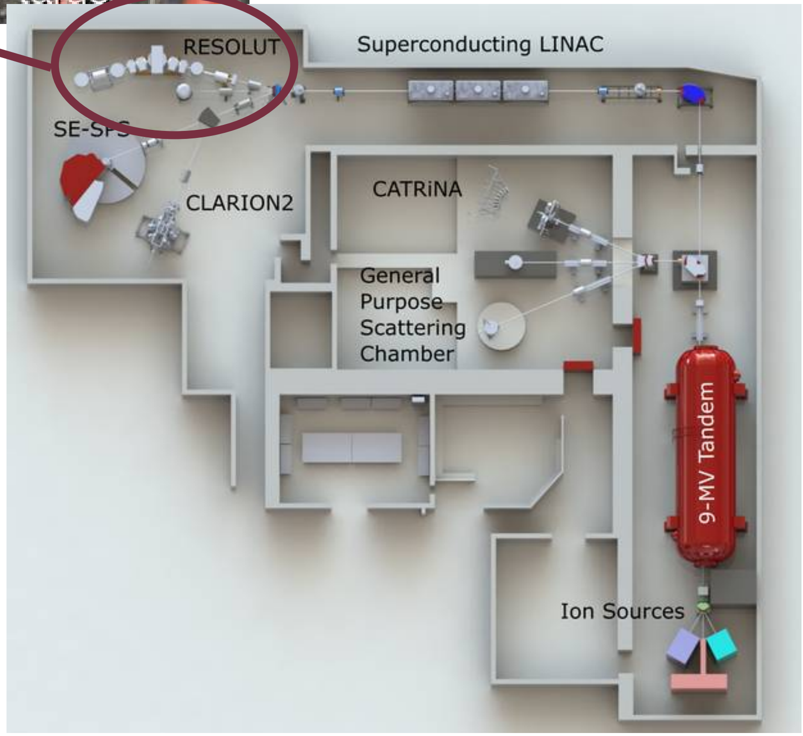




RESOLUT: a radioactive beam facility at Foxlab







In-flight production of radioactive beams in inverse kinematics,

^{7}Li(d,^{3}He) ^{6}He	18-29 MeV	~1· 10^{4} pps (40% pure)
^{7}Li(p,n) ^{7}Be	25-35 MeV	~2· 10^{5} pps (80% pure)
^{7}Li(d,p)^{8}Li	20-30 MeV	~5 · 10^{4} pps(90% pure)
^{7}Li(^{3}He,n)^{9}B	30-45 MeV	~1 · 10^{4} pps(10% pure)
^{9}Be(d,p)^{10}Be	45 MeV	~6· 10^{3} pps (60% pure)
^{18}O(d,n)^{17}F	80 MeV	~2 · 10^{5} pps (80% pure)
^{18}O(d,p)^{19}O	95 MeV	~5 · 10^{4} pps (90% pure)
^{18}O(^{3}He,n)^{18}Ne	70 MeV	~2· 10^{4} pps (25% pure)
^{24}Mg(d,n)^{25}Al	98 MeV	~2· 10^{4} pps (35% pure)

Beams are “purified” off-line by tracking / rf-correlations

Topic 1:
Measurement of the $^{25}Al(d, n)^{26}Si$ reaction and impact on the $^{25}Al(p, \gamma)^{26}Si$ reaction rate

E. Temanson, J. Baker, S. Kuvin, K. Hanselman, G. W. McCann, L. T. Baby, A. Volya, P. Höflich, and I. Wiedenhöver
Rev Phys. Rev. C 108, 065804 (2023)

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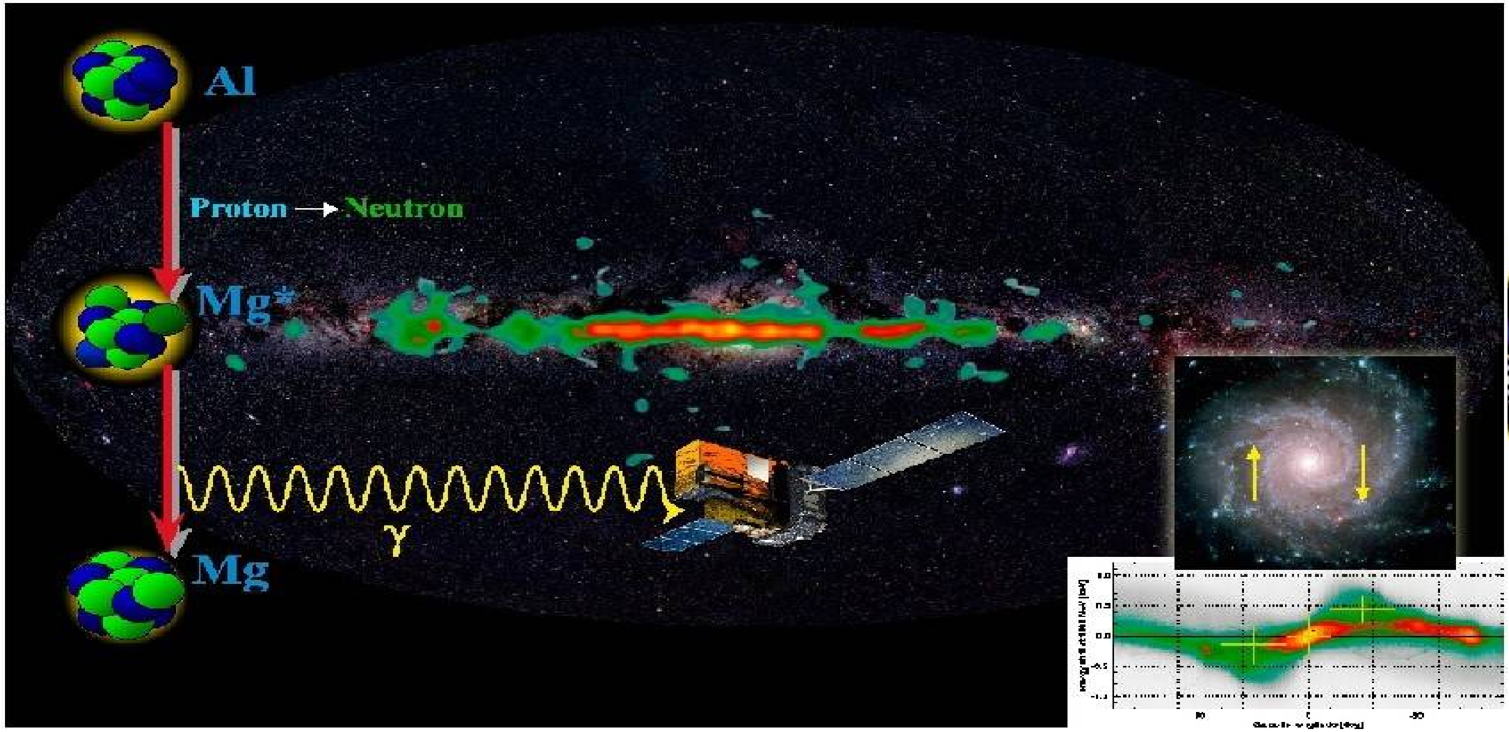
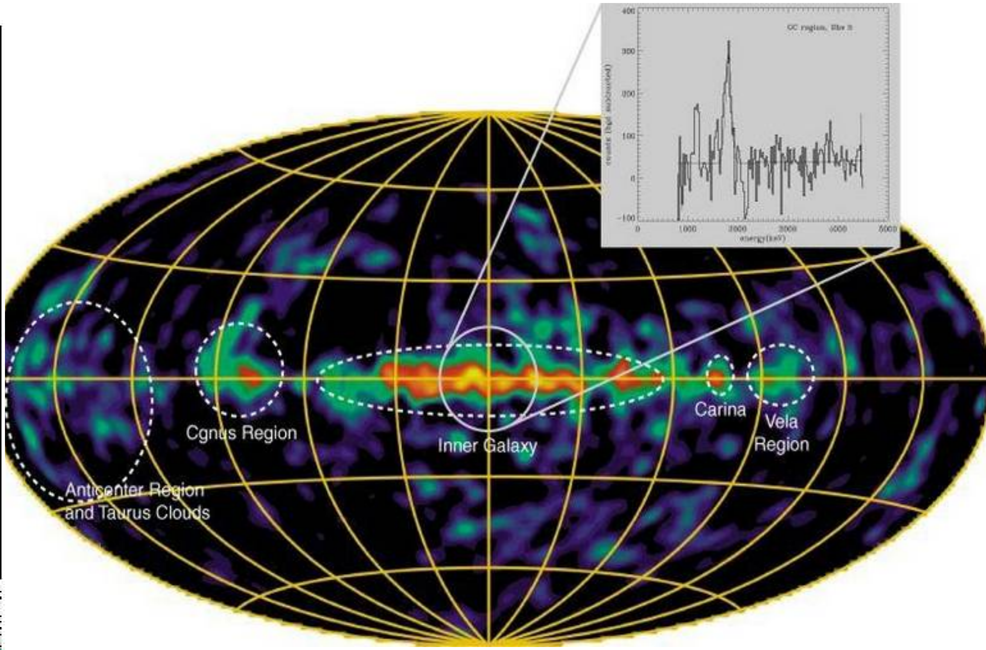
Galactic ^{26}Al- decay Activity

Roland Diehl et al.: nature 439,45 (2006) Wang et al. A&A 496 (2009)

FSU





- Observation: total of ~2M⊙ of ^{26}Al in the galaxy, $T_{1/2}$ = 0.72 Myr, effect of ongoing nucleosynthesis
- Spatial distribution: massive star origin, Type II SNe: Do other sources contribute ?

