Investigating Nuclear Shell Evolution in Neutron-Rich Calcium Isotopes

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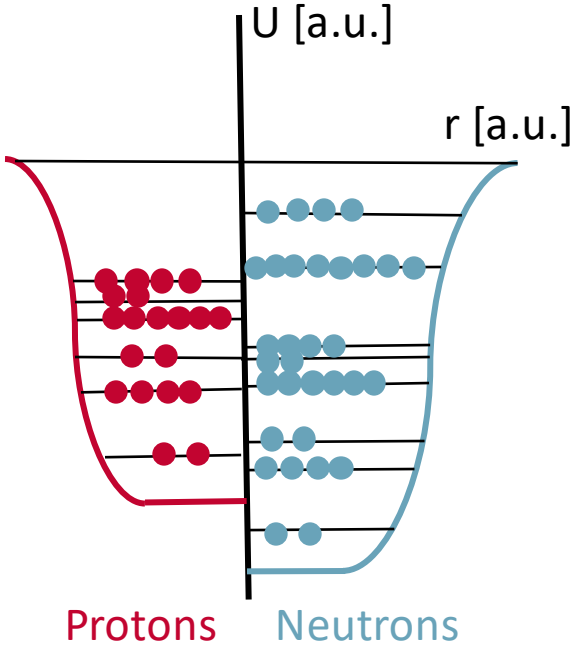
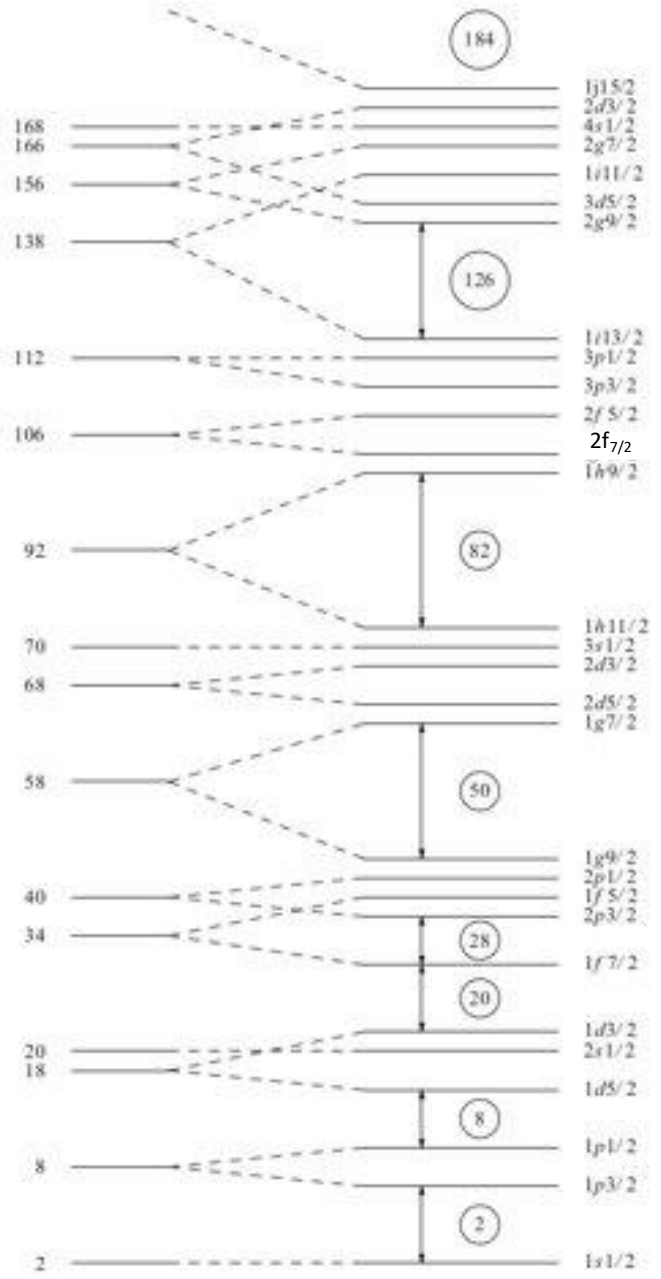
WNPPC FEBRUARY 2024

Nuclear Shell Model

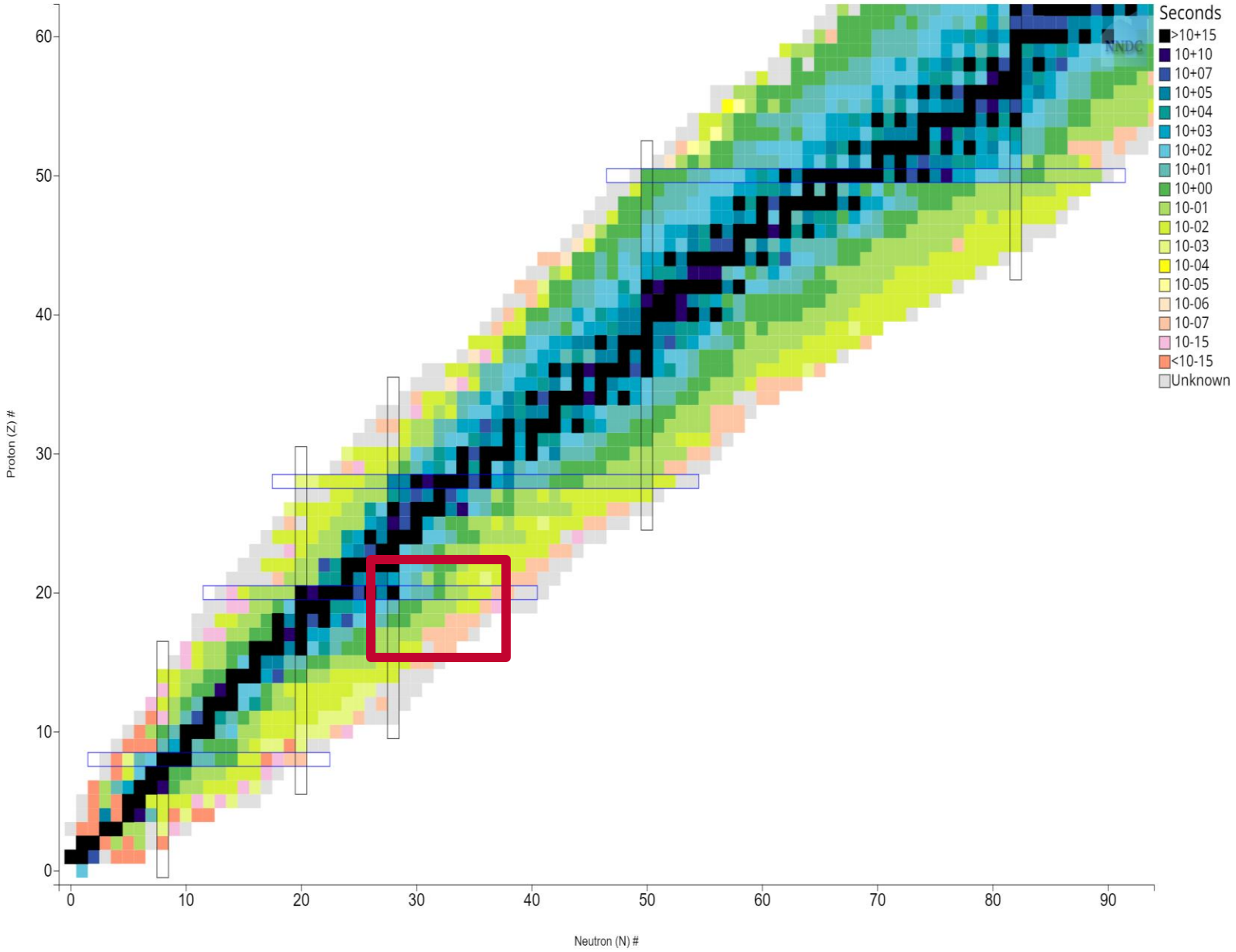
- Analogous to Electron Shells, Nucleons occupy energetic shells
- Starting from a Woods-Saxon Potential adding a spin orbit coupling reproduces observed shells



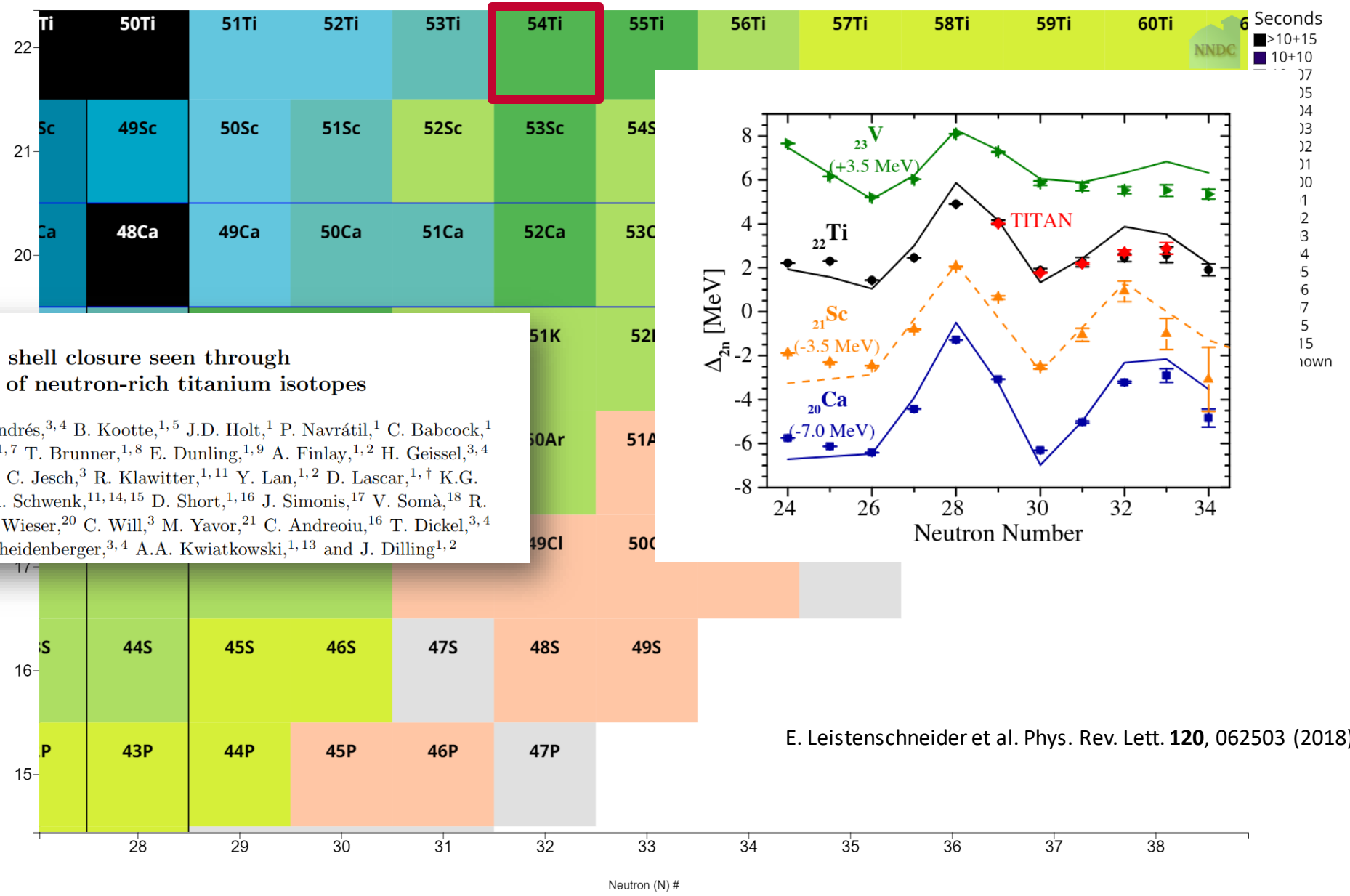


Shell Model Evolution

- Single particle energies drift away from β-stability
- Creates new magic numbers



