Lifetime measurements of the first excited states in ^{16}C and ^{18}N.

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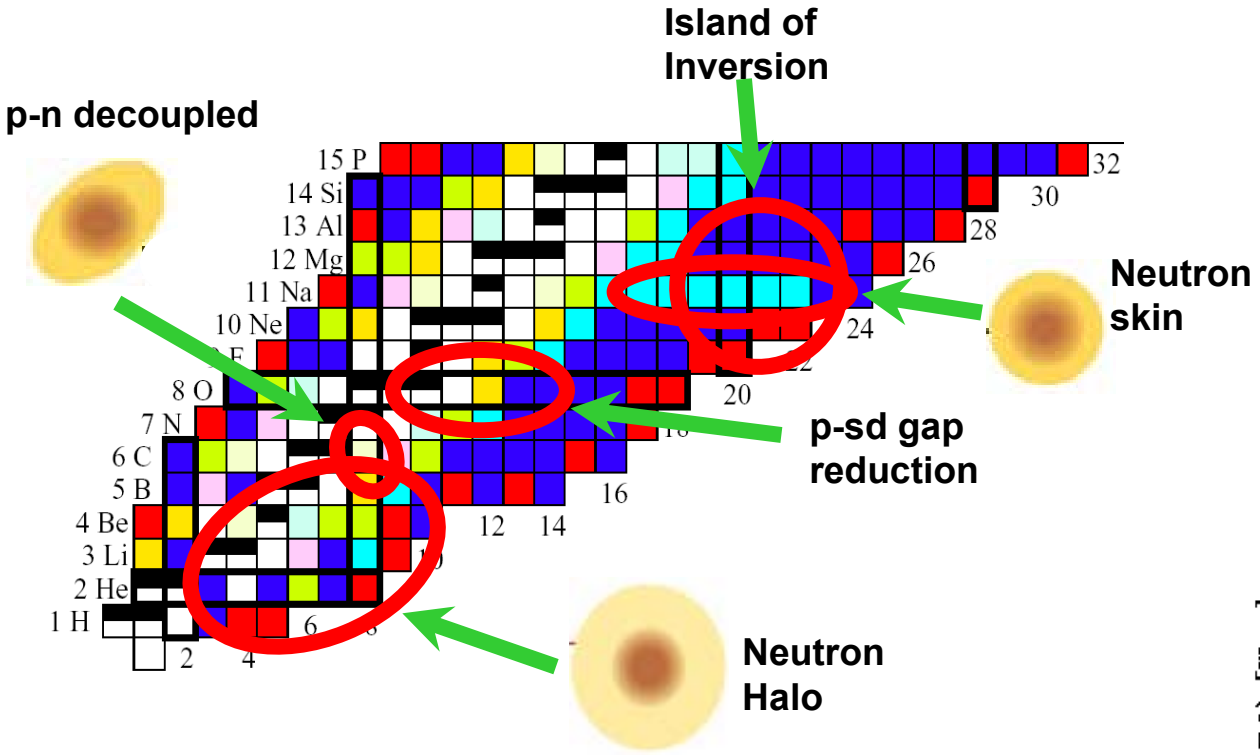
Outline

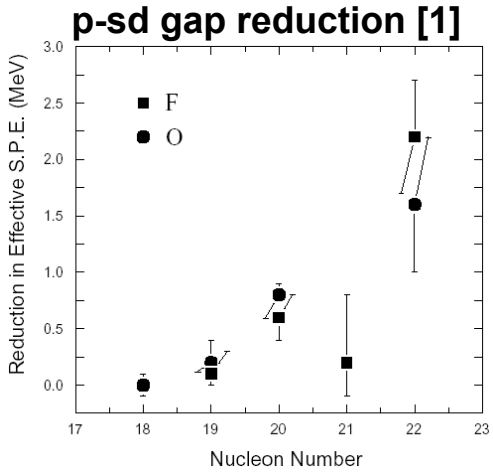
- **Why study light neutron-rich nuclei?**
- **2 charged particle evaporation program at LBNL.**
- **^{18}N:**

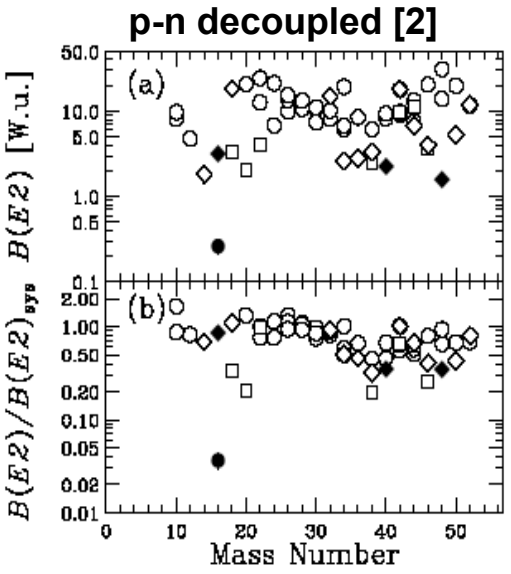
  Level structure and lifetime of first excited state. Ground-state spin inversion?
- **^{16}C:**

  Lifetime measurement of first excited state. Are the protons and neutrons decoupled?

Motivation: Recent results







Motivation: recent results on p-sd shell gap reduction and anomalous B(E2) value for first-excited 2^+ state in ^{16}C.

[1] M. Wiedeking et. al., Phys. Rev. Lett. **94**, 132501 (2005).

[2] N. Imai et. al., Phys. Rev. Lett. **92**, 062501 (2004).

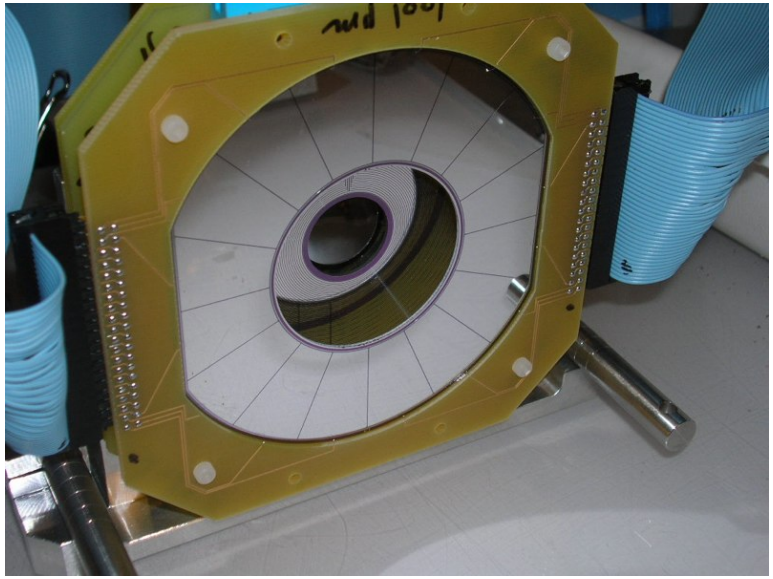
2 charged particle evaporation program at LBNL

- Initiated and developed a program at 88” cyclotron to study light neutron-rich p-sd shell nuclei
- These nuclei have previously been studied mainly by beta-decay and charge exchange reactions.
  → selective reaction mechanisms
- For a more complete picture need non-selective reaction.
  → fusion-evaporation reactions
- Stable beams and targets
  → low cross sections
- A key aspect is the detection and extraction of the 2 charged particle evaporation channel.
- Use **STARS-LIBERACE** detector array. Clover and Silicon detectors.