Why study ^{26}Si -Resonances ?

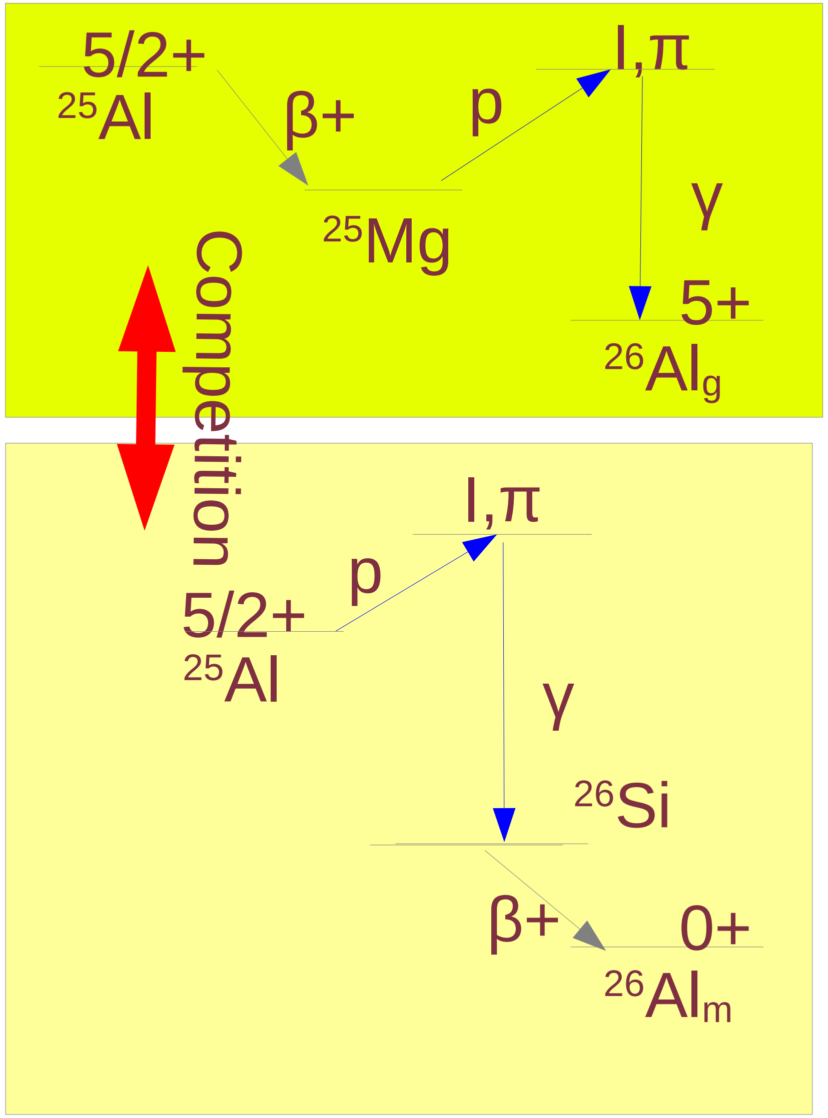
- $^{26}Al_{gs}$ emits β-delayed 1808 keV γ: observation with Comptel, Integral
- Assume production starts with ^{25}Al

Path 1) $^{25}Al \xrightarrow{\beta} {}^{25}Mg\,(p,\gamma){}^{26}Al_{gs}\,(5^+, T \xrightarrow{\beta} =0) \xrightarrow{\beta} {}^{26}Mg + \gamma$

in competition with

Path 2) $^{25}Al\,(p,\gamma)\,{}^{26}Si \xrightarrow{\beta} {}^{26}Al_m\,(0^+, T=1) \xrightarrow{\beta} {}^{26}Mg(0^+)$

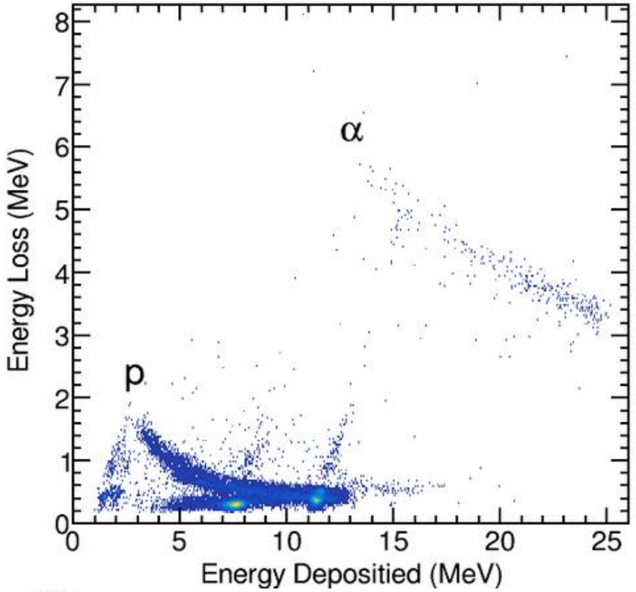
- $^{26}Al_m$, does not emit 1808 keV γ, Path 2 effectively by-passes the gamma-ray signal
- In order to quantify the ^{25}Al (p,γ) reaction rate, ne needs to study energy of ^{25}Al x p(l=0) resonances in ^{26}Si

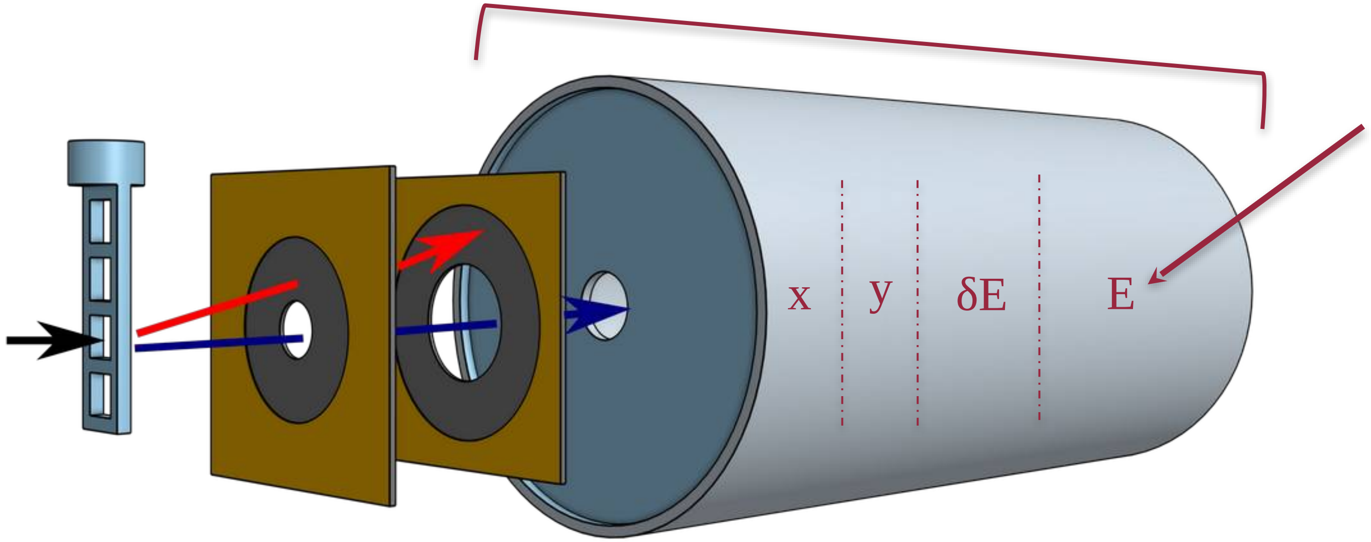


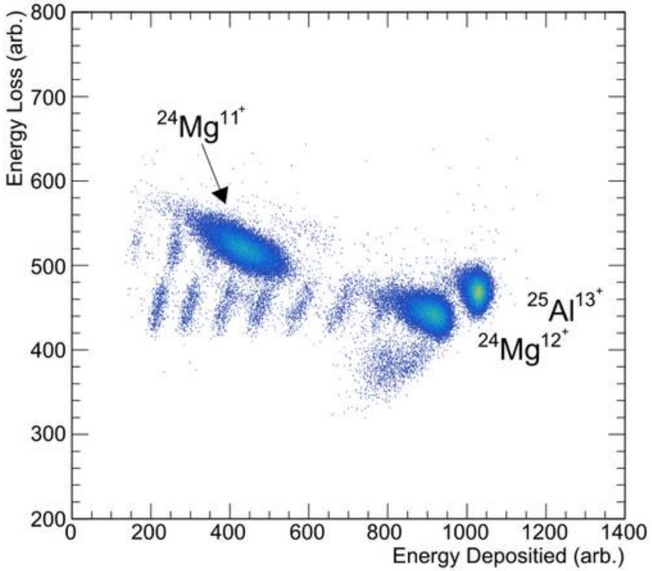
Exp. Setup – Ion Chamber & Silicon-Telescope

Radioactive ^{25}Al beam
at FSU's RESOLUT facility:

- Beam production: ^{24}Mg(d,n)^{25}Al
  ^{25}Al ~7500 pps, 25% purity
- Detect p+^{25}Al coincidences in ^{25}Al(d,n)^{26}Si(p)^{25}Al
- Reconstruct ^{26}Si resonances from p+^{25}Al invariant mass.