Shell Model Evolution

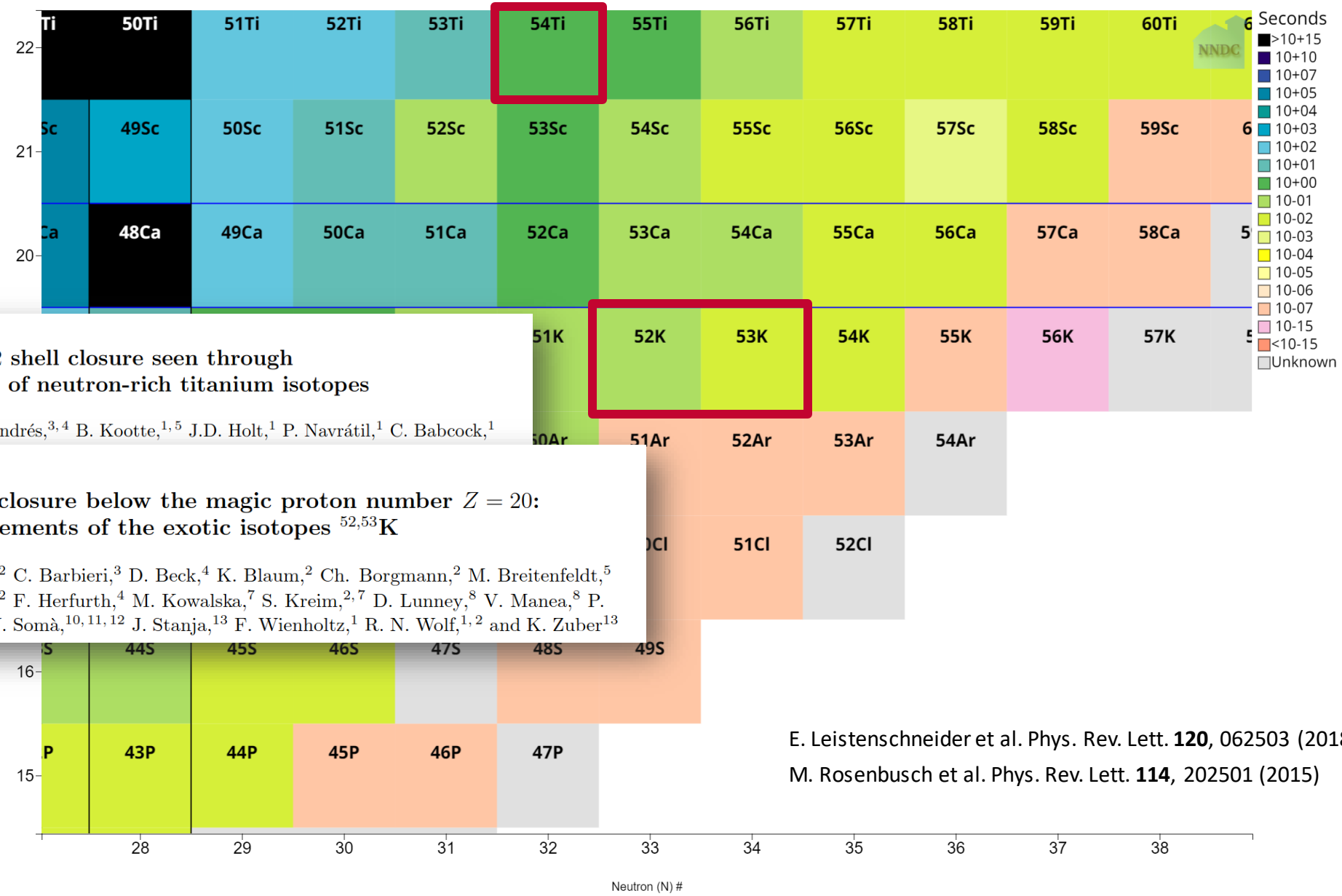


Dawning of the $N = 32$ shell closure seen through precision mass measurements of neutron-rich titanium isotopes

E. Leistenschneider,[1,2,*] M.P. Reiter,[1,3] S. Ayet San Andrés,[3,4] B. Kootte,[1,5] J.D. Holt,[1] P. Navrátil,[1] C. Babcock,[1] C. Barbieri,[6] B.R. Barquest,[1] J. Bergmann,[3] J. Bollig,[1,7] T. Brunner,[1,8] E. Dunling,[1,9] A. Finlay,[1,2] H. Geissel,[3,4] L. Graham,[1] F. Greiner,[3] H. Hergert,[10] C. Hornung,[3] C. Jesch,[3] R. Klawitter,[1,11] Y. Lan,[1,2] D. Lascar,[1,†] K.G. Leach,[12] W. Lippert,[3] J.E. McKay,[1,13] S.F. Paul,[1,7] A. Schwenk,[11,14,15] D. Short,[1,16] J. Simonis,[17] V. Somà,[18] R. Steinbrügge,[1] S.R. Stroberg,[1,19] R. Thompson,[20] M.E. Wieser,[20] C. Will,[3] M. Yavor,[21] C. Andreoiu,[16] T. Dickel,[3,4] I. Dillmann,[1,13] G. Gwinner,[5] W.R. Plaß,[3,4] C. Scheidenberger,[3,4] A.A. Kwiatkowski,[1,13] and J. Dilling[1,2]

E. Leistenschneider et al. Phys. Rev. Lett. **120**, 062503 (2018)

Shell Model Evolution



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C.
L.
Lea
Stei

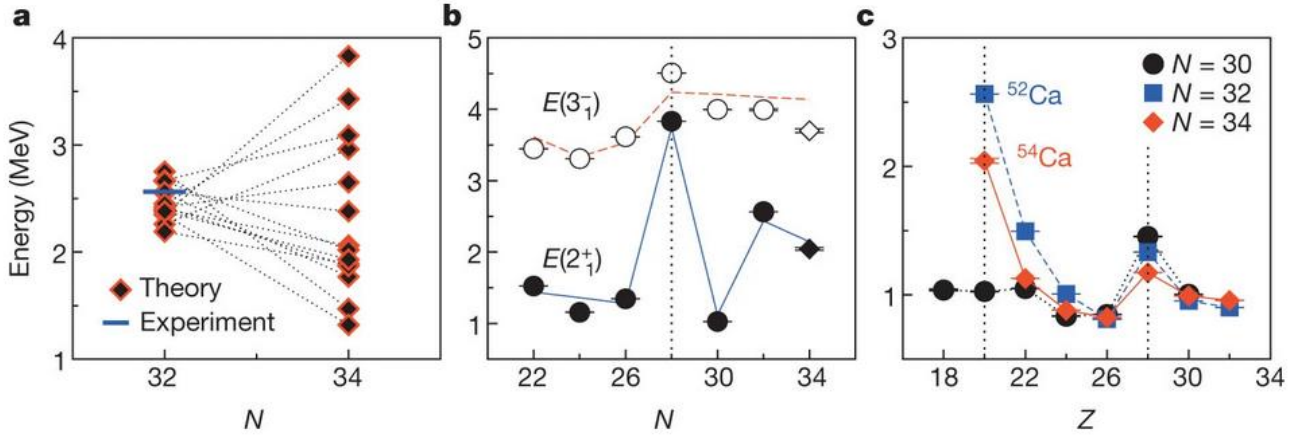
Probing the $N = 32$ shell closure below the magic proton number $Z = 20$: Mass measurements of the exotic isotopes ^{52,53}K

M. Rosenbusch,[1] P. Ascher,[2] D. Atanasov,[2] C. Barbieri,[3] D. Beck,[4] K. Blaum,[2] Ch. Borgmann,[2] M. Breitenfeldt,[5] R.B. Cakirli,[2,6] A. Cipollone,[3] S. George,[2] F. Herfurth,[4] M. Kowalska,[7] S. Kreim,[2,7] D. Lunney,[8] V. Manea,[8] P. Navrátil,[9] D. Neidherr,[4] L. Schweikhard,[1] V. Somà,[10,11,12] J. Stanja,[13] F. Wienholtz,[1] R. N. Wolf,[1,2] and K. Zuber[13]

E. Leistenschneider et al. Phys. Rev. Lett. **120**, 062503 (2018)

M. Rosenbusch et al. Phys. Rev. Lett. **114**, 202501 (2015)

Shell Model



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Navrátil,[9] D

Evidence for a new nuclear 'magic number' from the level structure of ^{54}Ca

D. Steppenbeck[1], S. Takeuchi[2], N. Aoi[3], P. Doornenbal[2], M. Matsushita[1], H. Wang[2], H. Baba[2], N. Fukuda[2], S. Go[1], M. Honma[4], J. Lee[2], K. Matsui[5], S. Michimasa[1], T. Motobayashi[2], D. Nishimura[6], T. Otsuka[1,5], H. Sakurai[2,5], Y. Shiga[7], P.-A. Söderström[2], T. Sumikama[8], H. Suzuki[2], R. Taniuchi[5], Y. Utsuno[9], J. J. Valiente-Dobón[10] & K. Yoneda[2]