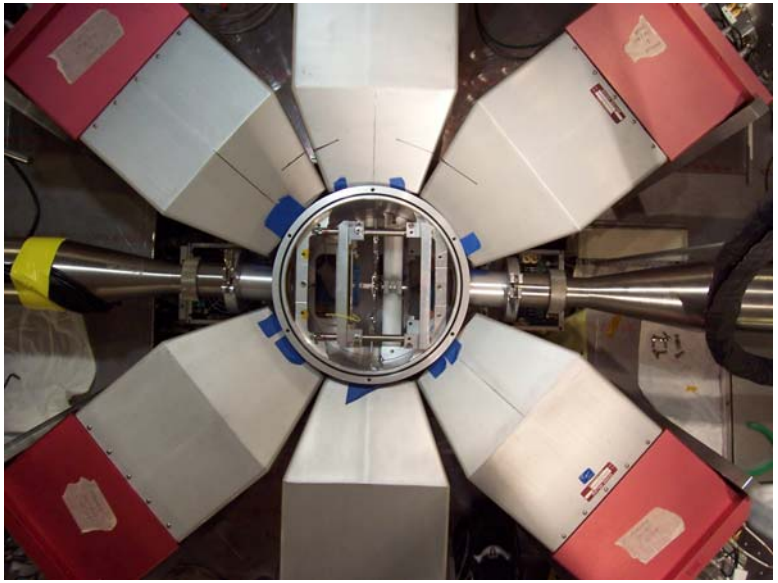
STARS-LIBERACE

Detector array: Collaboration between Livermore National Laboratory and Berkeley National Laboratory.

Charged particle detection with particle telescope ΔE-E.

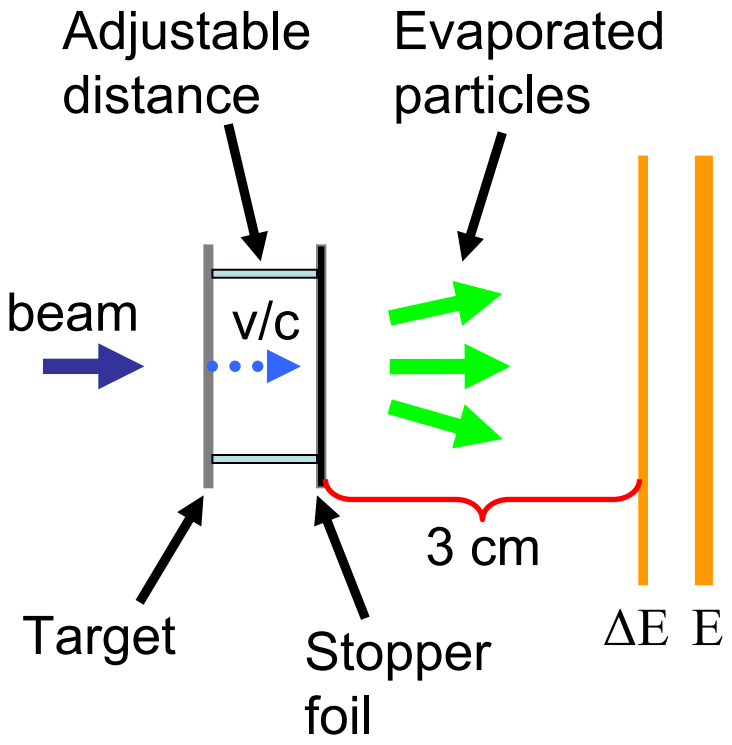


γ-radiation detected with Clover HPGe detectors.



Up and running for ~ 3 years with over 40 experiments to date.

Lifetime determination



- **Target thickness from α-energy loss.**
- **Adjustable distance: 0.08 to 3.0 mm.**
- **Recoil velocity from spectra.**
- **Recoil Distance Method.**
- **Use relation $N/N_0 = e^{-t/\tau}$**
  - **N = stopped**
  - **N_0 = stopped+moving**
  - **t = time for recoils to transverse gap**
  - **τ = mean lifetime**
- **Model independent τ.**
- **Use data from setup and measure previously known τ as internal calibration.**

Single particle motion: leads to shell structure and single-nucleon states.
M1 moments sensitive to single-particle effects.

Collective motion: deformation, vibration and rotational degrees of freedom.
E2 moments sensitive to collective effects

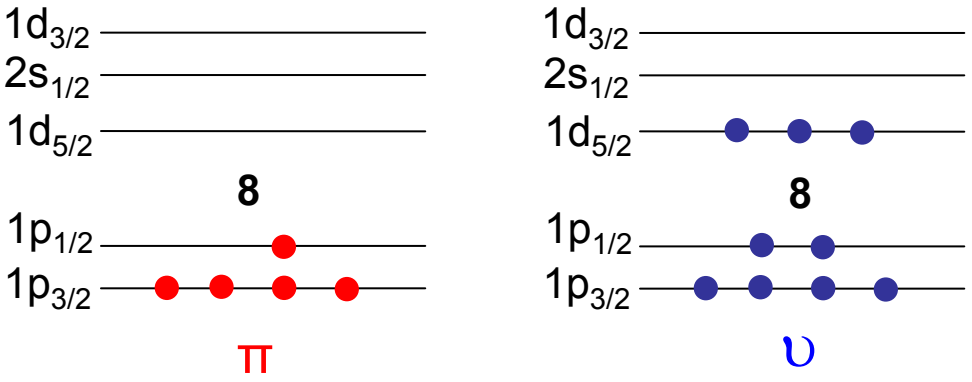
- Electric Quadrupole Transition Strength: $B(E2) \sim 1/(E_\gamma)^5 T_{1/2}$
- Magnetic Dipole Transition Strength: $B(M1) \sim 1/(E_\gamma)^3 T_{1/2}$

Reduced transition probability: $B(O_\lambda; I_i \rightarrow I_f) = (2I_i+1)^{-1} |\langle I_f || O_\lambda || I_i \rangle|^2$