Resonance Spectrum from p+^{25}Al Invariant Mass Reconstruction

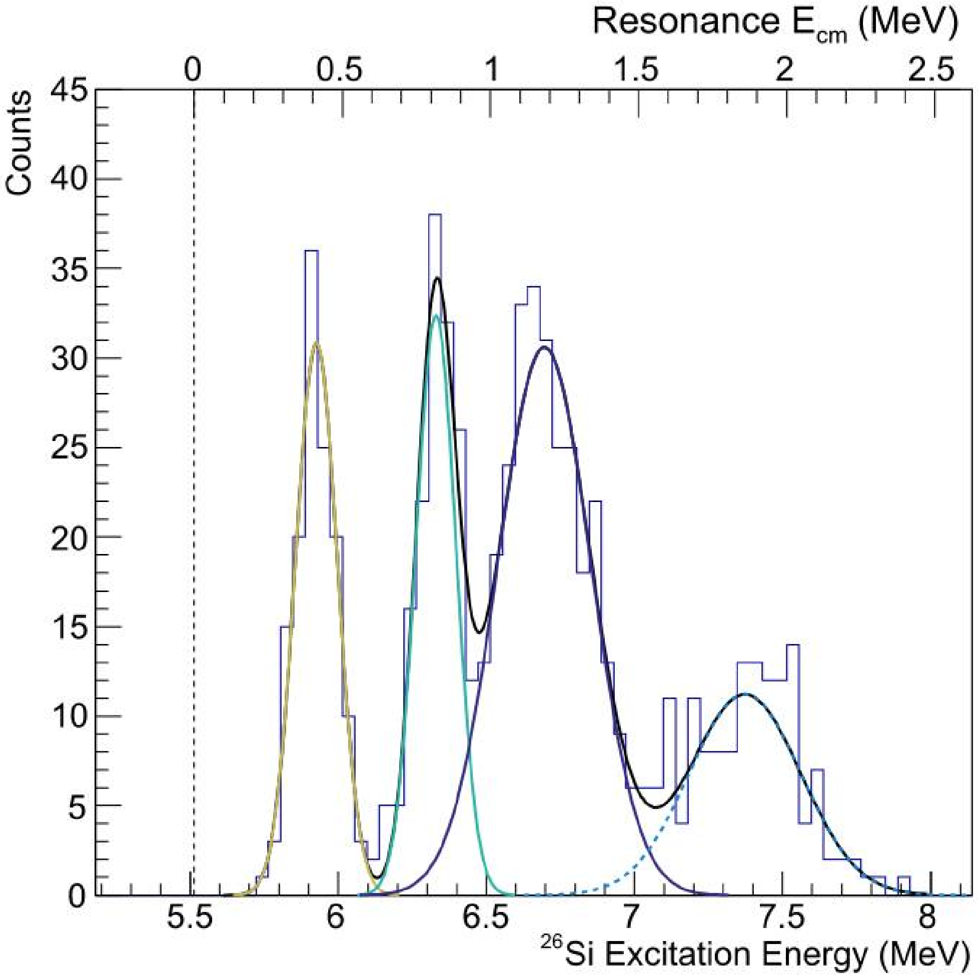


TABLE I. ^{26}Si excited states observed in ^{26}Si through the ^{25}Al(d,n)^{26}Si reaction, with the corresponding cross sections.

E_x (MeV)	Adopted E_x [a] (MeV)	$E_R^{c.m.}$ [a] (MeV)	J^π	$\sigma^{stat.}_{syst.}$ (mb)
5.92(2)	5.9294(8)	0.4154(8)	3_3^+	$5.83^{\pm 0.09}_{\pm 0.78}$
6.33(2)	6.2953(24)	0.7813(24)	2_6^+	$10.02^{\pm 0.09}_{\pm 1.42}$
	6.3827(29)	0.8687(29)	2_7^+	
6.70(2)	6.787(4)	1.273(4)	3_1^-	$30.12^{\pm 0.06}_{\pm 4.26}$

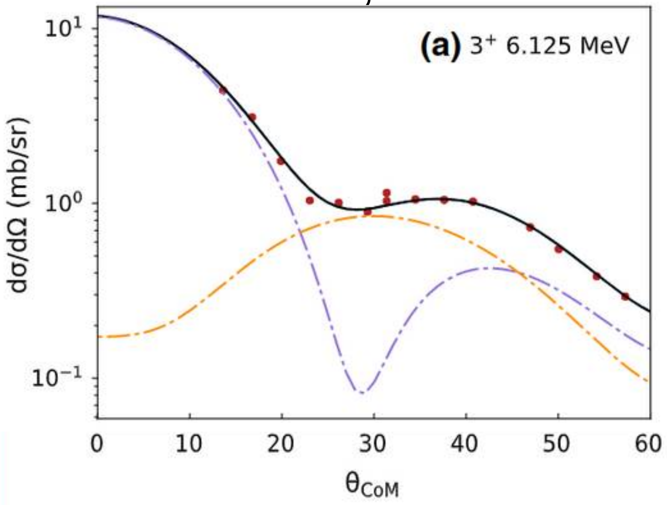
[a] Nuclear data reference [22, 23]

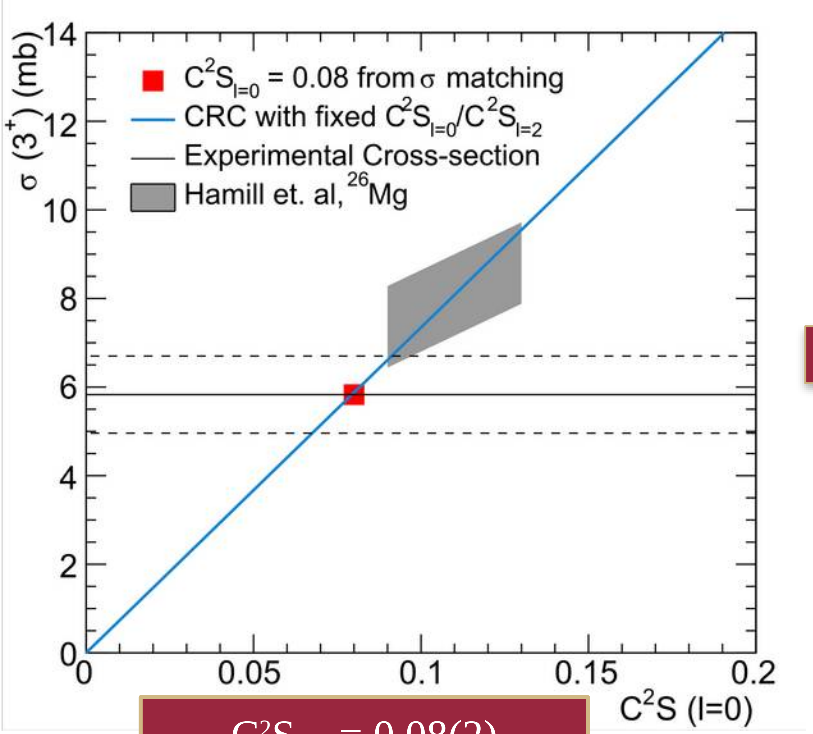
$$\vec{p}(^{26}Si^*) = \vec{p}(proton) + \vec{p}(^{25}Al)$$

$$E_x = M(\vec{p}(^{26}Si^*)) - M^{rest}(^{26}Si)$$

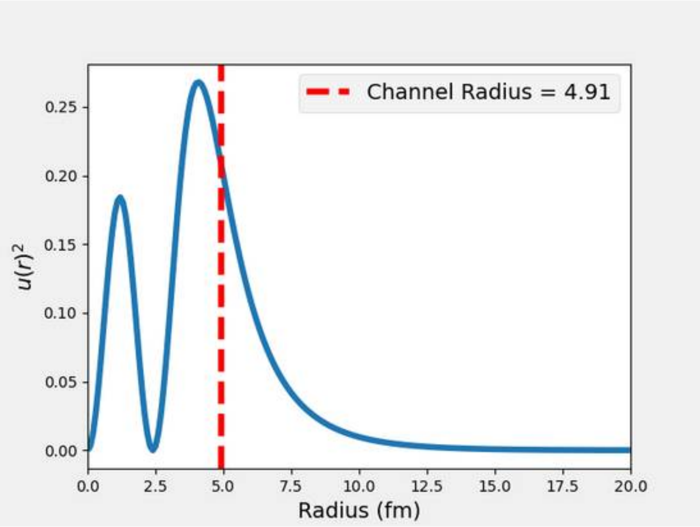
Extraction of the 3+ Proton Width:
Combine with information from Mirror Reaction $^{25}Mg(d,p)^{26}Mg$

TUNL Work,
R. Longland group
C. B. Hamill, 2020





$$\Gamma_p = C^2S_{l=0}\Gamma_{s.p.} = C^2S_{l=0}\frac{\hbar^2 P_c}{\mu r_c}u^2(r_c)$$



$C^2S_{l=0} = 0.11(2)$
$C^2S_{l=2} = 0.27(6)$

$C^2S_{l=0} = 0.08(2)$
$C^2S_{l=2} = 0.20(4)$

$\Gamma_p = 2.2\ (6)$ eV

Take spectroscopic factors from mirror reaction Hamill *et al.* (2020),
scale down to match experimental cross section.
l=0 spectroscopic factor is applied to barrier penetration calculation: $\Gamma_p = 2.2(6)$ eV