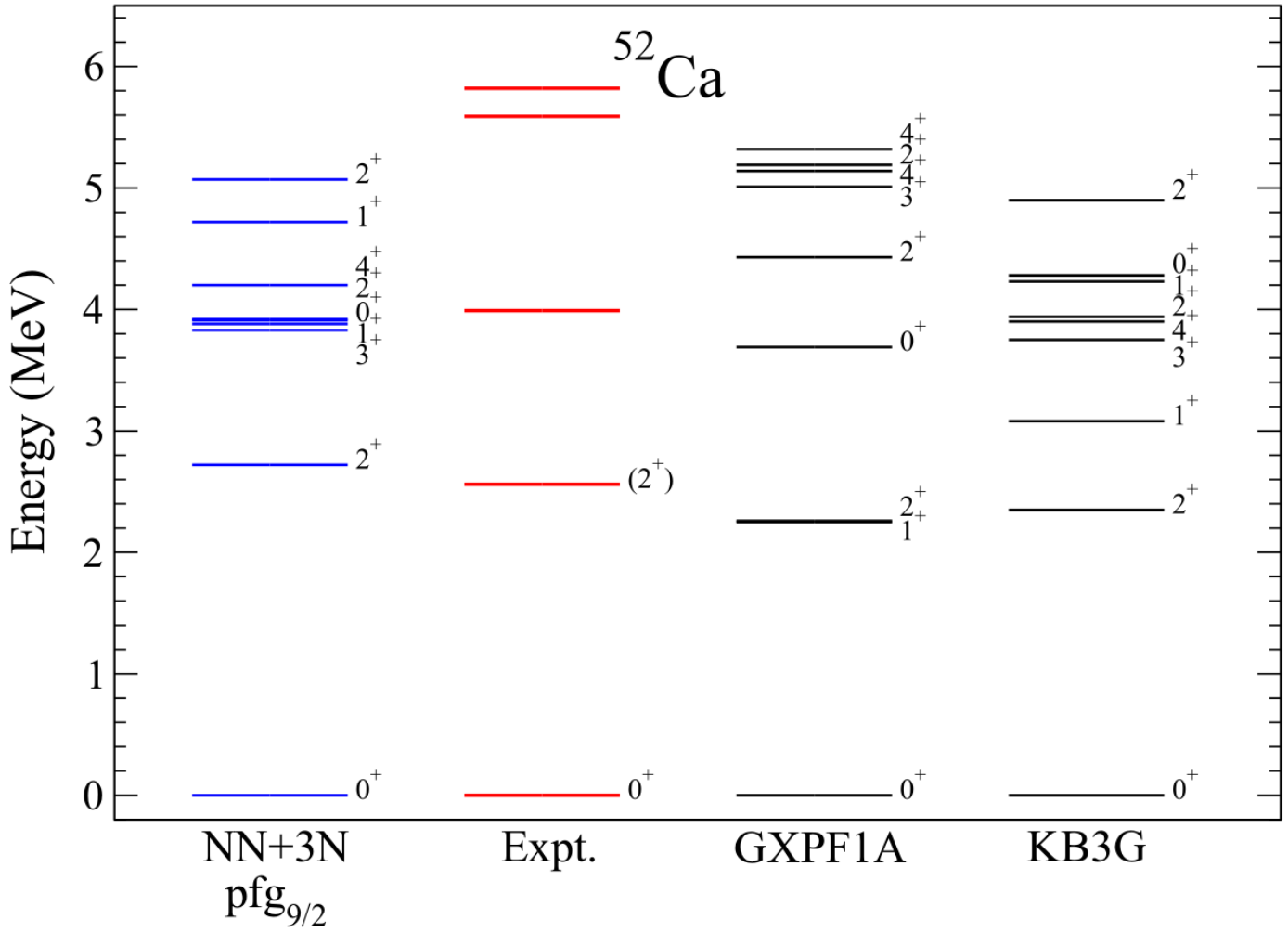
E. Leistenschneider et al. Phys. Rev. Lett. **120**, 062503 (2018)

M. Rosenbusch et al. Phys. Rev. Lett. **114**, 202501 (2015)

D. Steppenbeck et al., Nature **502**, 207 (2013).

Shell Model Evolution

- Various Interactions can describe this behavior
- Phenomenological models require spectroscopic validation



J. D. Holt, J. Menéndez, J. Simonis, and A. Schwenk, Physical Review C **90** (2014).

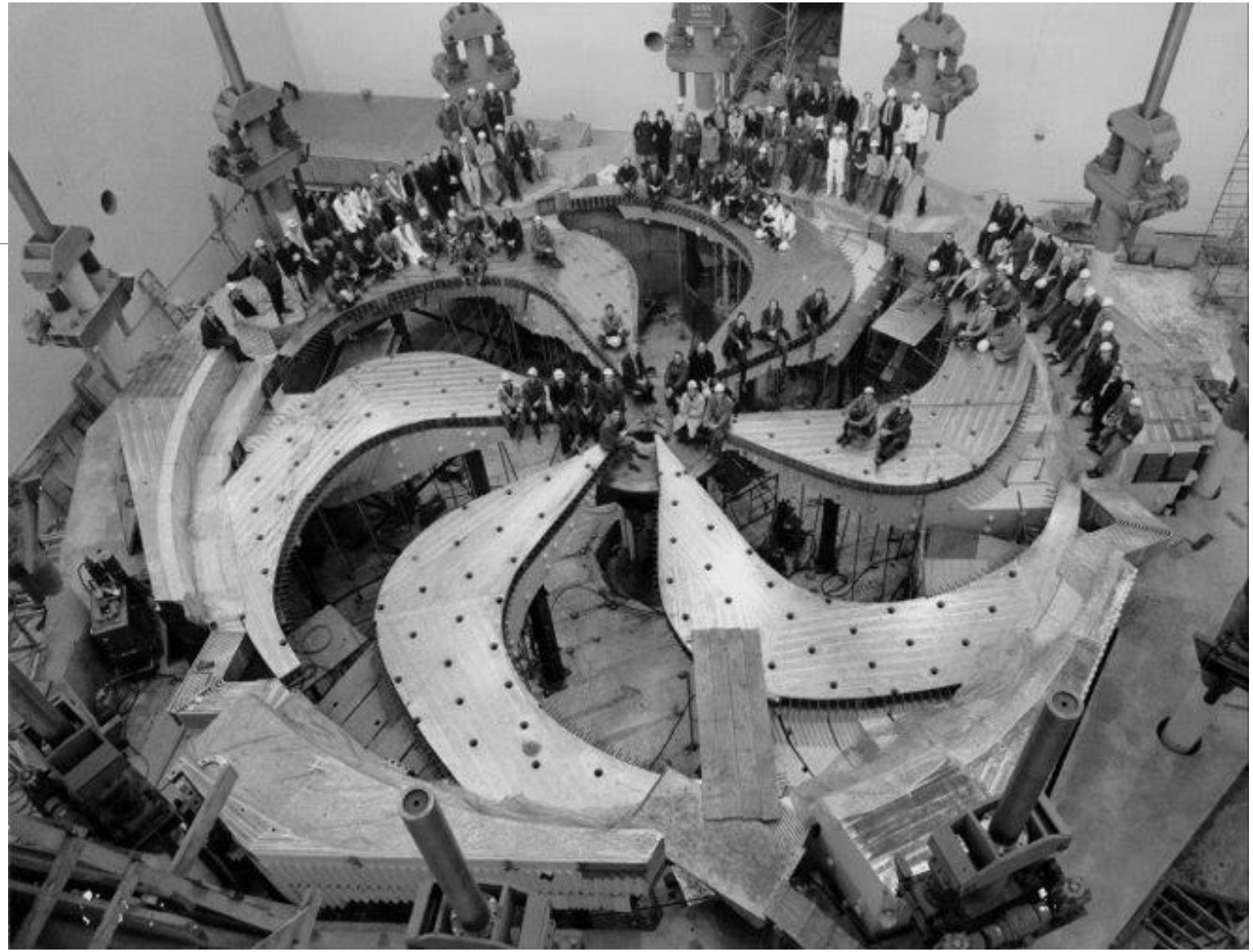
TRIUMF

TRI-**U**niversity **M**eson **F**acility

Isotope **S**eparation **O**n **L**ine (ISOL) Facility

520 MeV Cyclotron

UCx Target



"GRIFFIN Collaboration," triumf.ca

Beta Detectors

- **Beta Detectors**
  - **SC**intillating **E**lectron **P**ositron **T**agging **AR**ray (SCEPTAR)
  - **Z**ero **D**egree **S**cintillator (ZDS)
- Isotopes Delivered
  - ^{52}K ~ 200 pps (38 hours)
  - ^{53}K ~ 20 pps (48 hours)
  - ^{54}K ~ 2 pps (84 hours)