^{18}N background

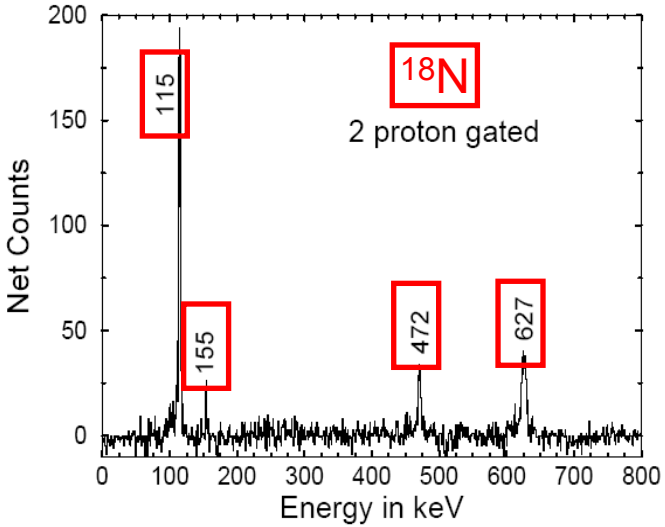
$T_z = 2$:
7 protons and 11 neutrons

$$\pi(p_{1/2})^1 \otimes \upsilon(d_{5/2})^3$$



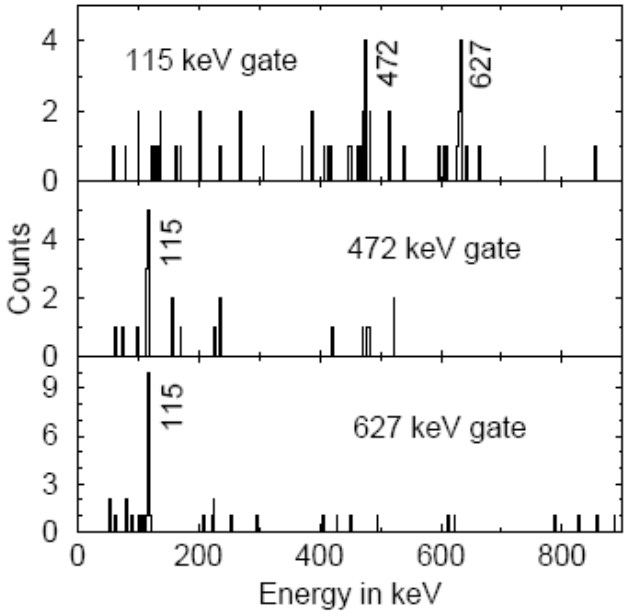
- **B(M1)** for first-excited state:
  - Shell model: **$B(M1)_{theory}$ = 0.054 W.u.** → $T_{1/2}$ = 0.3 ns.
  - Also from ^{19}O systematic (built on the same neutron configuration) expect **τ ~ 0.7 ns**.
- Measure τ and study **low-energy level structure**.
- ^{9}Be(^{11}B,2p)^{18}N @ 50 MeV.
- Plunger setup with 3 mm distance.
- STARS-LIBERACE detector array at LBNL.
- 5 Clovers at 40, 90 and 140 degrees.
- 150 μm ΔE detector and 1000 μm E detector telescope.

^{18}N Results



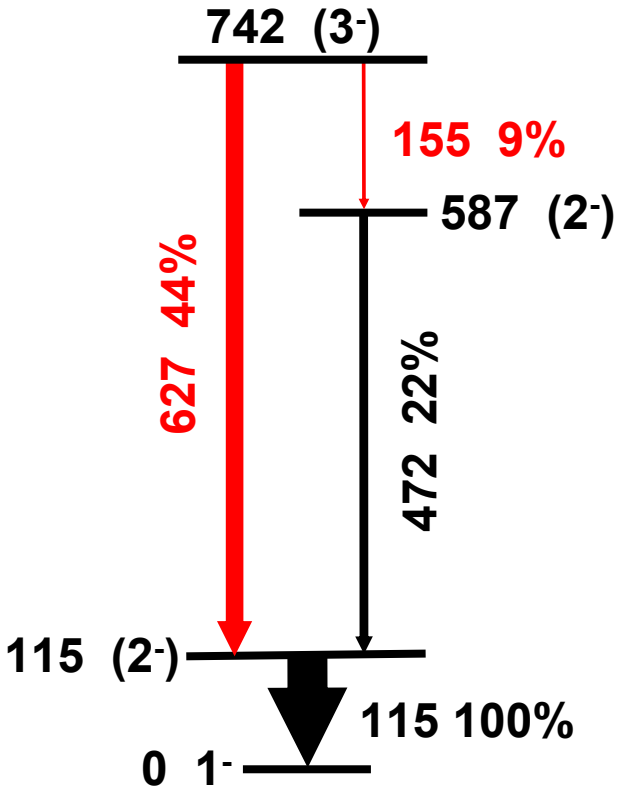
2 proton gate successfully extracts very weak channels.

9.3×10^{-4} %

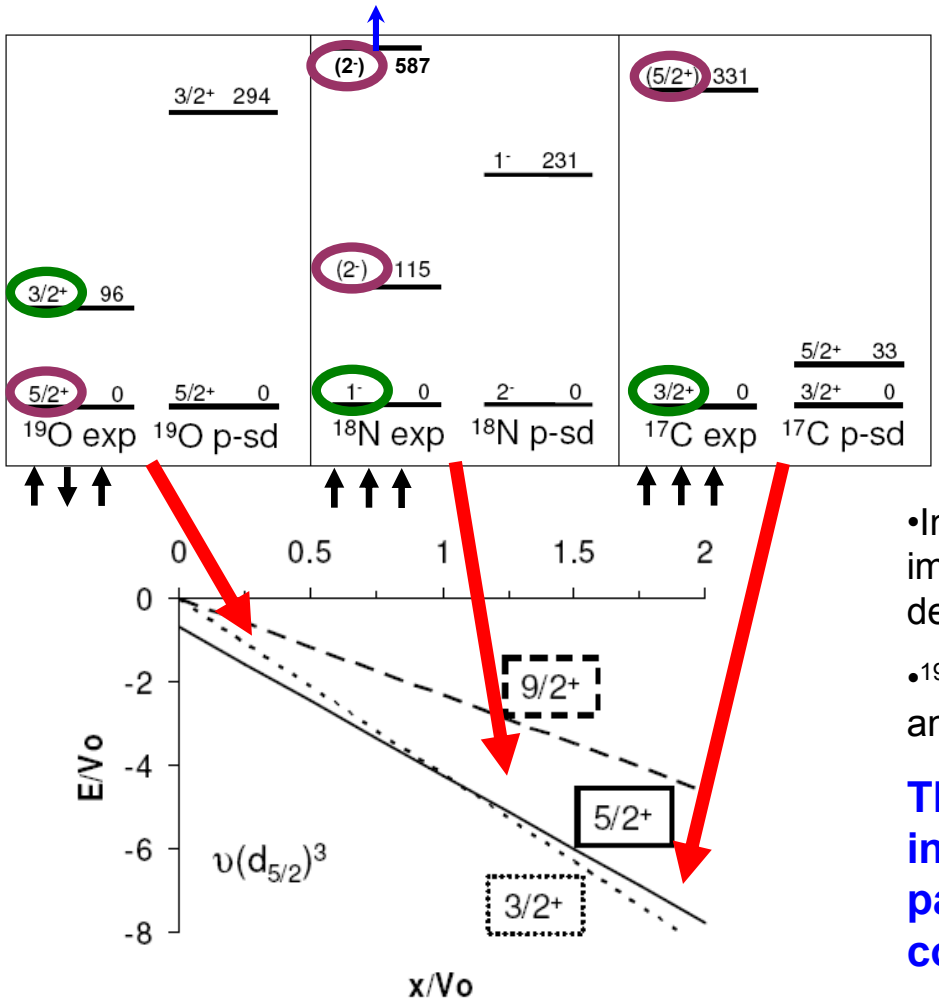


Coincidences established in ^{18}N for the first time.