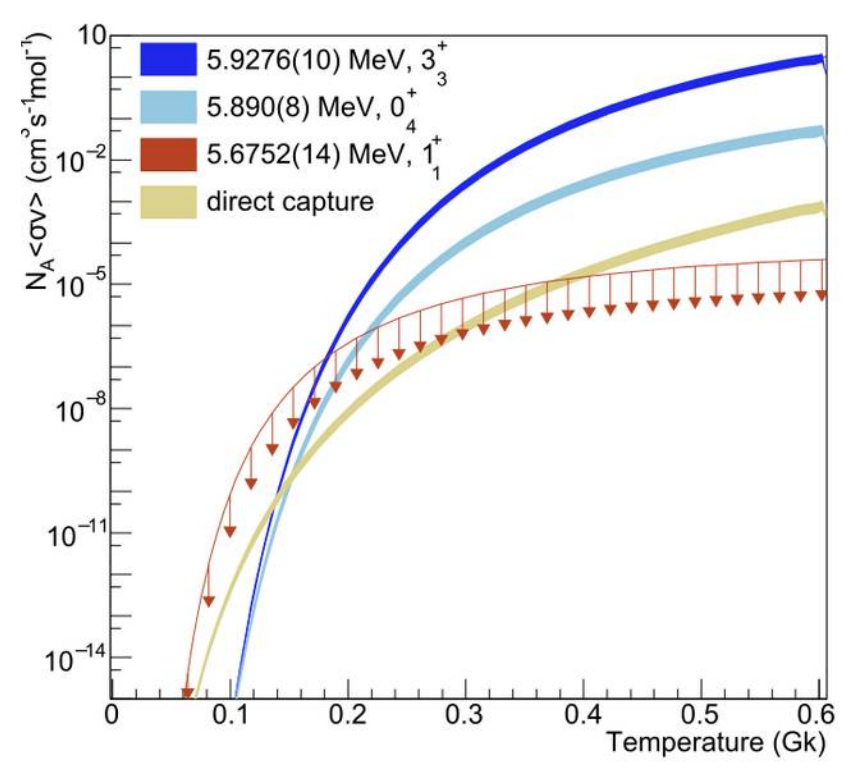
Thermal Reaction Rate Extraction

Three ingredients:
1) Cross section from RIB ^{25}Al(d,n)^{26}Si
2) & Relative $C^2S(l=0)$ / $C^2S(l=2)$ => Γ_p
3) & Branching Ratio from *Liang et al.*: Γ_γ
Extract resonance strength and calculate ^{25}Al(p,γ) reaction rate

$$N_A\langle\sigma\nu\rangle_r = \frac{1.5399\times10^{11}}{(\mu T_9)^{3/2}}\sum_i(\omega\gamma)_i\, e^{-11.605E^{c.m.}_{Ri}/T_9}$$

TABLE II. Parameters of the most important proton resonances in ^{26}Si with reference sources. The values of the underlined references were used in the reaction rate calculations (See Fig. 6 and Fig. 7)

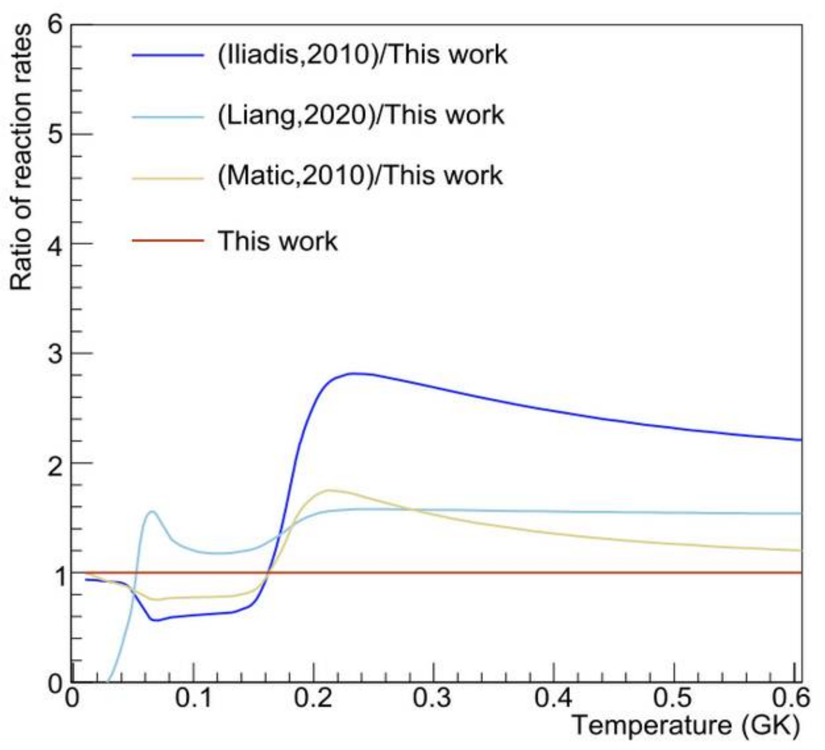
J^π	Reference	$E_R^{c.m.}$ (MeV)	C^2S	Γ_p (eV)	Γ_γ/Γ_p	Γ_γ (eV)	$\omega\gamma$ (meV)
1_1^+	Hamill *et al.* [13]	0.1622(3)[a]	$< 5.70\times10^{-3}$	$< 8.90\times10^{-9}$		0.12[b]	$< 2.60\times10^{-6}$
0_4^+	Hamill *et al.* [13]	0.3761(3)[a]	0.042(10)	0.0042		0.0088[b]	0.24
0_4^+	Perello *et al.* [11]	0.375(2)		0.0042		0.0075[c]	0.22
3_3^+	Bennett *et al.* [18]	0.4149(15)		2.9(10)[d]	0.014(9)[e]	0.040(30)	23(17)
3_3^+	Hamill *et al.* [13]	0.4154(8)[a]	0.11(2), 0.27(6)	2.9(10)[d]	0.014(9)	0.040[g]	23[g]
3_3^+	Liang *et al.* [19]	0.4124(19)[f]		2.9(10)[d]	0.0207(75)	0.060(30)	34(17)
3_3^+	Perello *et al.* [11]	0.4138(11)		2.9(10)[d]	0.025(14)	0.071(32)	40(17)
3_3^+	This work	0.4154(8)[a]	0.08(2), 0.20(4)	2.2(6)	0.021(8)	0.046(20)	26(7)



Thermal Reaction Rate Calculation

Three ingredients:
1) Cross section from RIB ^{25}Al(d,n)^{26}Si
2) & Relative $C^2S(l=0)$ / $C^2S(l=2)$ => Γ_p
3) & Branching Ratio from *Liang et al.*: Γ_γ
Extract resonance strength and calculate ^{25}Al(p,γ) reaction rate

$$N_A\langle\sigma\nu\rangle_r = \frac{1.5399\times10^{11}}{(\mu T_9)^{3/2}}\sum_i(\omega\gamma)_i e^{-11.605E_{Ri}^{c.m.}/T_9}$$



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3_3^+	This work	0.4154(8)[a]	0.08(2), 0.20(4)	2.2(6)	0.021(8)	0.046(20)	26(7)

Topic 2:

Observation of a Near-Threshold Proton Resonance in ^{11}B

Study of alpha-resonances in ^{11} B via the ^{7}Li(^{7}Li, t) reaction

E. Lopez-Saavedra, S. Almaraz-Calderon, B.W. Asher, L.T. Baby, N. Gerken, K. Hanselman, K.W. Kemper, A.N. Kuchera, A.B. Morelock, J. Perello, E.S. Temanson, A. Volya, and I. Wiedenhöver

Phys. Rev. Lett. 129, 012502 (2022)

E. Lopez-Saavedra, S. Almaraz-Calderon, K. W. Kemper , R. Aggarwal , S. Ajayi , L. T. Baby, C. Benetti, A. L. Conley, J. Esparza, D. Houlihan, B. Kelly, G. W. McCann, A. B. Morelock, V. Sitaraman , E. Temanson , M. Wheeler, I. Wiedenhöver, C. Wibisono, A. N. Kuchera, and G. Ryan

Phys. Rev. C 112, 024324 (2025)

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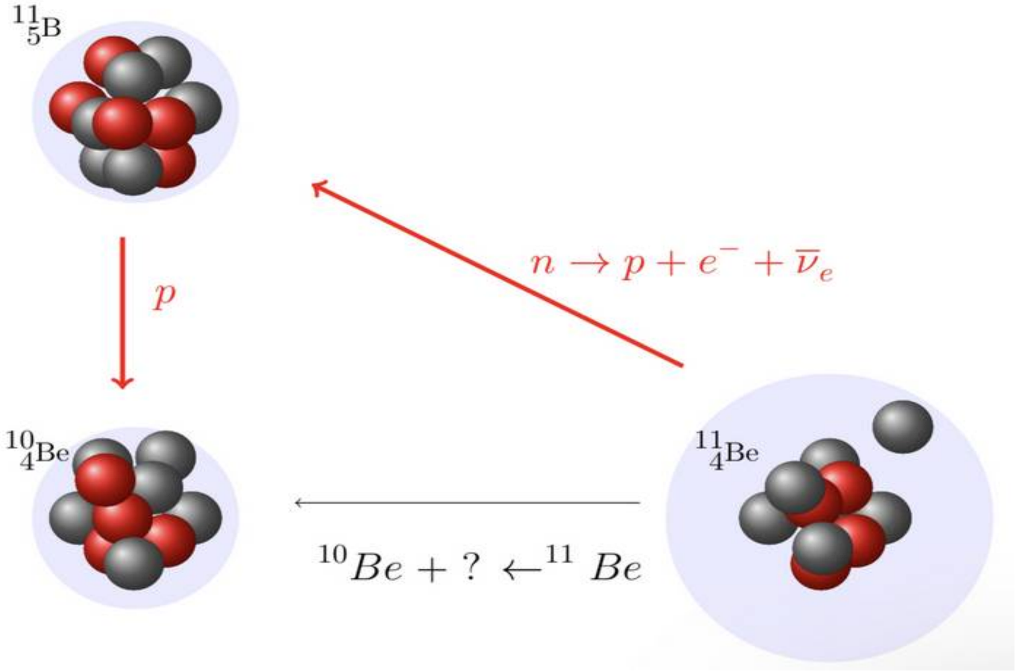
A puzzling exotic decay of ^{11}Be

Rijsager *et al*: A surprisingly high branching ratio of the ^{11}Be → ^{10}Be decay was observed:

β-delayed proton decay in neutron rich nucleus ?

quasi-free neutron decay ?