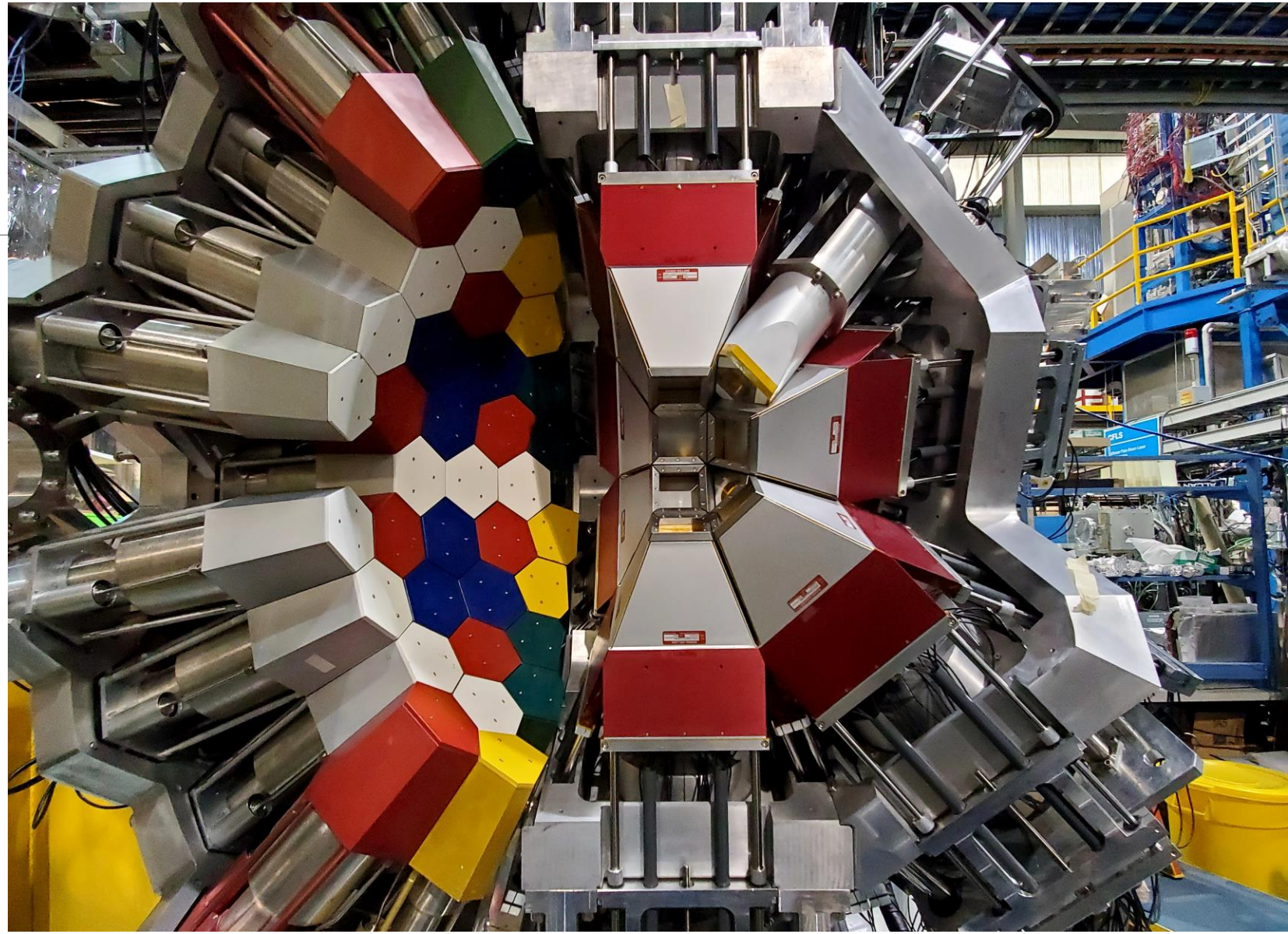
GRIFFIN + DESCANT

Gamma-**R**ay **I**nfrastructure **F**or **F**undamental **I**nvestigation of **N**uclei (GRIFFIN)

- 12 HPGe clover detectors

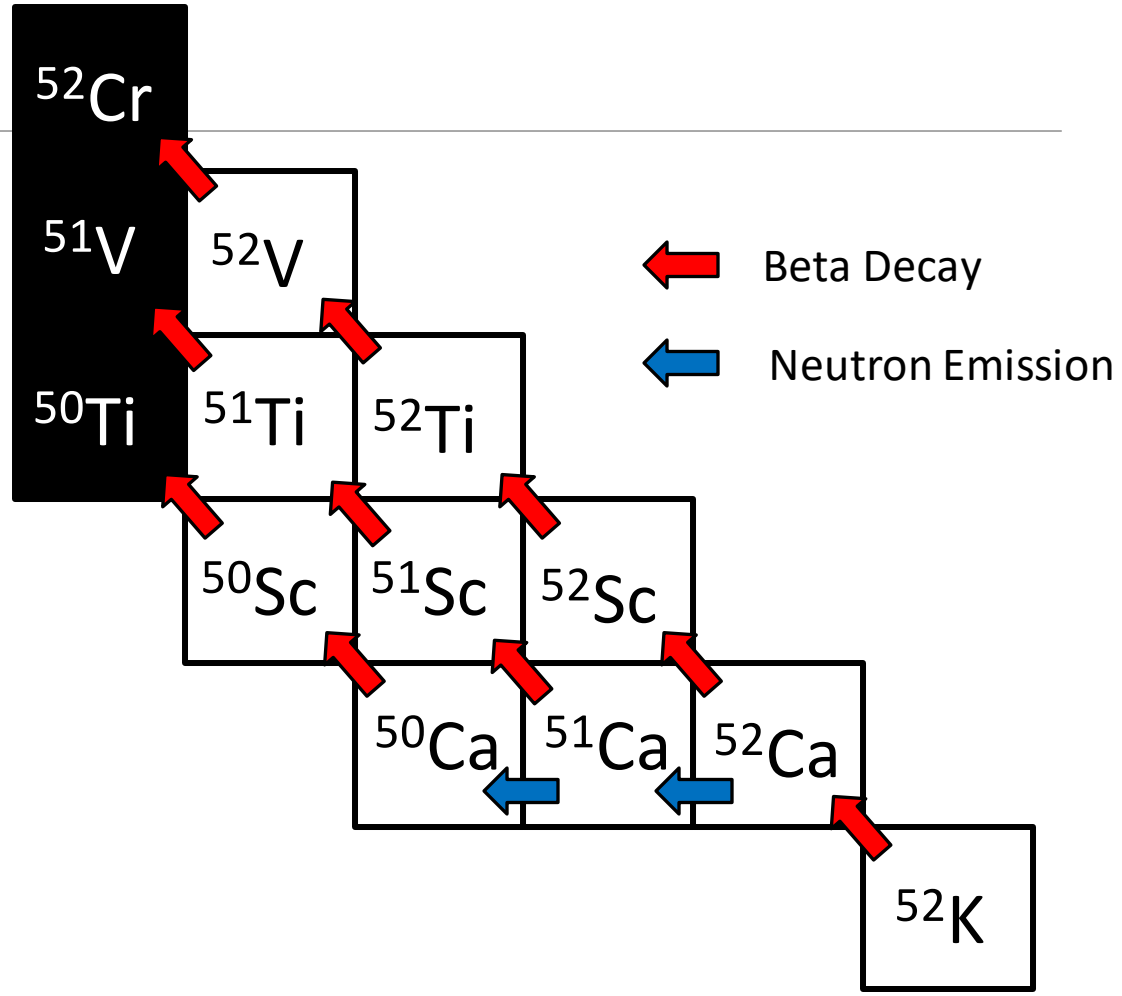
DEuterated **SC**intillator **A**rray for **N**eutron-**T**agging (DESCANT)

- 69 detectors installed downstream



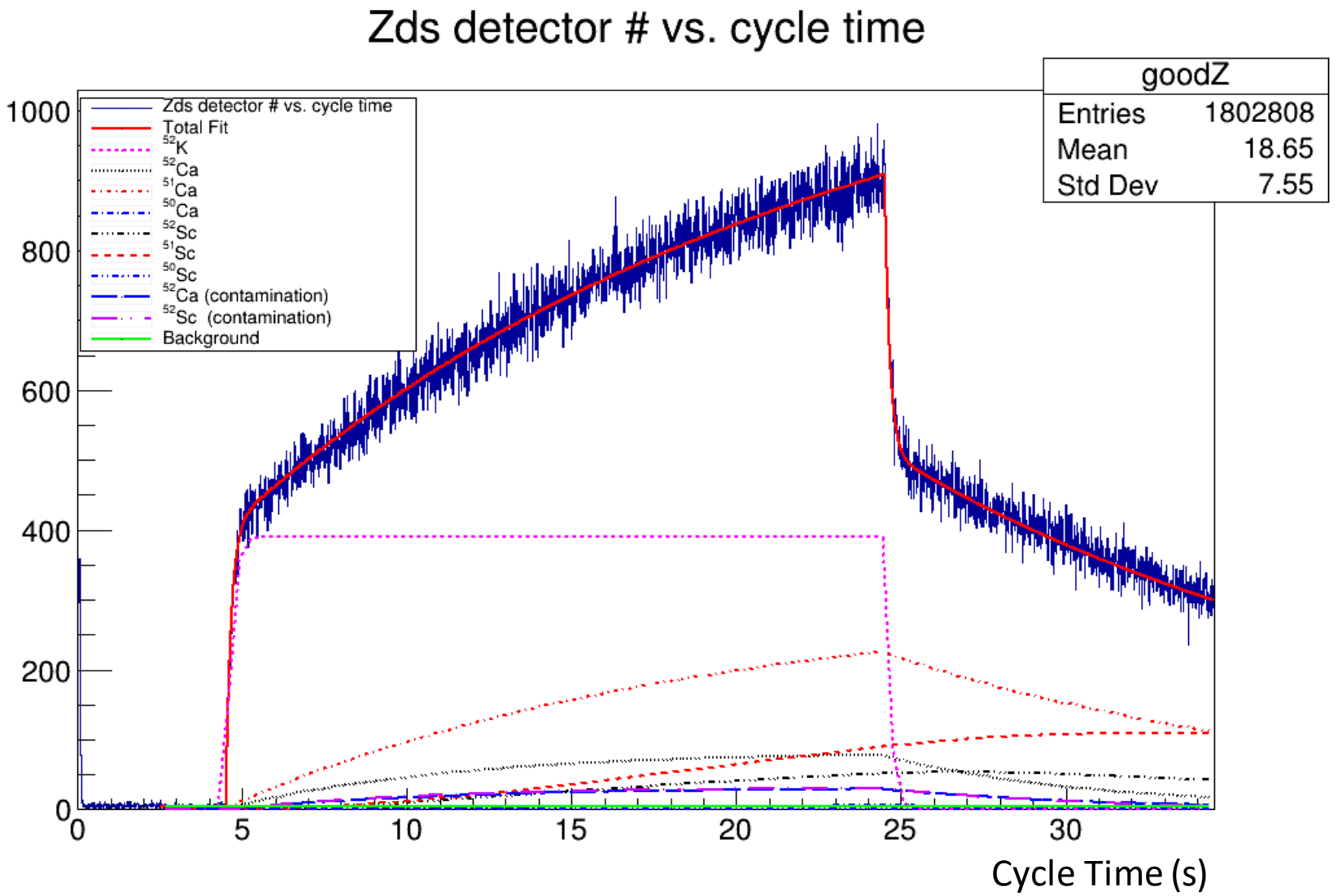
Isotopes Produced

- Neutron emission probabilities are >70% for all potassium isotopes delivered
- Large Q-value of beta-n branch can kick some of the daughter nuclei out of mylar tape



Beta Data

- Dependent on
  - Half lives
  - β-n probabilities
  - Relative efficiencies for nuclei