^{18}N level scheme:



Ground-state spins and deformation



$$\text{P+Q: } E = V_0\,\delta_{(5/2,0)} + x\,P_2$$

N=11 isotones ^{17}C, ^{18}N, ^{19}O: Inversion from a paired to unpaired n coupling scheme due to p-n interaction (^{18}N transitional).

Shell model calculations from CoSMo [6] in p-sd model space.

Nature of second 2$^-$ state in ^{18}N?

- Increase in *x*/Vo corresponds to increasing importance of the Q interaction → increase in deformation.
- ^{19}O: $x/V_o < 1$ (paired, lower def.), ^{18}N with $x/V_o \sim 1$, and ^{17}C with $x/V_o > 1$ (unpaired, larger deformation).

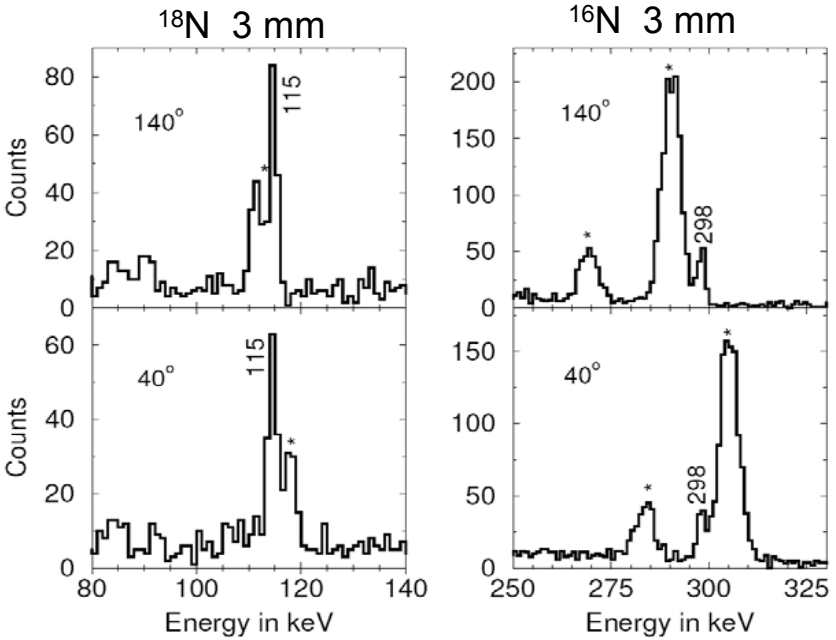
The switch in g.s. spins is due to increasing quadrupole strength relative to pairing → increased deformation. This is consistent with $\beta_2 = 0.52(4)$ for ^{17}C [7].

SM: Quadrupole from p-n interaction.

[6] A. Volya and V. Zelevinsky, Phys. Rev. Lett. **93**, 062501 (2005).

[7] Z. Elekes et al., Phys. Lett. **B 614**, 174 (2005).

^{18}N mean lifetime



277 keV: Fully shifted

298 keV: 10.6(7)% stopped

Measured τ = 145(16) ps

Published τ = 131.7(19) ps

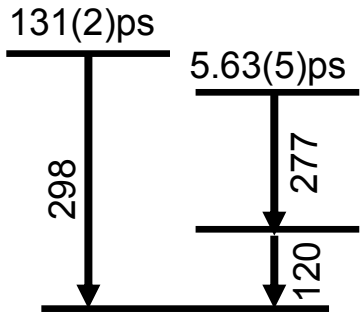
→ values agree

115 keV: 62(11)% stopped component

Feeding transitions are fully shifted.

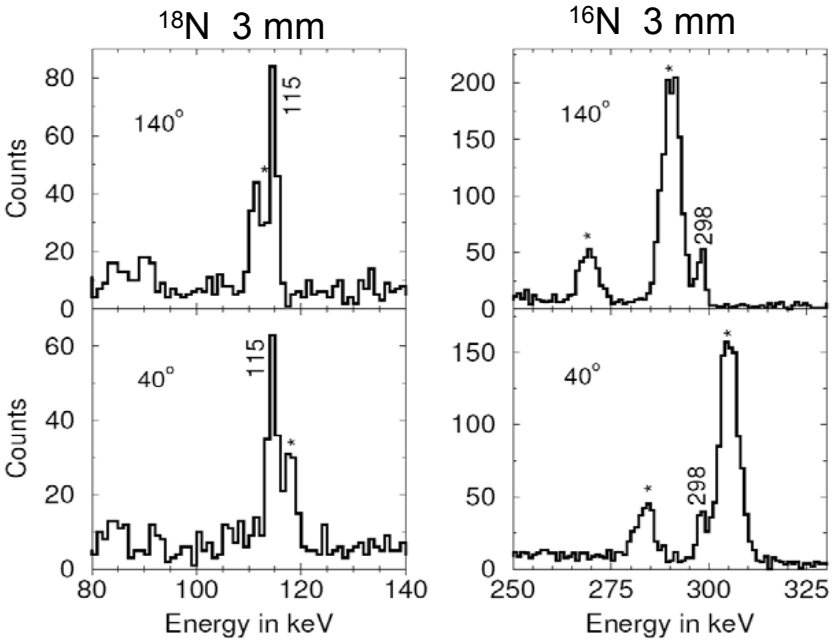
τ = 582 (165) ps

B(M1) = 0.036(10) W.u.