Or decay of ^{11}Be into ^{10}Be, mediated by a 'dark' particle ?



ELSEVIER
Physics Letters B
Volume 732, 1 May 2014, Pages 305-308

^{11}Be(βp), a quasi-free neutron decay?

K. Riisager [a], O. Forstner [b c], M.J.G. Borge [d e], J.A. Briz [e], M. Carmona-Gallardo [e], L.M. Fraile [f], H.O.U. Fynbo [a], T. Giles [g], A. Gottberg [e g], A. Heinz [h], J.G. Johansen [a 1], B. Jonson [h], J. Kurcewicz [d], M.V. Lund [a], T. Nilsson [h], G. Nyman [h], E. Rapisarda [d], P. Steier [b], O. Tengblad [e], R. Thies [h]...
S.R. Winkler [b]

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Editors' Suggestion

Direct Observation of Proton Emission in ^{11}Be

Y. Ayyad *et al.*
Phys. Rev. Lett. **123**, 082501 – Published 22 August 2019; Erratum Phys. Rev. Lett. **124**, 129902 (2020)

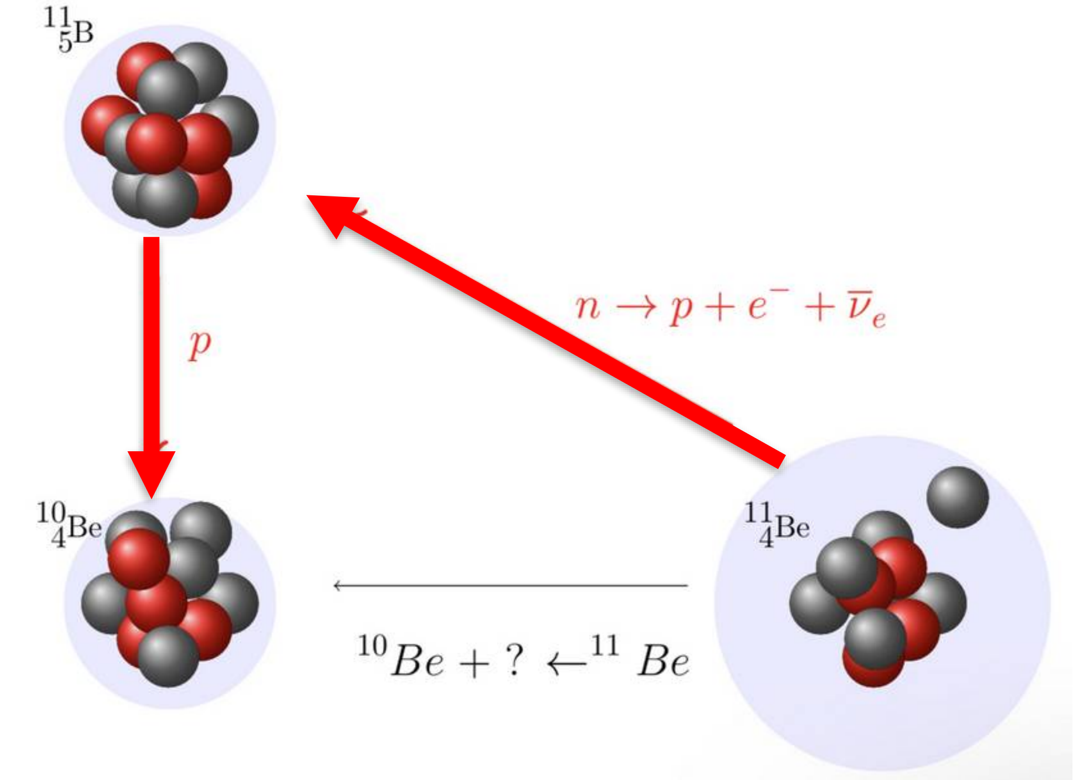
Eur. Phys. J. A (2020) 56:100
https://doi.org/10.1140/epja/s10050-020-00110-2
THE EUROPEAN PHYSICAL JOURNAL A
Check for updates
Regular Article - Experimental Physics

Search for beta-delayed proton emission from ^{11}Be

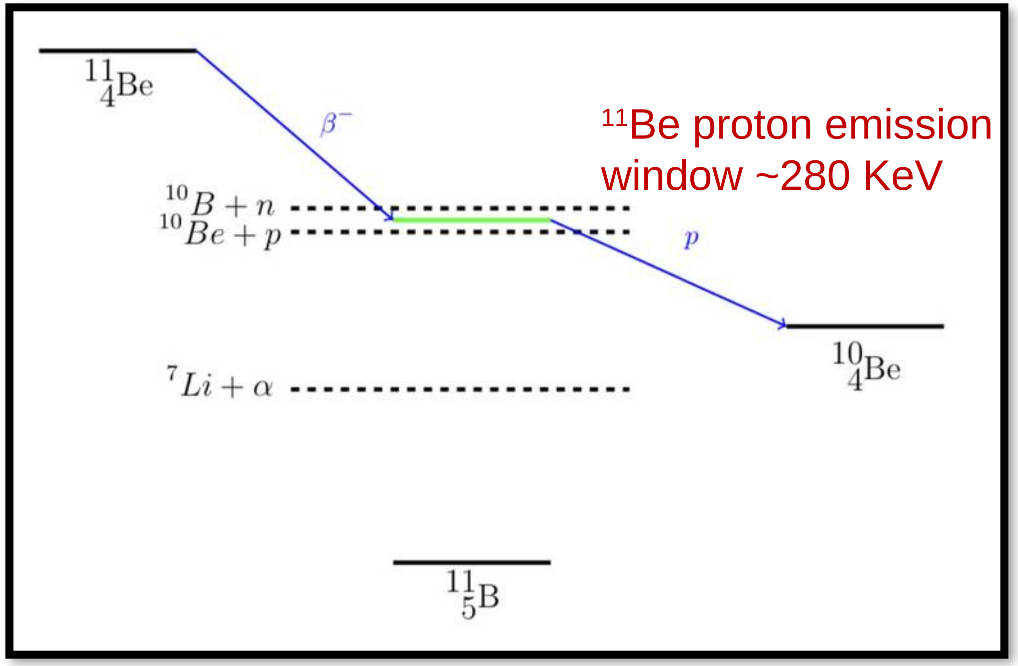
K. Riisager[1,a], M. J. G. Borge[2,3], J. A. Briz[3], M. Carmona-Gallardo[4], O. Forstner[5], L. M. Fraile[4], H. O. U. Fynbo[1], A. Garzon Camacho[3], J. G. Johansen[1], B. Jonson[6], M. V. Lund[1], J. Lachner[5], M. Madurga[2], S. Merchel[7], E. Nacher[3], T. Nilsson[6], P. Steier[5], O. Tengblad[3], V. Vedia[4]