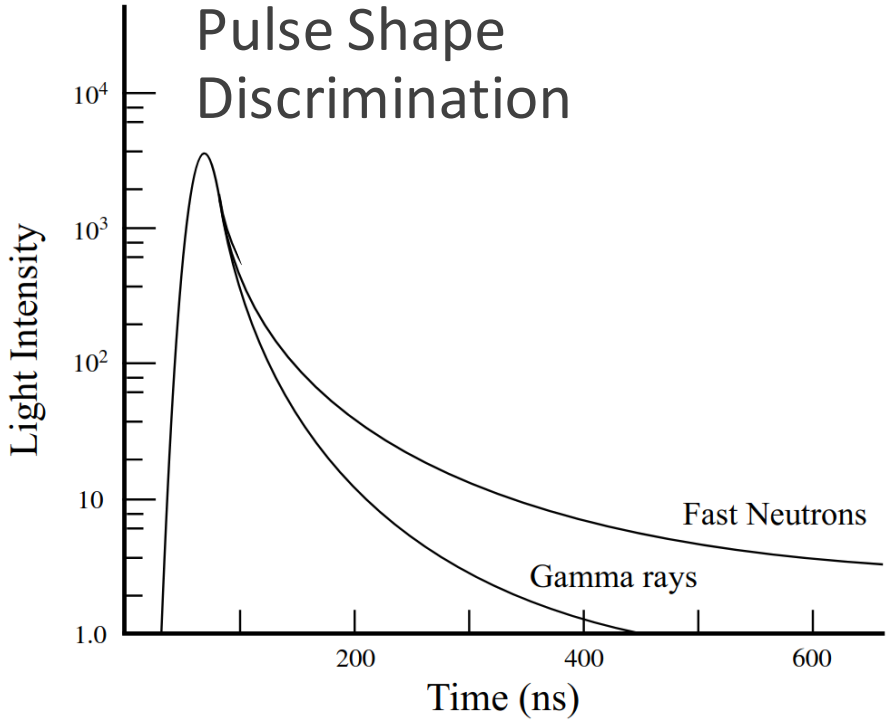


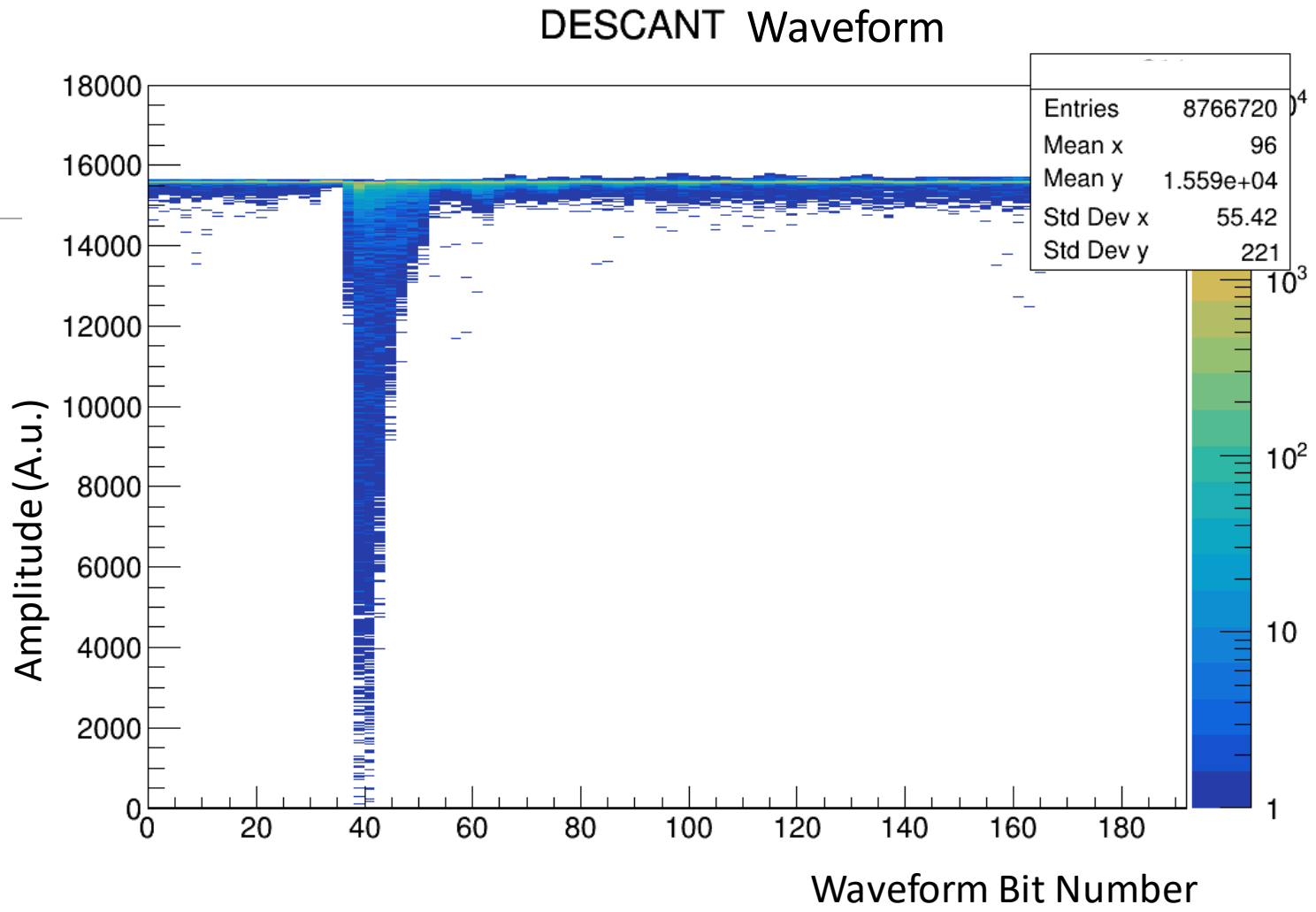
Neutron Selection

Time of Flight

- ZDS starts the clock

Pulse Shape Discrimination





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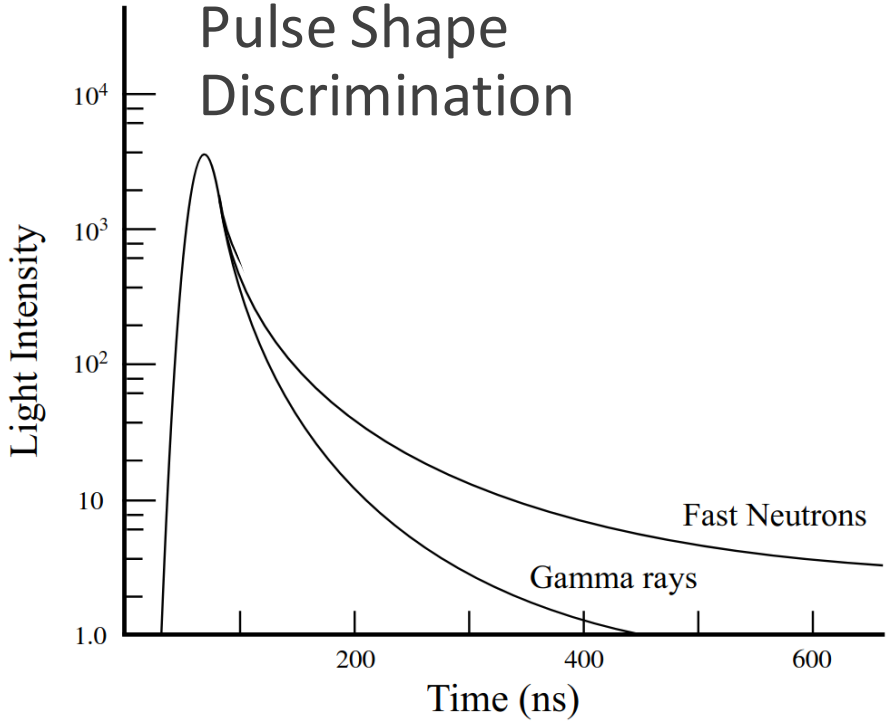