^{16}N: Internal calibration for τ

^{18}N mean lifetime



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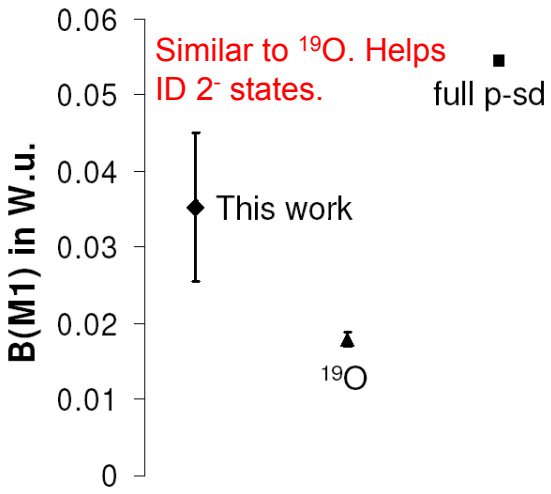

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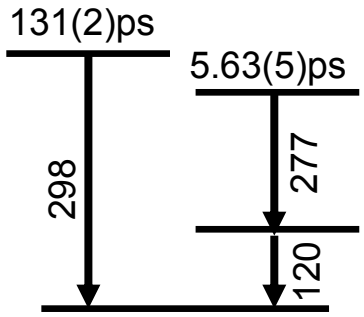

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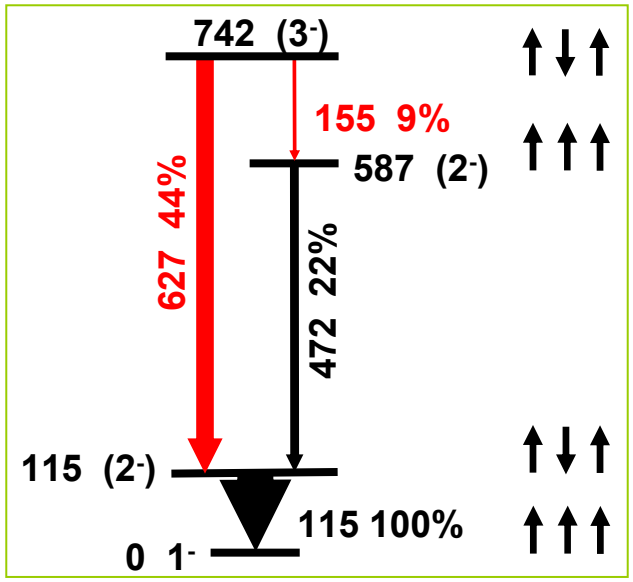
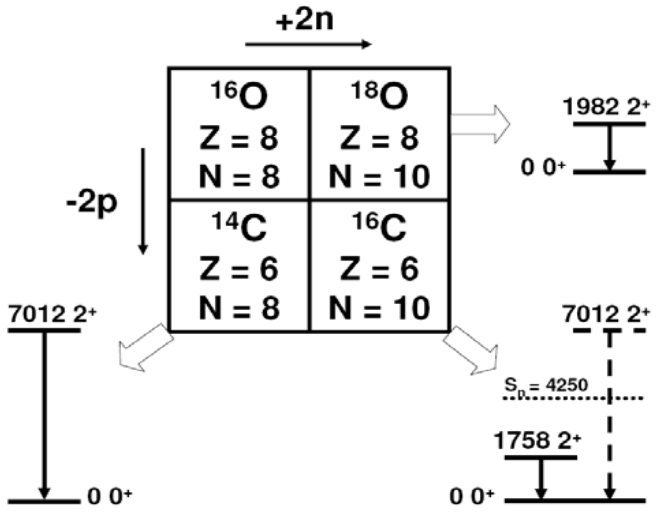


^{16}C B(E2, $2^+ \rightarrow 0^+$)

- Anomalous hindered B(E2, $2^+ \rightarrow 0^+$) of 0.26 W.u. in ^{16}C [2]
- Inelastic scattering → neutron distribution consistent with systematic [3][4].
- Combination leads to surprising result: decoupled p and n [3][4].

p and n decoupled

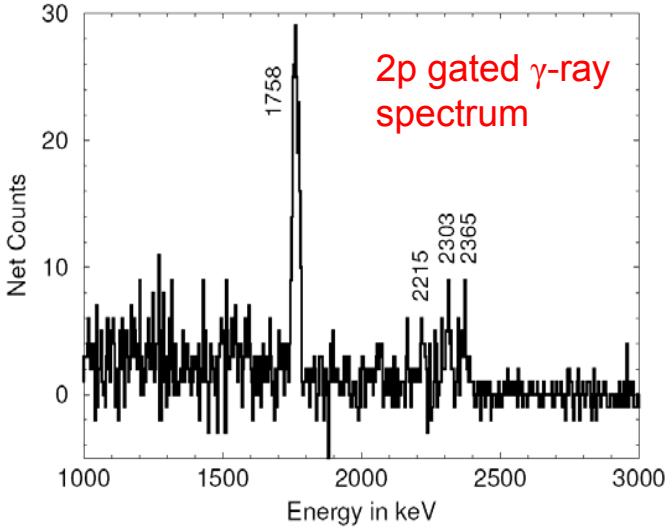
- ^{18}O systematic: first excited 2^+ state at 1982 keV has $T_{1/2}$ = 1.94 ps [5].
- A similar lifetime and energy is expected for the 2^+ state in ^{16}C.
- Expect similar B(E2; $2^+ \rightarrow 0^+$) for ^{16}C.

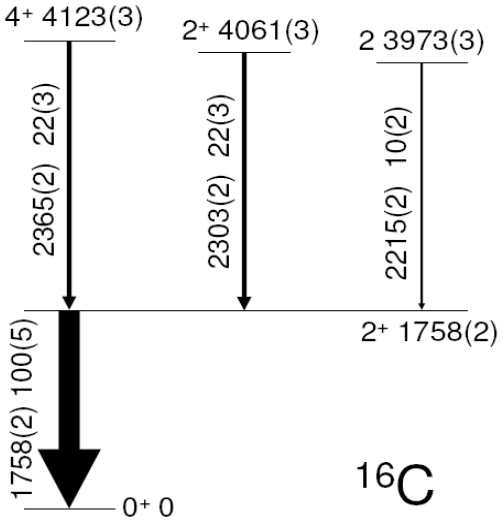


Measure lifetime using fusion-evaporation reactions utilizing the STARS-LIBERACE detector array.

[2] N. Imai et. al., Phys. Rev. Lett. **92**, 062501 (2004).
[3] Z. Elekes *et al.,* Phys. Lett. **B586**, 34 (2004).
[4] H.J. Ong *et. al.,* Phys. Rev. C **73**, 024610 (2006).
[5] www.nndc.bnl.gov/ensdf

$^{9}Be(^{9}Be,2p)^{16}C$ at 40 MeV





Transitions and spins previously observed and reported in Refs. [1-4].

Measure τ for 1758 keV with the Recoil Distance Method and determine B(E2).