A puzzling exotic decay of ^{11}Be

The non-exotic path from ^{11}Be to ^{10}Be



Resonant enhancement through a narrow state in ^{11}B

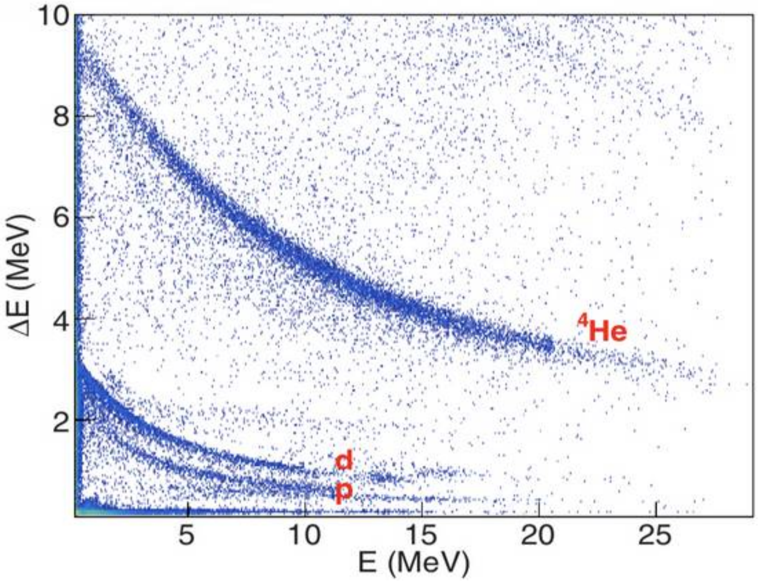


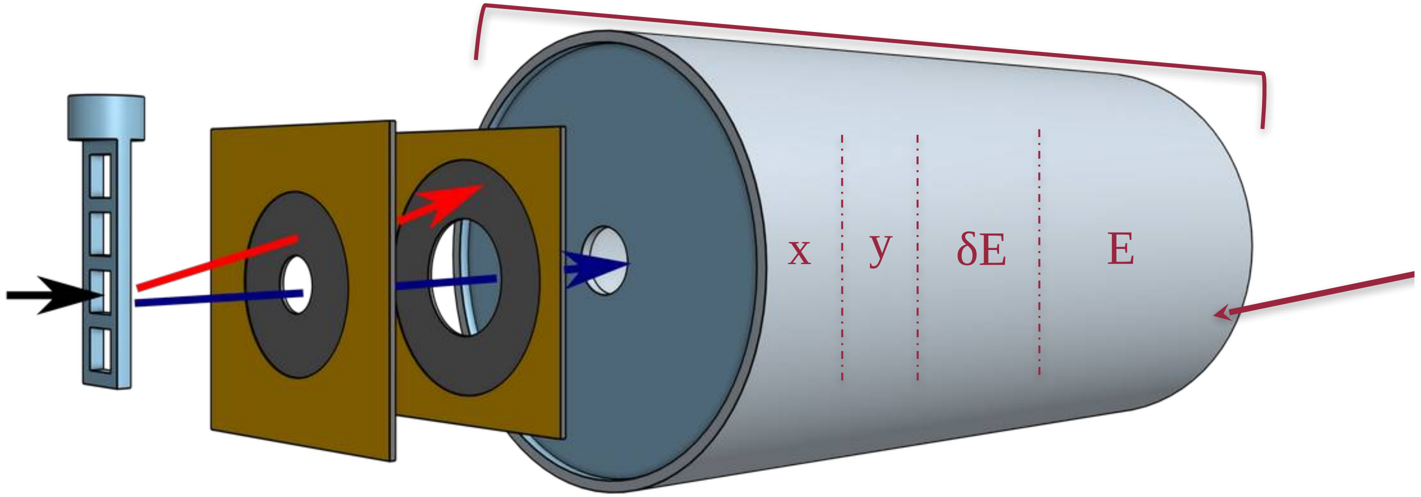
The large decay branching ratio ^{11}Be-> ^{10}Be can not be explained easily:
A strong and unobserved, near-threshold proton resonance in ^{11}B would be needed, inside a very narrow energy window

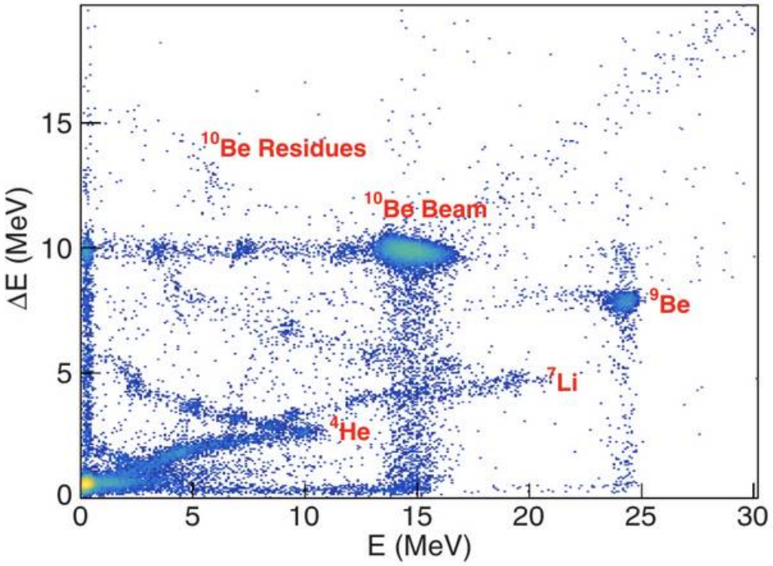
Exp. Setup – Ion Chamber & Silicon-Telescope

Radioactive ^{10}Be beam
at FSU's RESOLUT facility:

- Beam production: ^{9}Be(d,p)^{10}Be
  ^{10}Be ~6000 pps, 60% purity
- Detect p+^{10}Be coincidences in ^{10}Be(d,n)^{11}B(p)^{10}Be
- Reconstruct ^{11}B resonances from p+^{10}Be invariant mass or α+^{7}Li invariant mass







A proton-resonance in ^{11}B

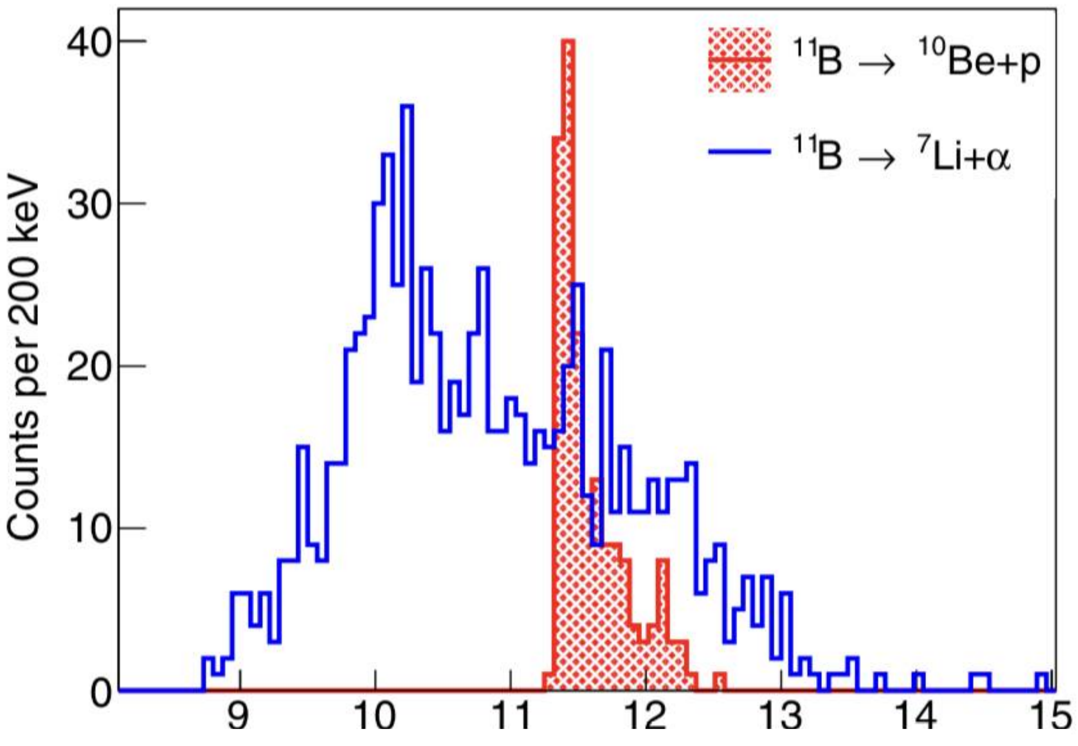
Reconstructed $^{11}B \rightarrow {}^{7}Li + \alpha$ spectrum:
Observation of the known resonances in ^{11}B

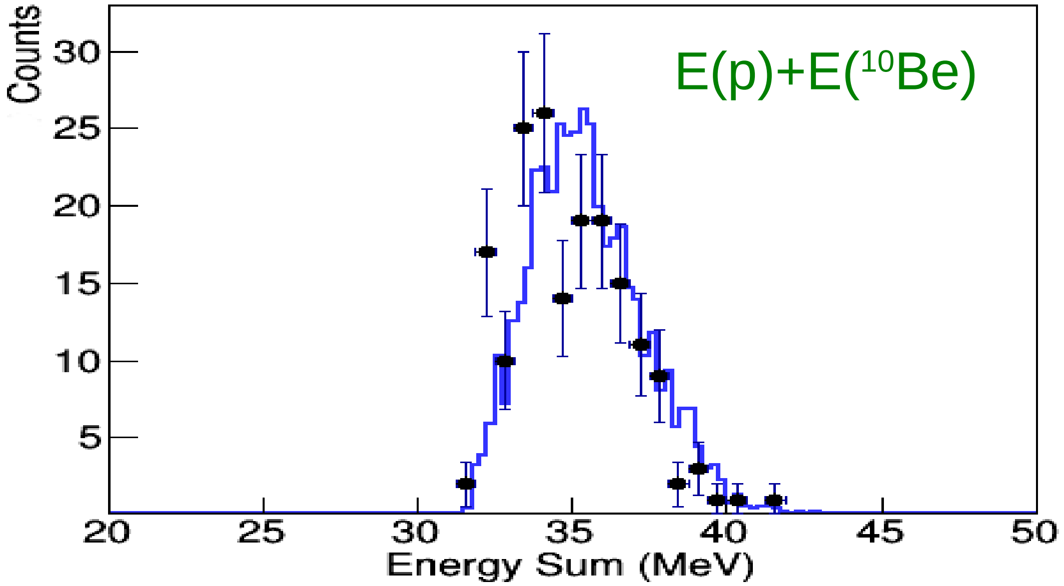
- Peak at E_{ex} = 11.46 MeV

Reconstructed $^{11}B \rightarrow {}^{10}Be+p$ spectrum:
Observation of a sharp proton resonance in ^{11}B at E_{res}=211(40) keV!