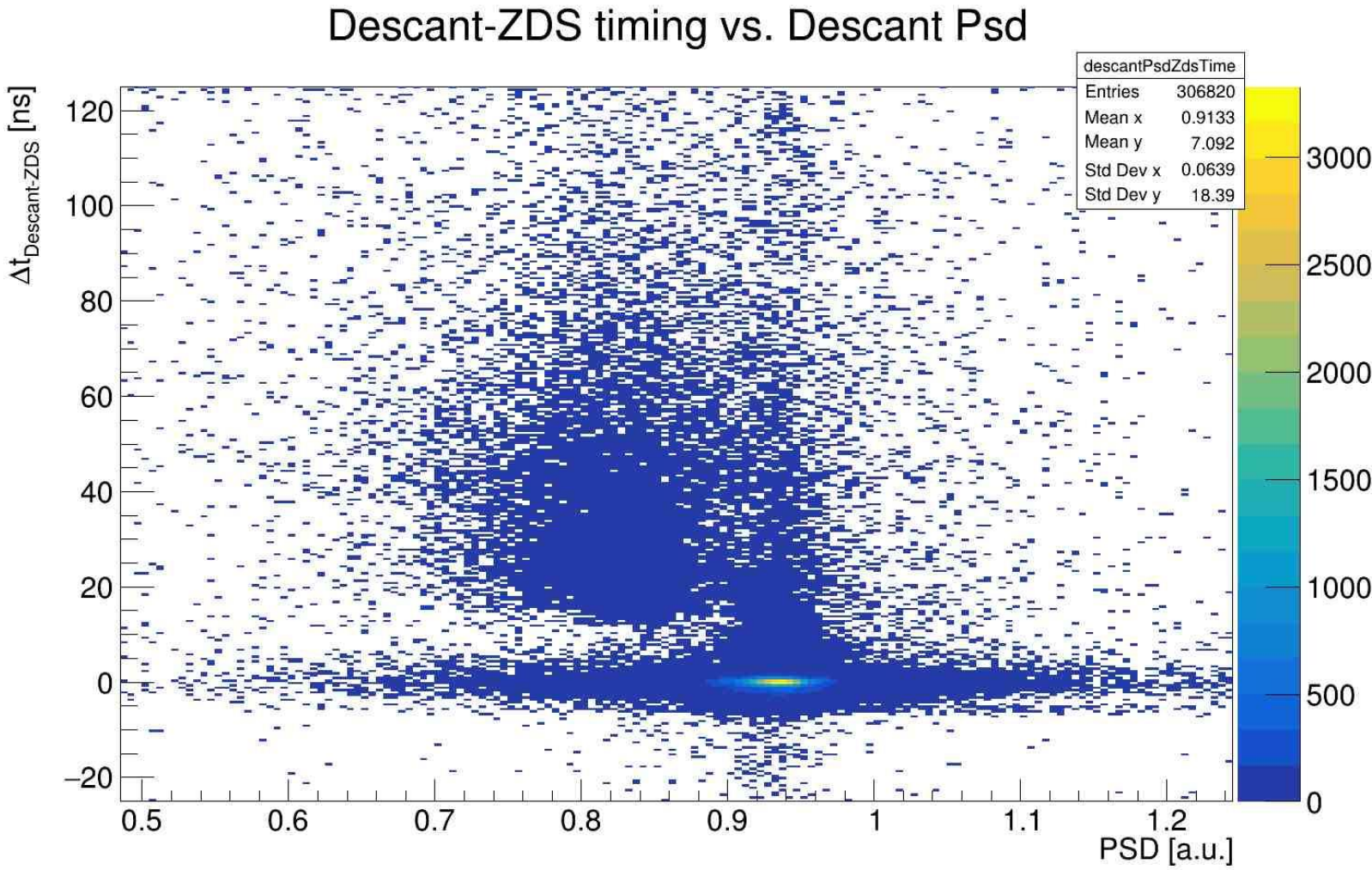

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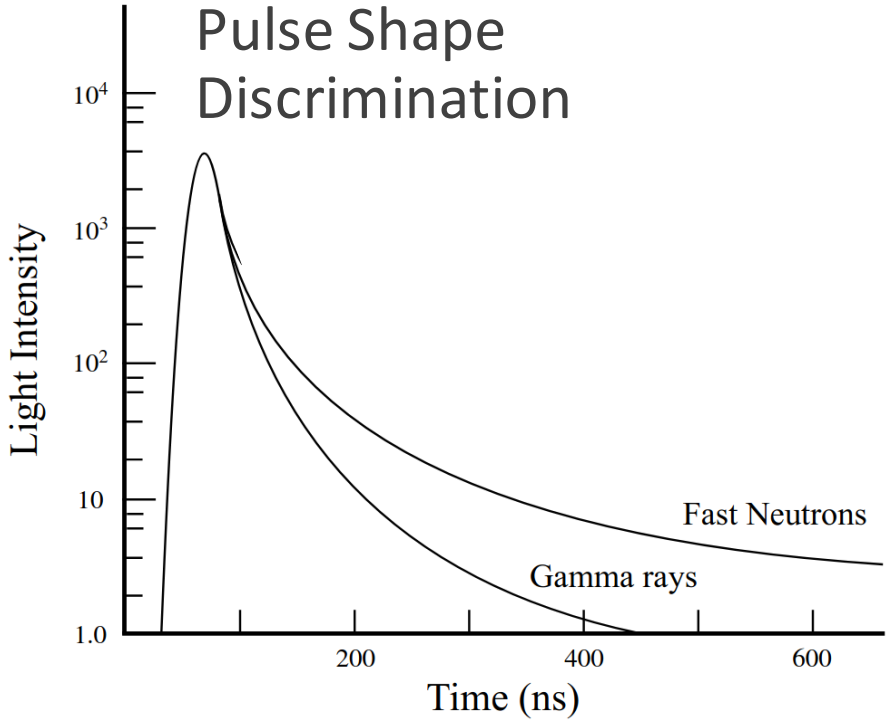
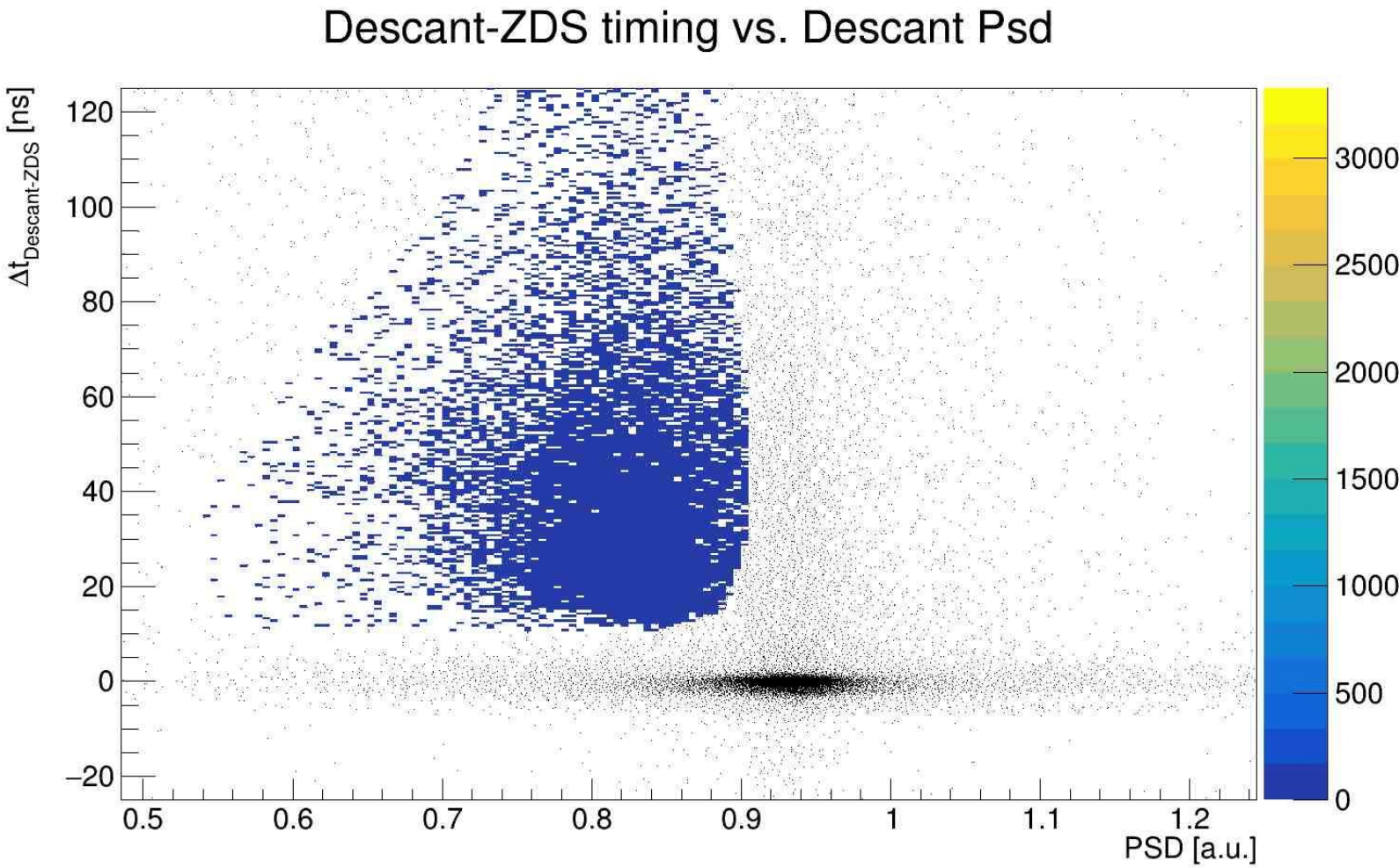
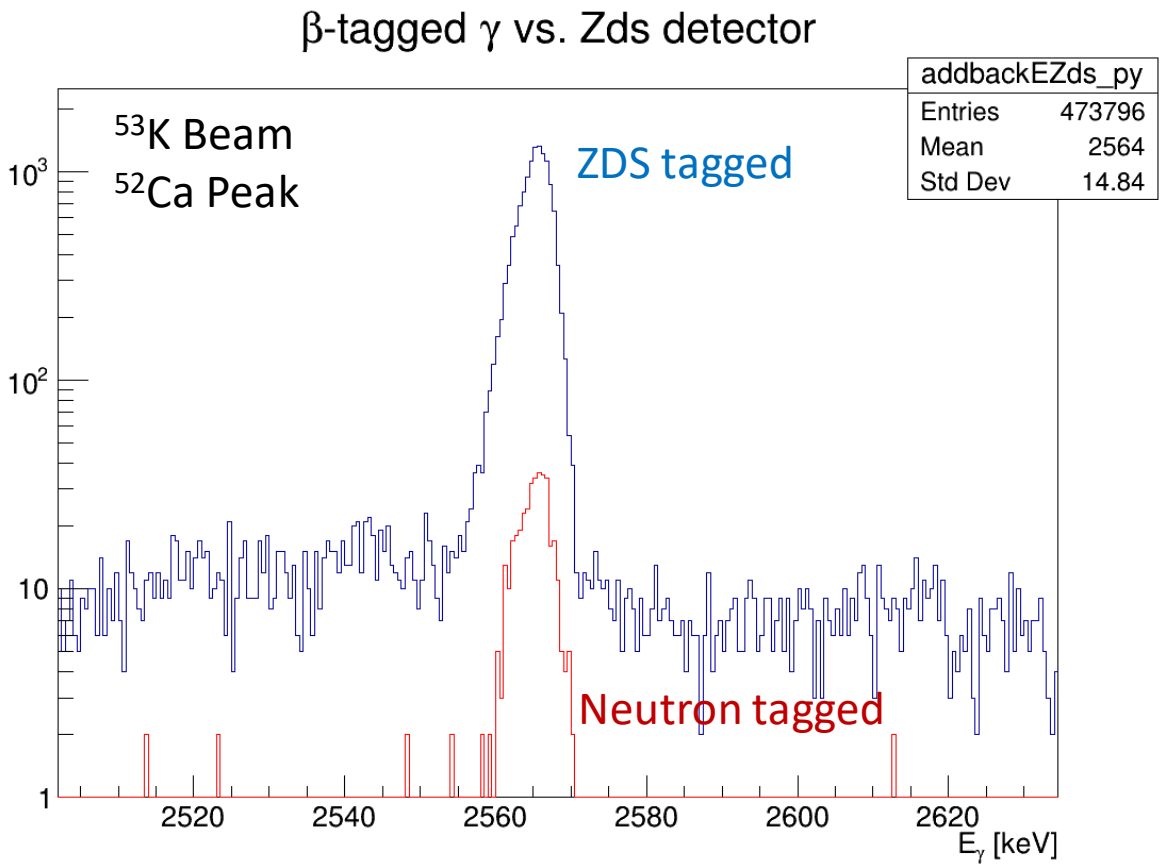
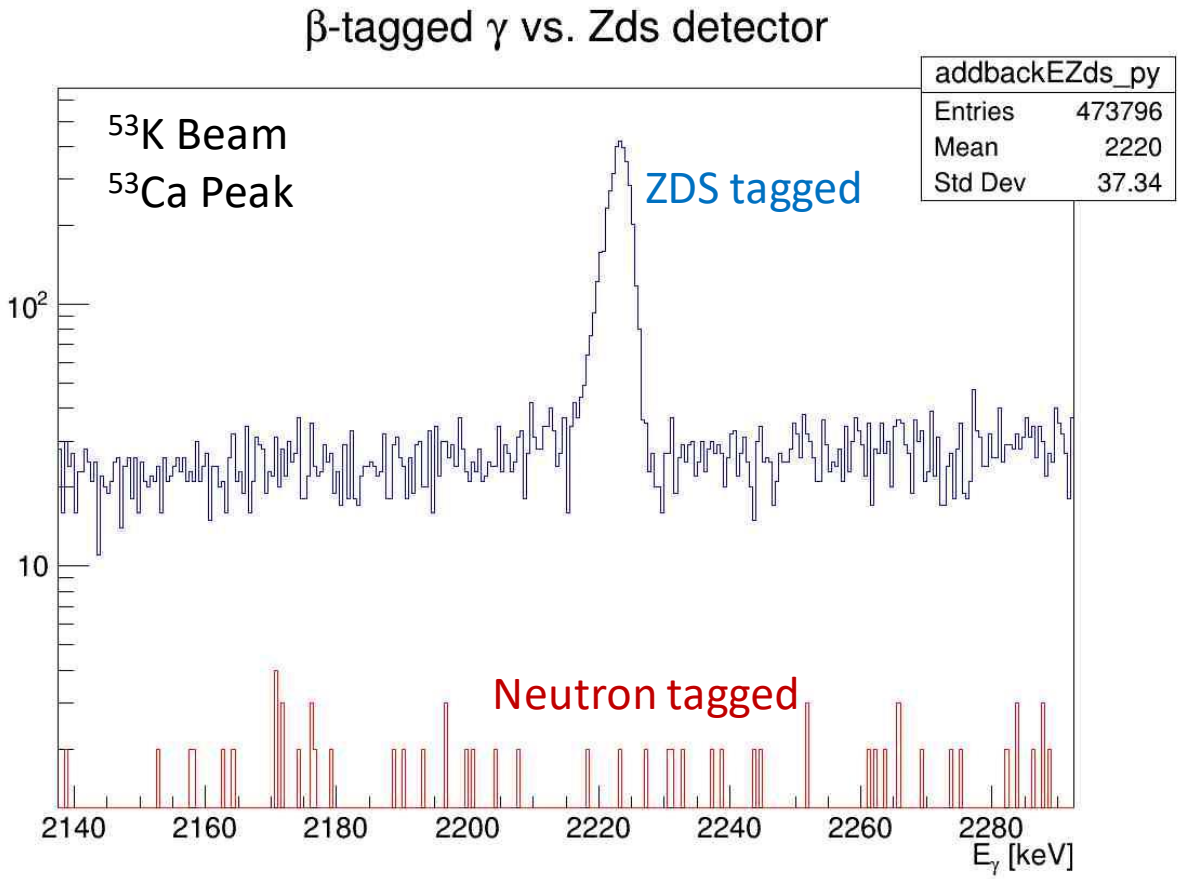