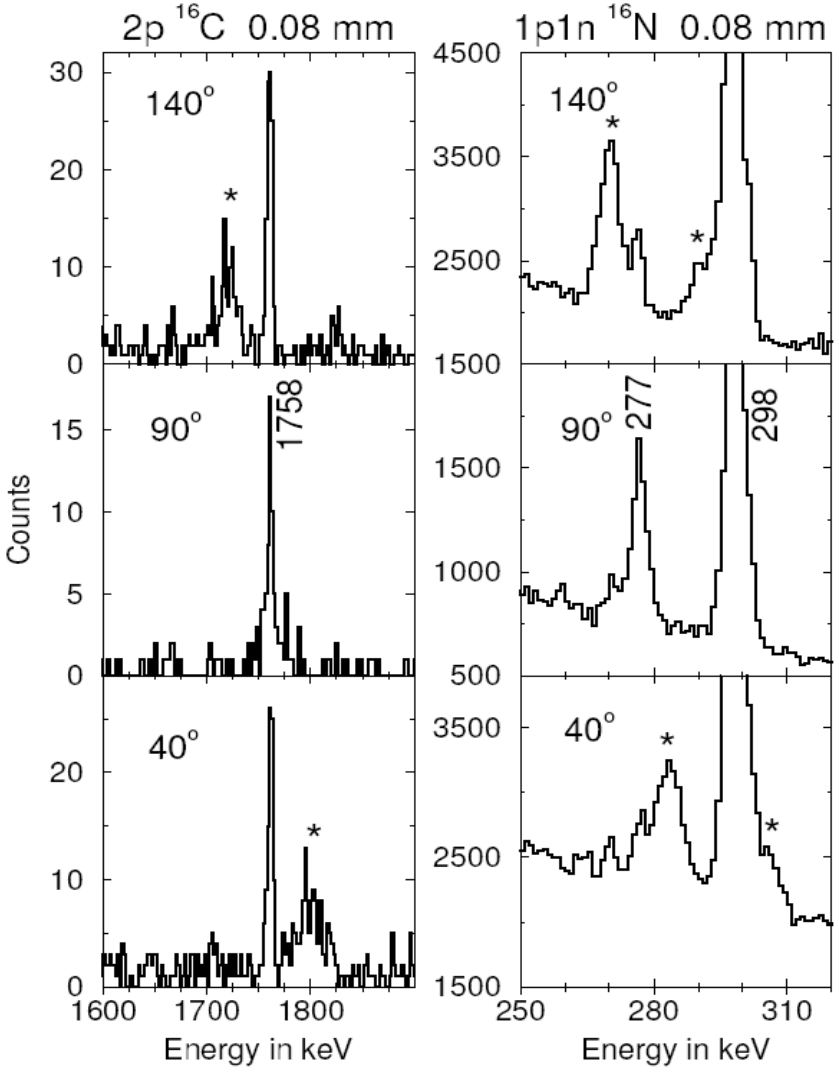
Previously: Tau = 77 ± 14(stat) ±19(sys) ps with Recoil Shadow Method [5].

Setup:

- 9Be(11B,2p)18N @ 50 MeV.
- Plunger setup with 3 distances 0.64, 0.21, 0.08 mm.
- STARS-LIBERACE detector array at LBNL.
- 5 Clovers at 40, 90 and 140 degrees.
- 150 μm ΔE detector and 1000 μm E detector telescope.

[1] D.P. Balamuth et. al., Nucl. Phys. A290, 65 (1977). [2] H.T. Fortune et. al., Phys. Lett. B 70, 408 (1977). [3] H.T. Fortune et. al., Phys. Rev. Lett. 40, 1236 (1978).
[4] R.R. Sercely et. al., Phys. Rev. C 17, 1919 (1978). [5] N. Imai et. al., Phys. Rev. Lett. **92**, 062501 (2004).

^{16}C: 2^+ lifetime results



1758 keV: 46.7(50)% stopped peak.

277 keV: 21.1(26)% stopped.

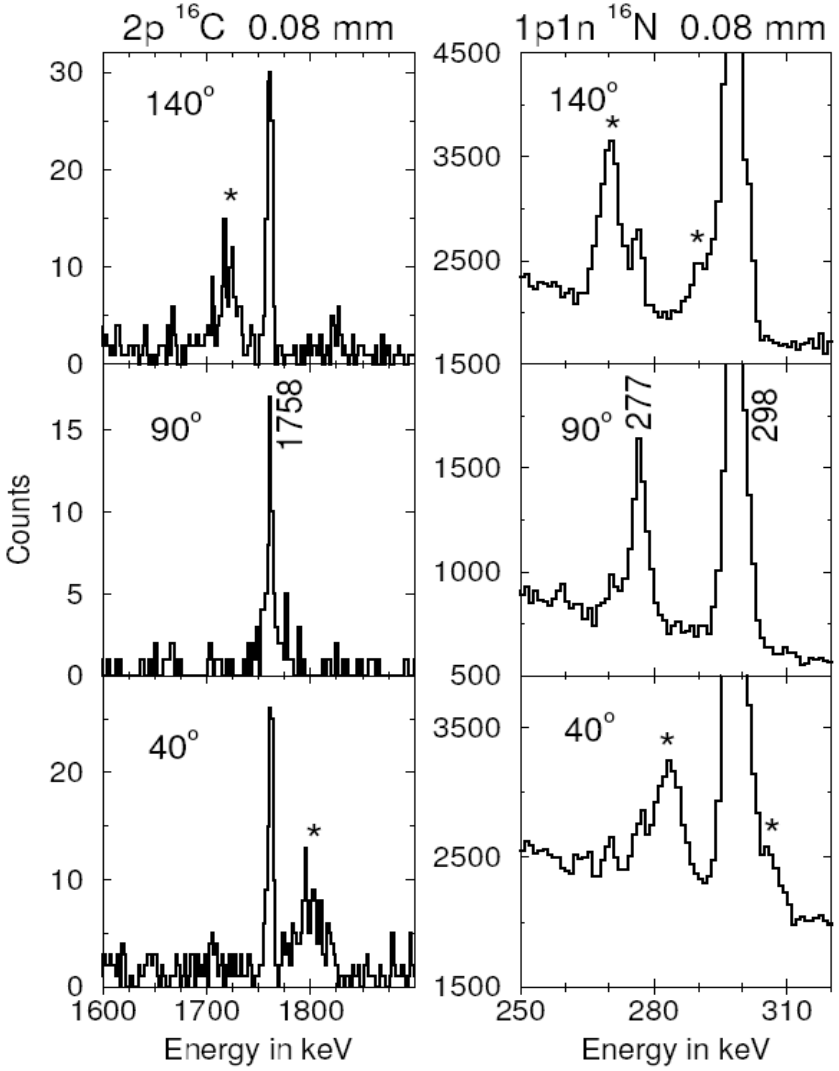
277 keV τ internal calibration for 0.08 mm:

Measured τ = 5.6(10) ps

Published τ = 5.63(5) ps

} values agree

^{16}C: 2^+ lifetime results



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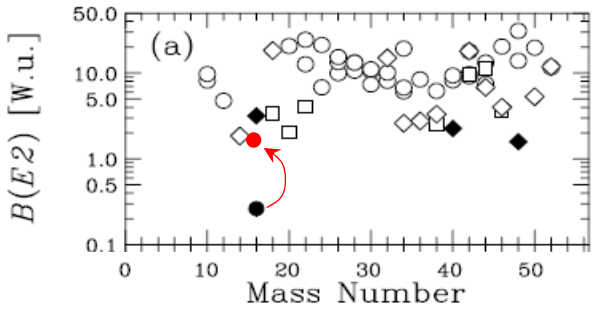
} values agree

54(5)% Feeding states are fully shifted → τ < 4 ps

τ = 11.7(20) ps for first excited 2^+ in ^{16}C.