- $E_{ex} = 11.44 \pm 0.04$ MeV
- σ_{exp} = 9mb , Γ_{sp}=20 keV
- $C^2S \sim 0.27(6)$ (IF BR(p)=100%)
- Γ_p= 5.4 keV

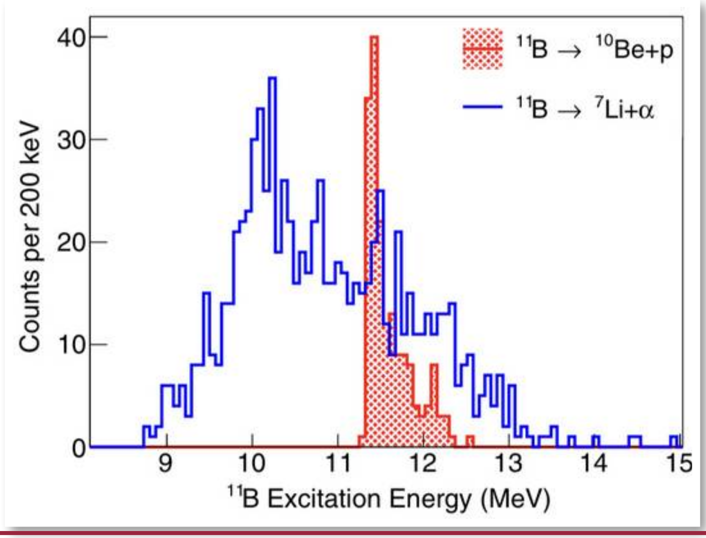
E(p)+E(^{10}Be):
Reconstruct "missing" n-energy=> n-angle
Monte-Carlo of DWBA:
J^{π} = (1/2+) to the state at E_{ex}=11.44(4) MeV.





FSU

The ^{11}B resonance at FSU



E_{ex} = 11.44 ± 0.04 MeV, J^π = (1/2+),
Γ_{sp}=20 keV, Γ_p= 5.4 keV

PHYSICAL REVIEW LETTERS **129,** 012502 (2022)

Observation of a Near-Threshold Proton Resonance in ^{11}B

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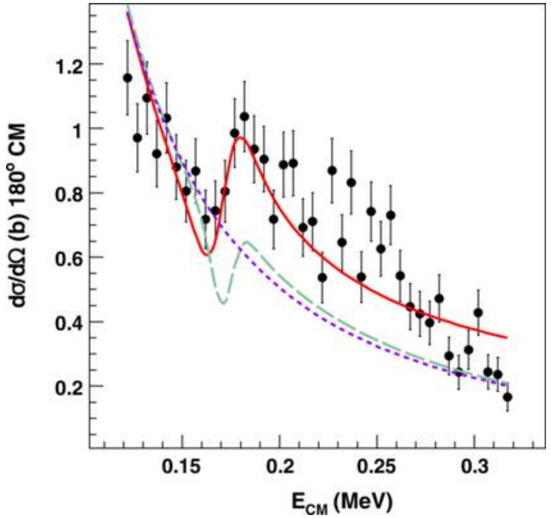
The ^{11}B resonance at MSU



$(E_x = 11.4\,\mathrm{MeV},\ J^\pi = 1/2^+$, and $\Gamma_p = 4.4\,\mathrm{keV})$

"R-matrix analysis shows a sizable partial decay width for both, proton and α (Γ_α ~ 11 keV) emission channels."

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Evidence of a Near-Threshold Resonance in ^{11}B Relevant to the β-Delayed Proton Emission of ^{11}Be

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Open Systems - Open Questions

- Does the near-proton threshold resonance have alpha strength?
- Are the appearance and properties of this resonance a threshold effect, a consequence of coupling with the continuum?

Clarification of large-strength transitions in the β decay of ^{11}Be

J. Refsgaard, J. Büscher, A. Arokiaraj, H. O. U. Fynbo, R. Raabe, and K. Riisager
Phys. Rev. C **99**, 044316 – Published 25 April 2019

LETTER • OPEN ACCESS

$\beta^{-}p$ and $\beta^{-}\alpha$ decay of the ^{11}Be neutron halo ground state

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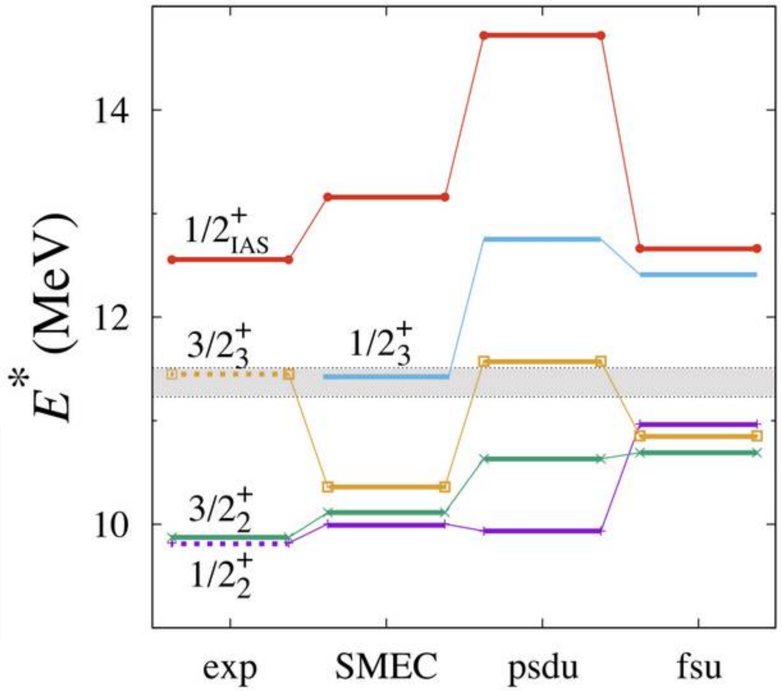
Journal of Physics G: Nuclear and Particle Physics, Volume 49, Number 10



High-resolution spectroscopy α-transfer → α-decay

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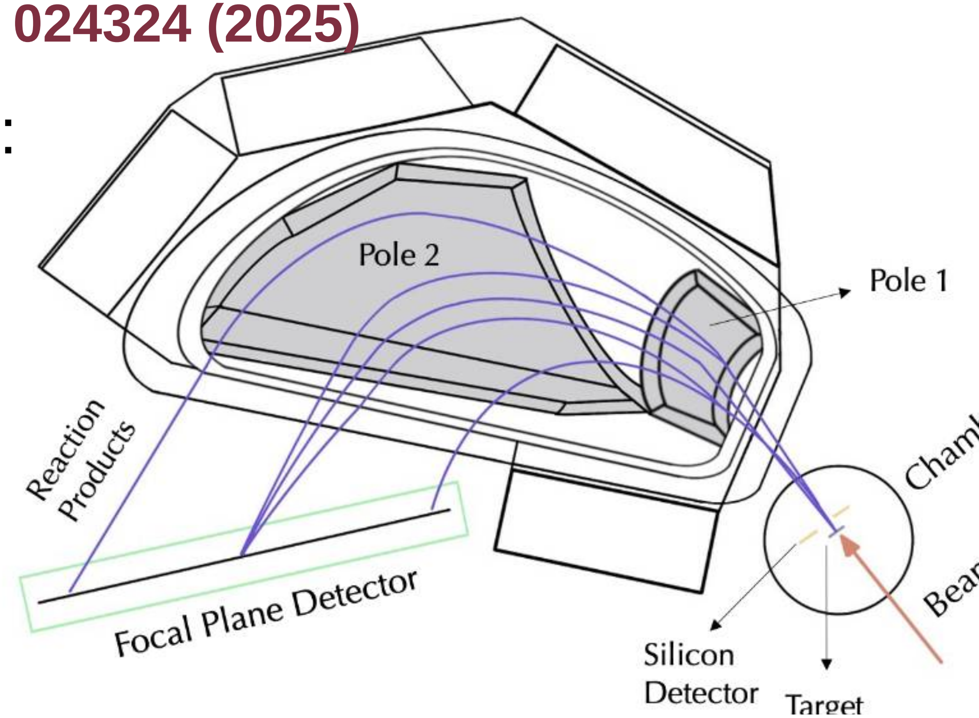
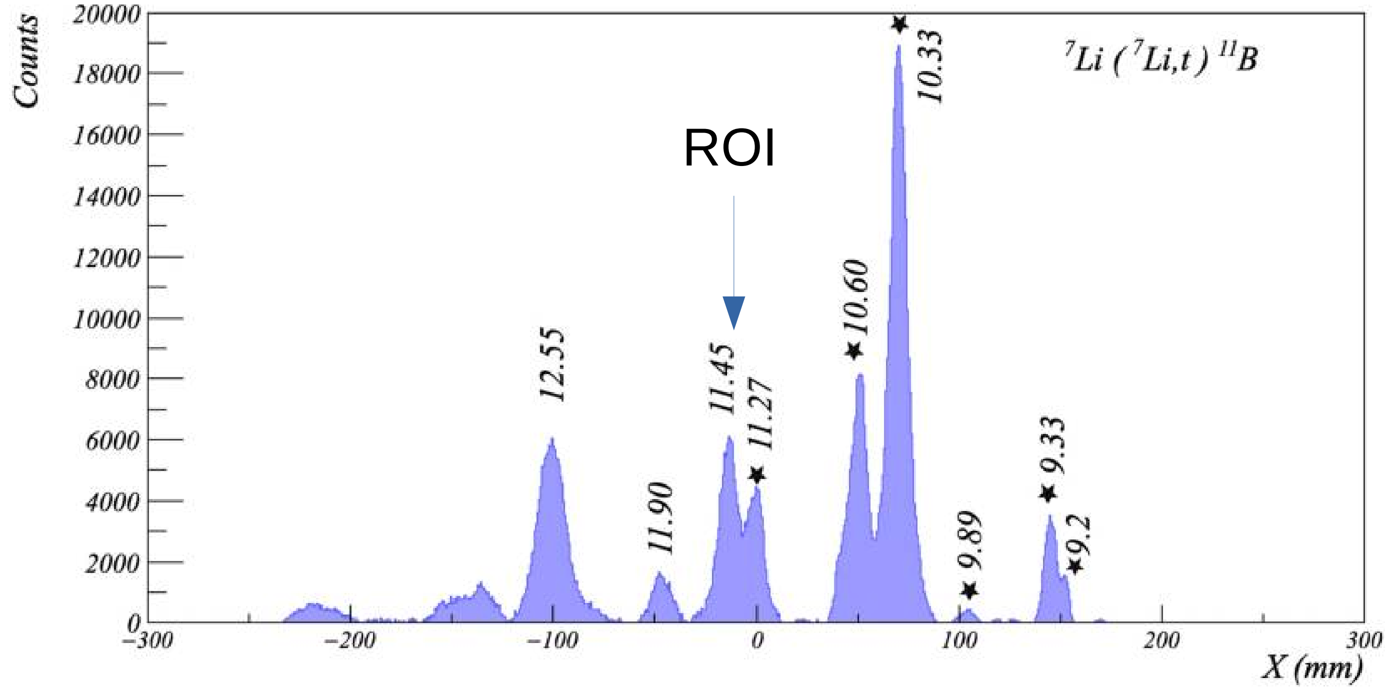
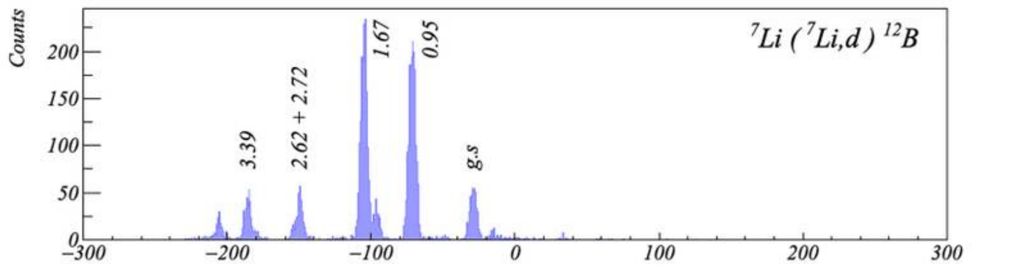
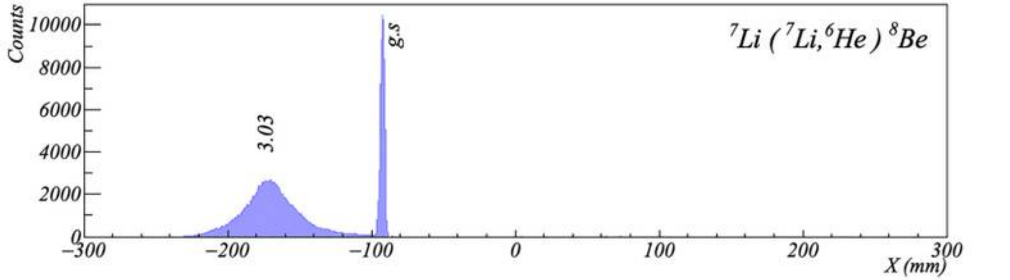
$^{7}Li(^{7}Li,t)^{11}B^{*} \rightarrow \alpha + ^{7}Li$ α-transfer measured at FSU:
Super-Enge Split-Pole Spectrograph (SPS)