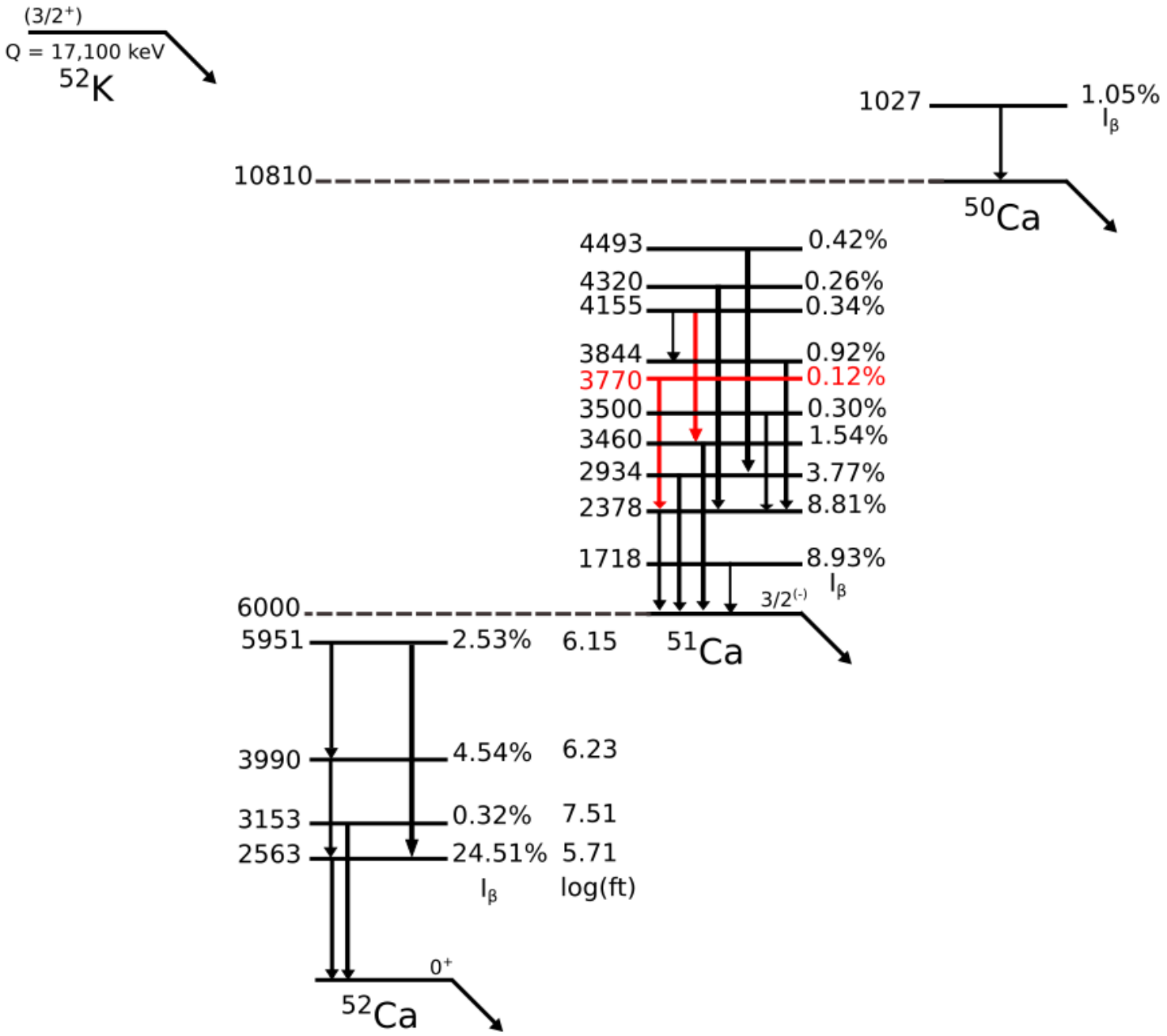
GRIFFIN Results





^{52}K Decay Level Schema

Not Pictured: scandium and titanium isotopes populated



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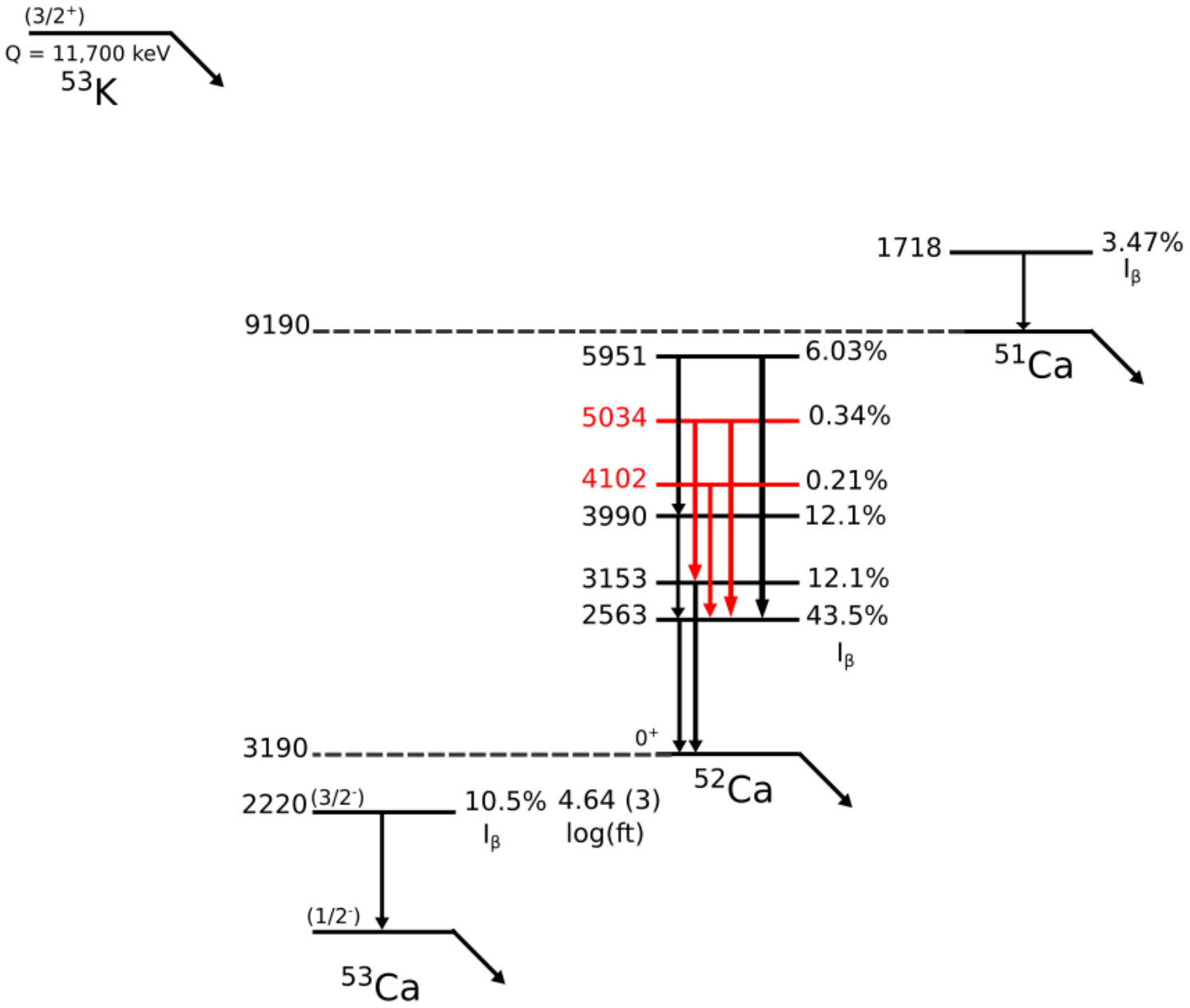
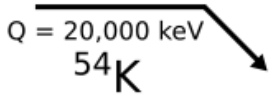
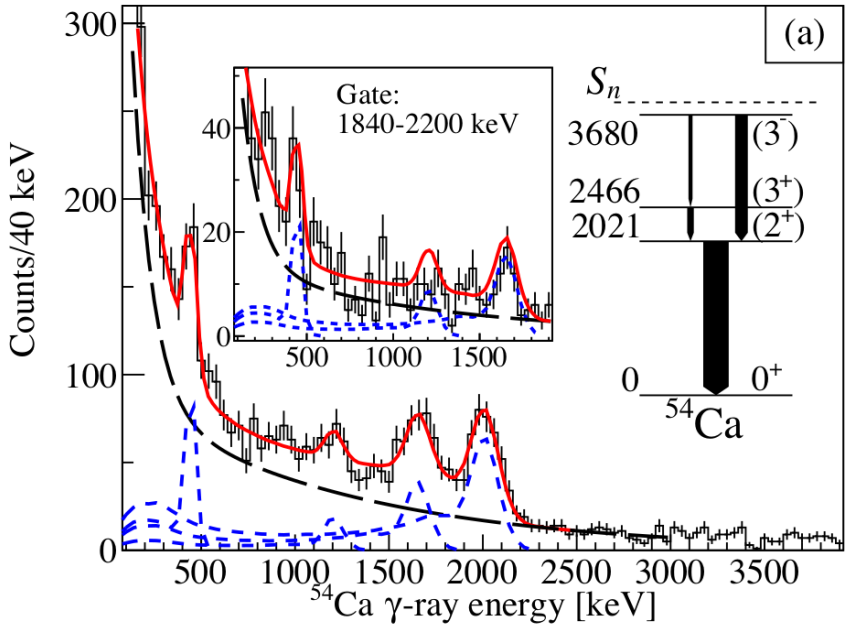
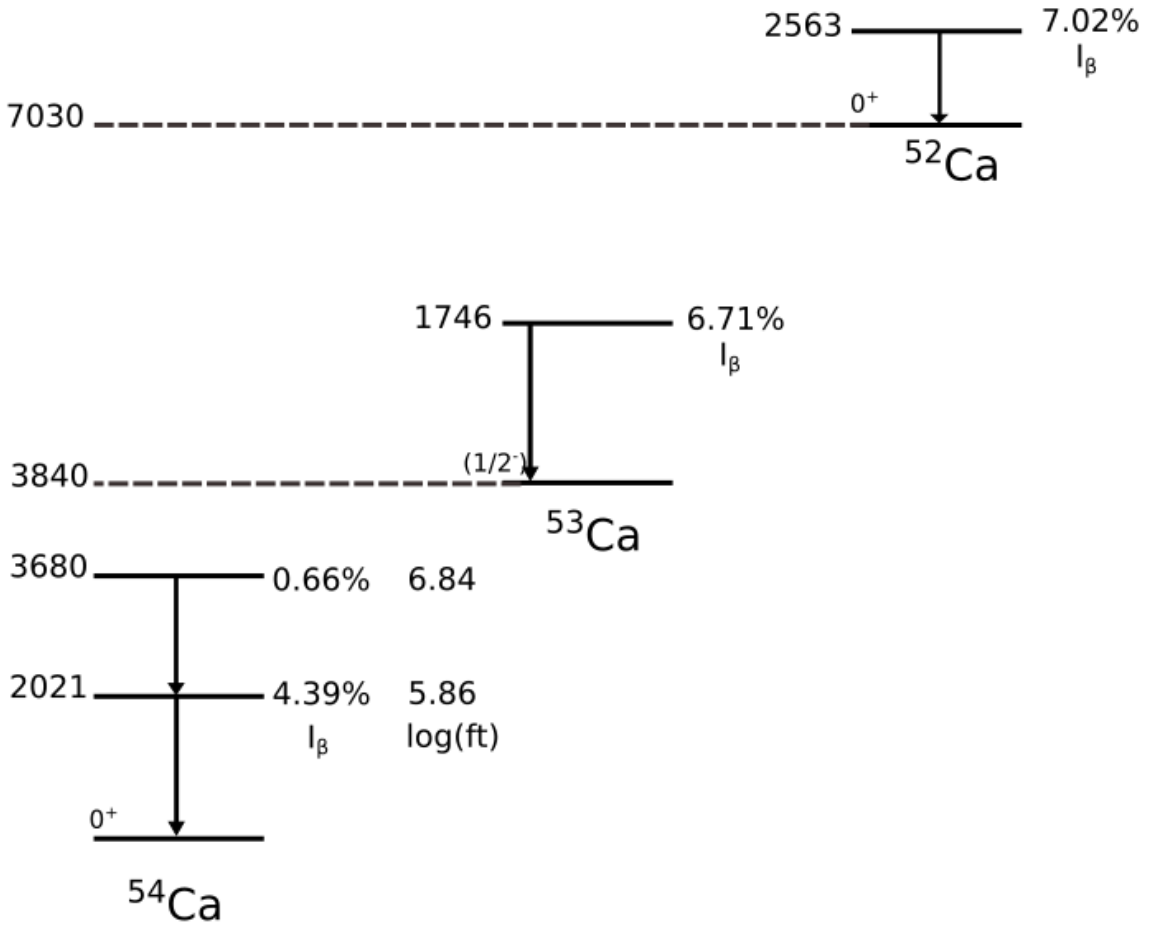