B(E2; $2^+ \rightarrow 0^+$) = 4.15(73) e^2fm^4 = 1.73(30) W.u.



p and n shapes consistent with other nuclei

They are not decoupled!

Weak coupling model

Core Polarization:

B(E2) results in ^{18}O and ^{16}C are similar when scaled by (6/8)^2 → can be described by effective charge induced by core polarization for a predominant neutron $(sd)^2$ configuration.

^{16}C: B(E2) = 4.15(73) e^2fm^4

^{14}C: B(E2) = 3.7(6) e^2fm^4

^{18}O: B(E2) = 9.5(3) e^2fm^4

Weak coupling model:

From transition $d_{5/2} \rightarrow s_{1/2}$ in ^{15}C, lifetime of 3.77(10) ns reproduced with effective neutron charge of 0.44. (^{17}O: e_{eff}=0.4)

From Oxbash USD model space: B(E2) = 3 e^2fm^4.

The difference between ^{16}C and USD B(E2) values comes from mixing of the 2^+ states in ^{18}O $\nu(sd)^2$ and ^{14}C $\pi(p)^{-2}$.

$$B(E2) \approx \left| \alpha \langle USD | E2 | USD \rangle + \beta \langle p^{-2} | E2 | p^{-2} \rangle \right|^2$$

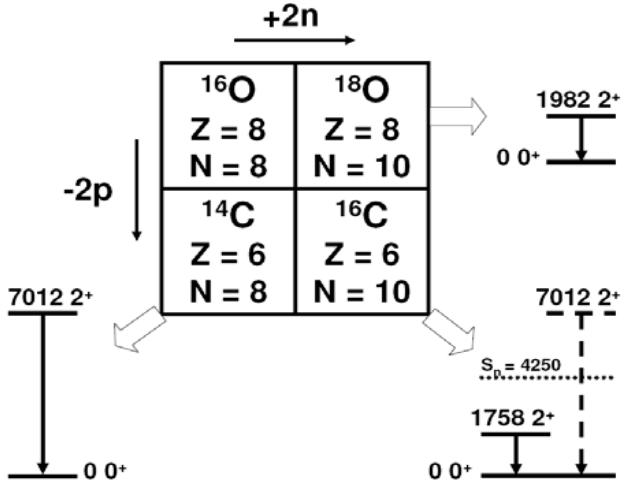
4.15 e^2fm^4 from ^{16}C

3 e^2fm^4 from USD model

3.7 e^2fm^4 from ^{14}C

$$\left| 2_1^+; {}^{16}C \right\rangle = 0.97 \left| \nu(ds)^2 \right\rangle + 0.24 \left| \pi(p)^{-2} \right\rangle$$

94% 6%



Interaction matrix element V in β between proton holes and neutrons is ~ 1MeV.

→ Consistent with p^{-1} and $(sd)^4$ value in ^{19}F [1]

[1] Arima and Hamamoto, Annual Review of Nucl. Sci. 21 (1971).

Conclusions

Can extract weak channels by gating on 2 charged particles with the **STARS-LIBERACE** array at LBNL.

2p channel successfully extracted in 3 reactions ^{16}C, ^{18}N, and ^{17}N

^{18}N:

- Observed two new γ-transitions and γ-γ coincidences.
- Measured τ = 582(165) ps for the first-excited state.
- B(M1) = 0.036(10) W.u value agrees with model and systematic.
- From P+Q: unpaired $\upsilon(d_{5/2})^3$ configuration becomes ground state in ^{18}N and ^{17}C due to increase in quadrupole interaction.

^{16}C:

- Generated much interest with measurement of B(E2) = 0.26 W.u.
- Observed four γ-transitions.
- Measured τ = 11.7(20) ps for the first-excited 2^+ state.
- B(E2) = 1.73(30) W.u value consistent with other even-even nuclei.
- Results do not support interpretation of a nearly spherical proton core within a deformed neutron distribution.

Collaborators

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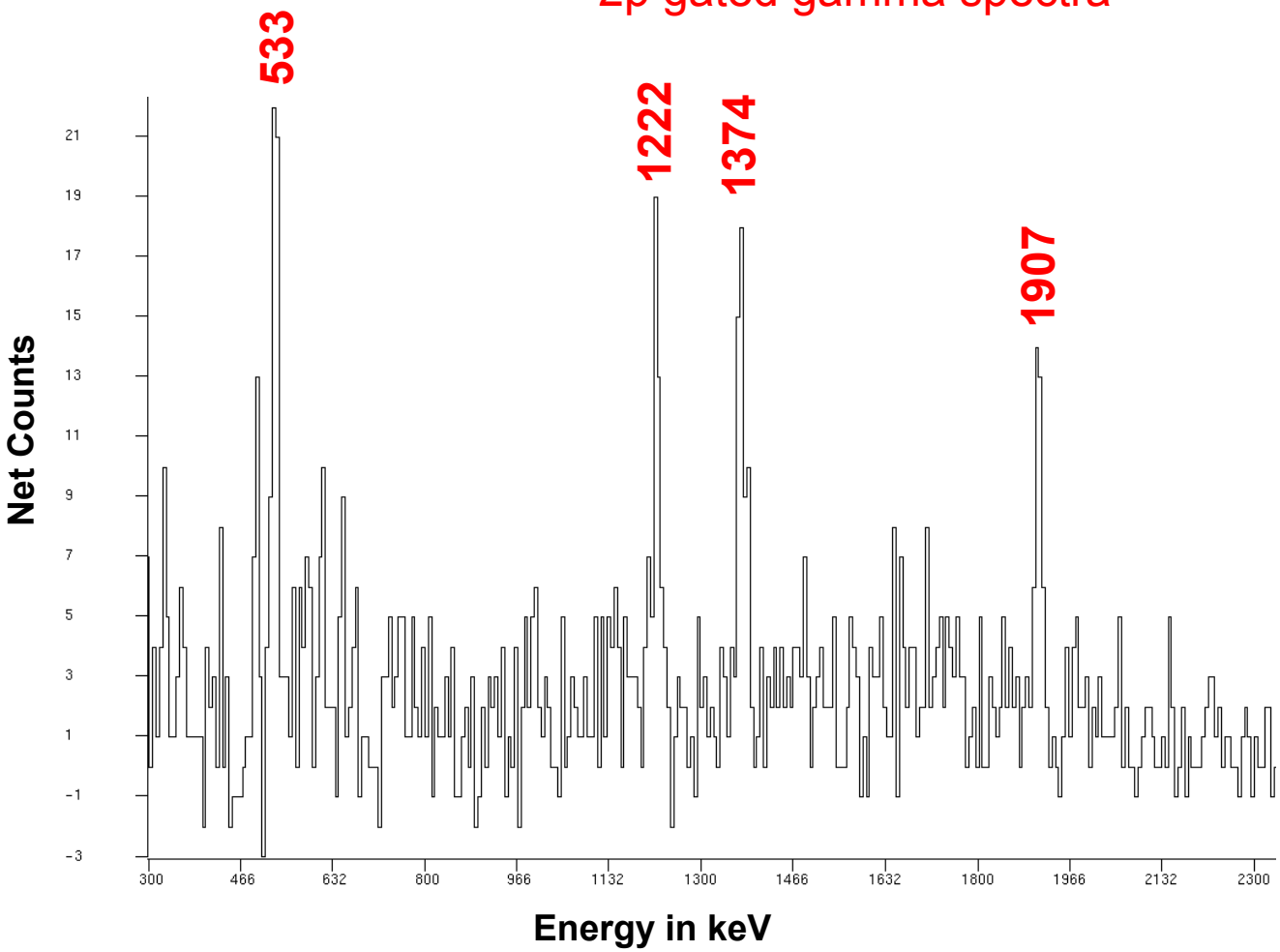
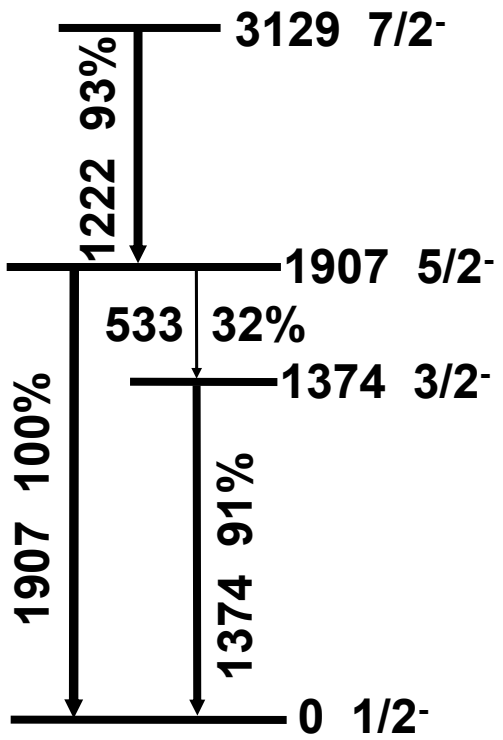
$^{12}C(^{7}Li,2p)^{17}N$, 35 MeV