- 100 μg/cm^2 metallic self-supporting ^{7}Li target
- Clean separation of different reactions
- ^{11}B region of interest (11.3-11.5 MeV) is complex









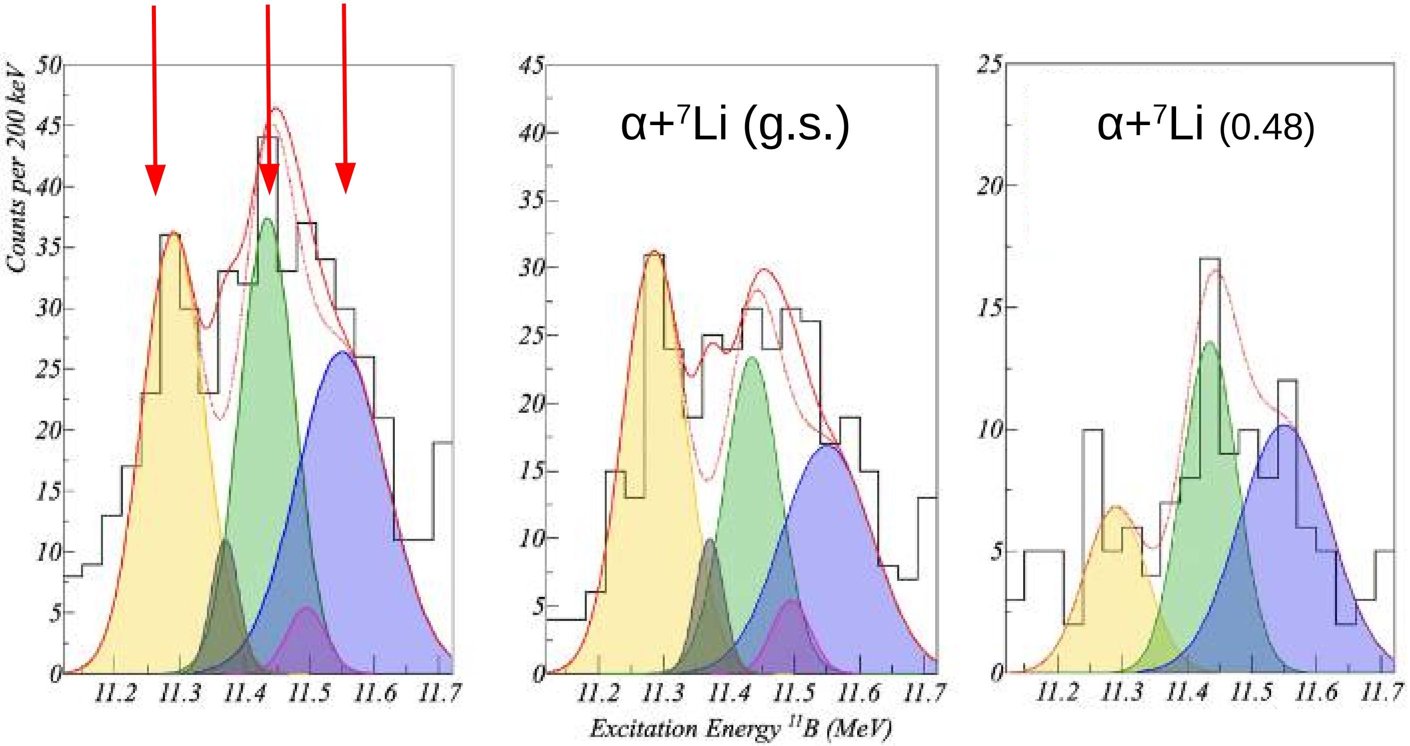
High-resolution spectroscopy α-transfer → α-decay

E. Lopez-Saavedra et al. PRC 112, 024324 (2025)

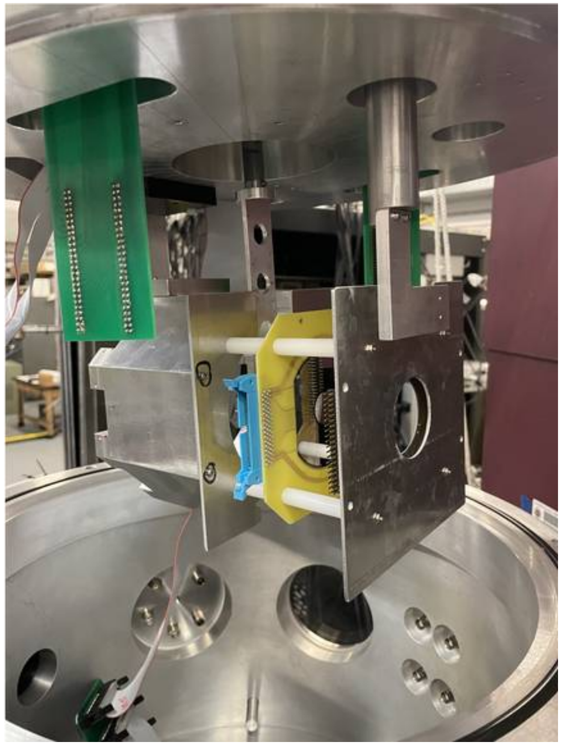
^{7}Li(^{7}Li,t)^{11}B*→α+^{7}Li α-transfer reaction & **α-decay in coincidence**

- Upper limit on α-decay width for 11.4 MeV resonance: Γ_α <11 keV
- Still consistent with Γ_α = 11(3) keV by Ayaad et al.
- The quest to characterize the 11.4 MeV proton-resonance continues.

3 known resonances, Γ_α
Cusson: Nucl. Phys. 86, 481 (1966)



Compact Silicon array



Summary

- The study of resonant states embedded in the continuum is central to Nuclear Astrophysics and Nuclear Structure science of exotic, nearly-unbound nuclei.
- The FSU laboratory has developed a suite of high-quality experimental tools for radioactive and high-quality stable beams to investigate this interface between “inside” and “outside” the nucleus.
- Things I learned from Robert along the way:
  If you want to advance science, make sure you master the craft.
  Be a specialist, but always strive to expand your tool-set.
  ”Fellowship”: If you want to lead people, you have to be close to them.
  Pursuing science is a privilege: Work hard.
- Robert made me (us) do it.