2p gated gamma spectra

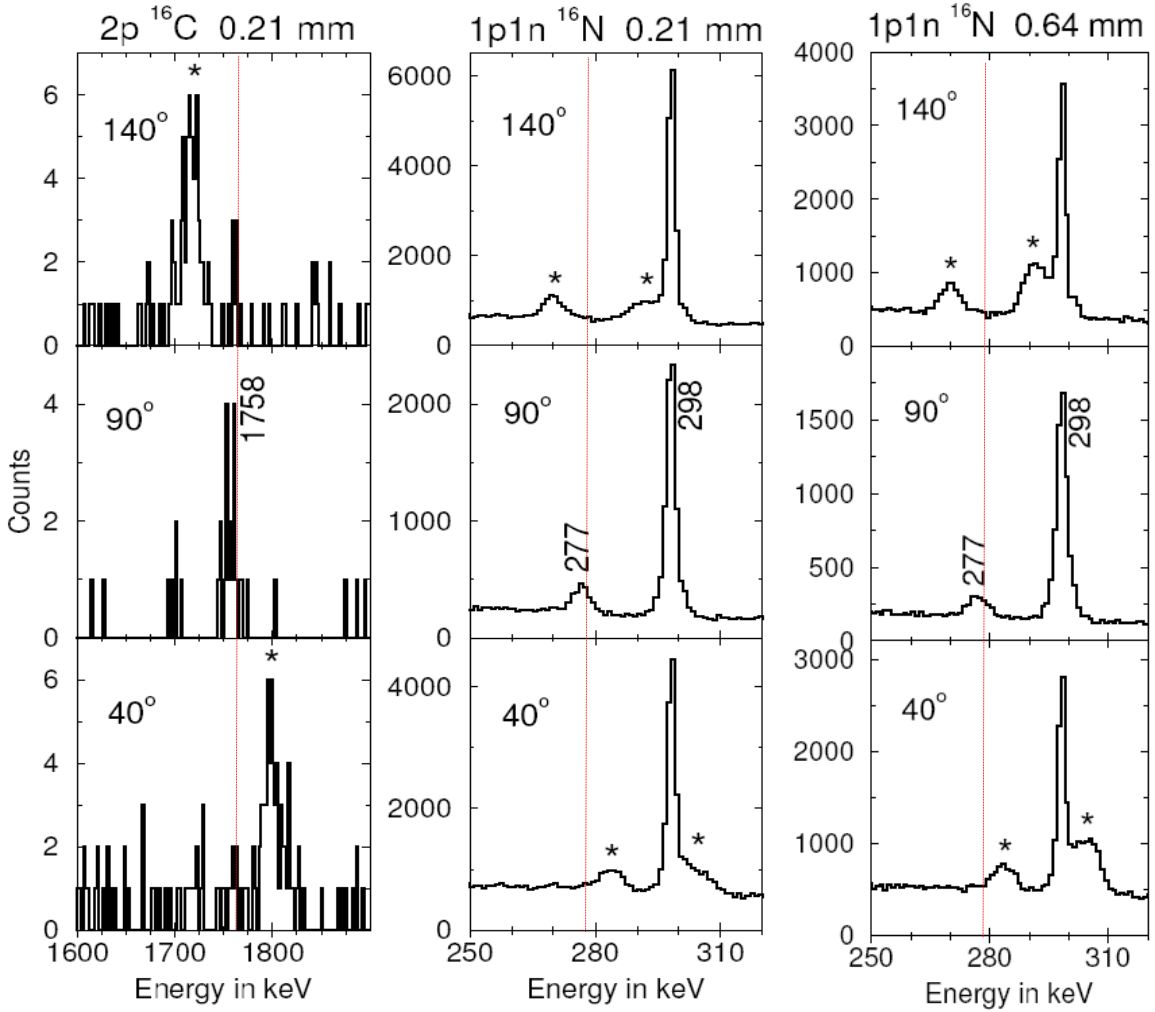


7.6×10^{-3} %



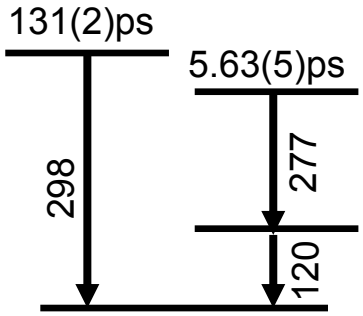
ENSDF: http://www.nndc.bnl.gov/

^{16}C: 2$^+$ lifetime results



1758 keV: No stopped peak (10% level).

^{16}N: Internal calibration for τ



277 keV: Fully shifted

298 keV: Shifted and stopped.

Get 298 keV τ from 0.64 mm with 55.7(33)% stopped:

Measured τ = 119(14) ps

Published τ = 131.7(19) ps

→ values agree

^{16}C 2$^+$ lifetime << 77 ps