^{54}K Decay Level Schema



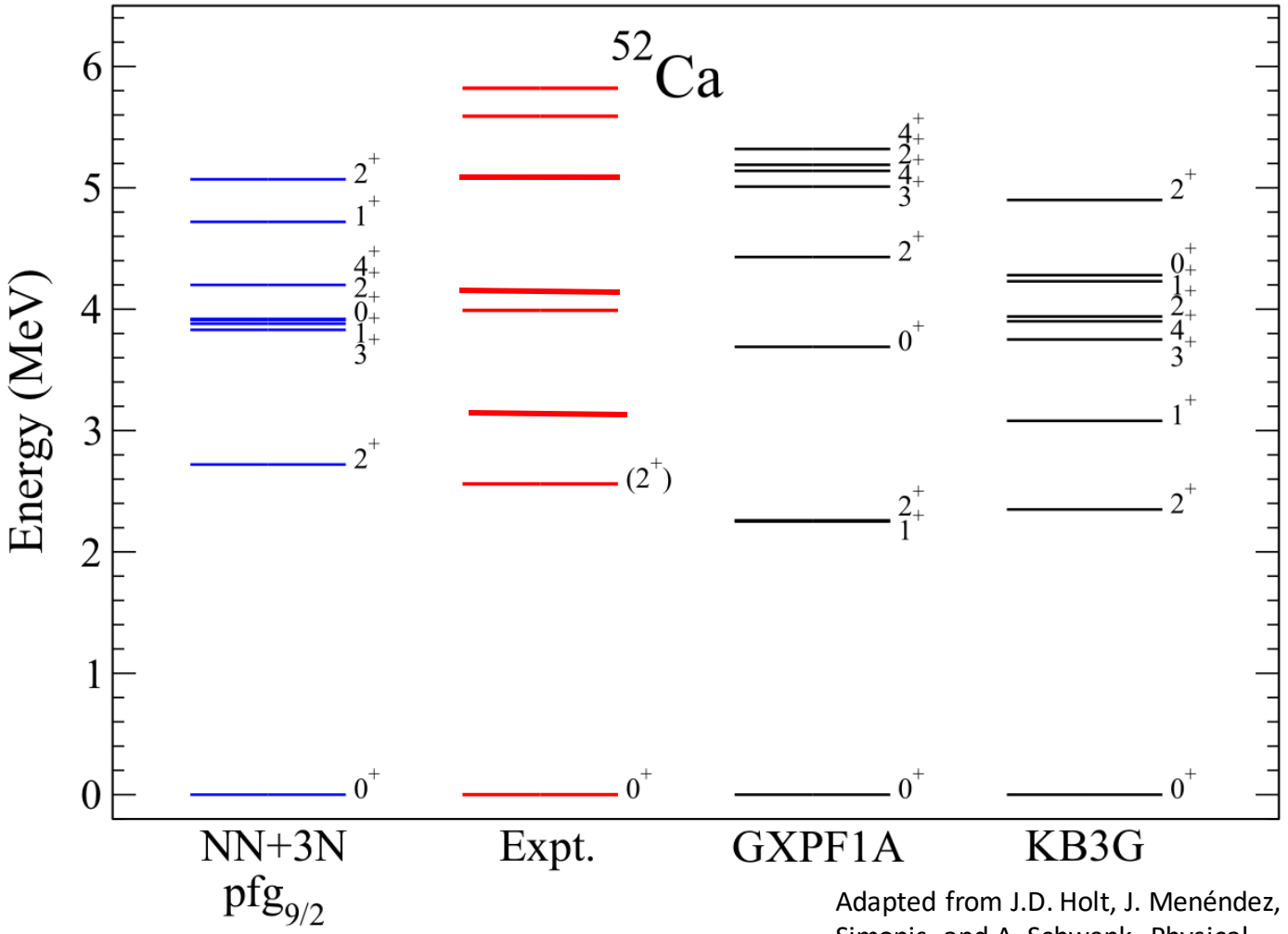


F. Browne et al. PHYSICAL REVIEW LETTERS **126**, 252501 (2021)



Summary

- Expanded Level Schemes
  - ^{52}Ca, ^{51}Ca
  - Scandium Isotopes
  - Non-observation of ^{54}Ca state
- Assign Spins where possible through angular correlations



Adapted from J.D. Holt, J. Menéndez, J. Simonis, and A. Schwenk, Physical Review C **90** (2014).

Acknowledgements

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H. Bidaman
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F. Wu

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S. Sharma
A. Talebitaher

M. Hanley
C.R. Natzke
F. Sarazin
S. Shadrick

Thank You

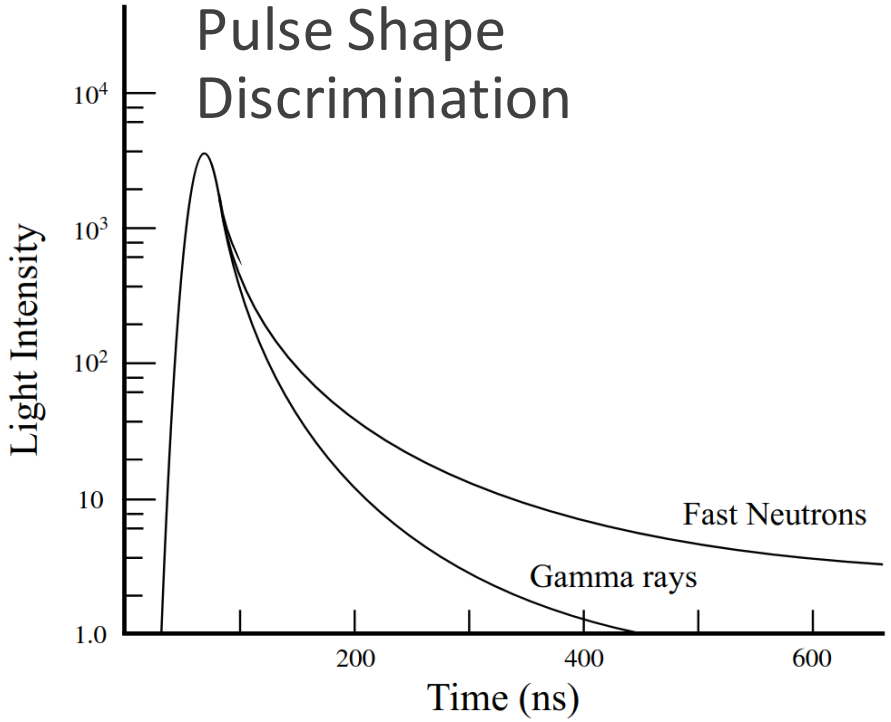
ANY QUESTIONS?

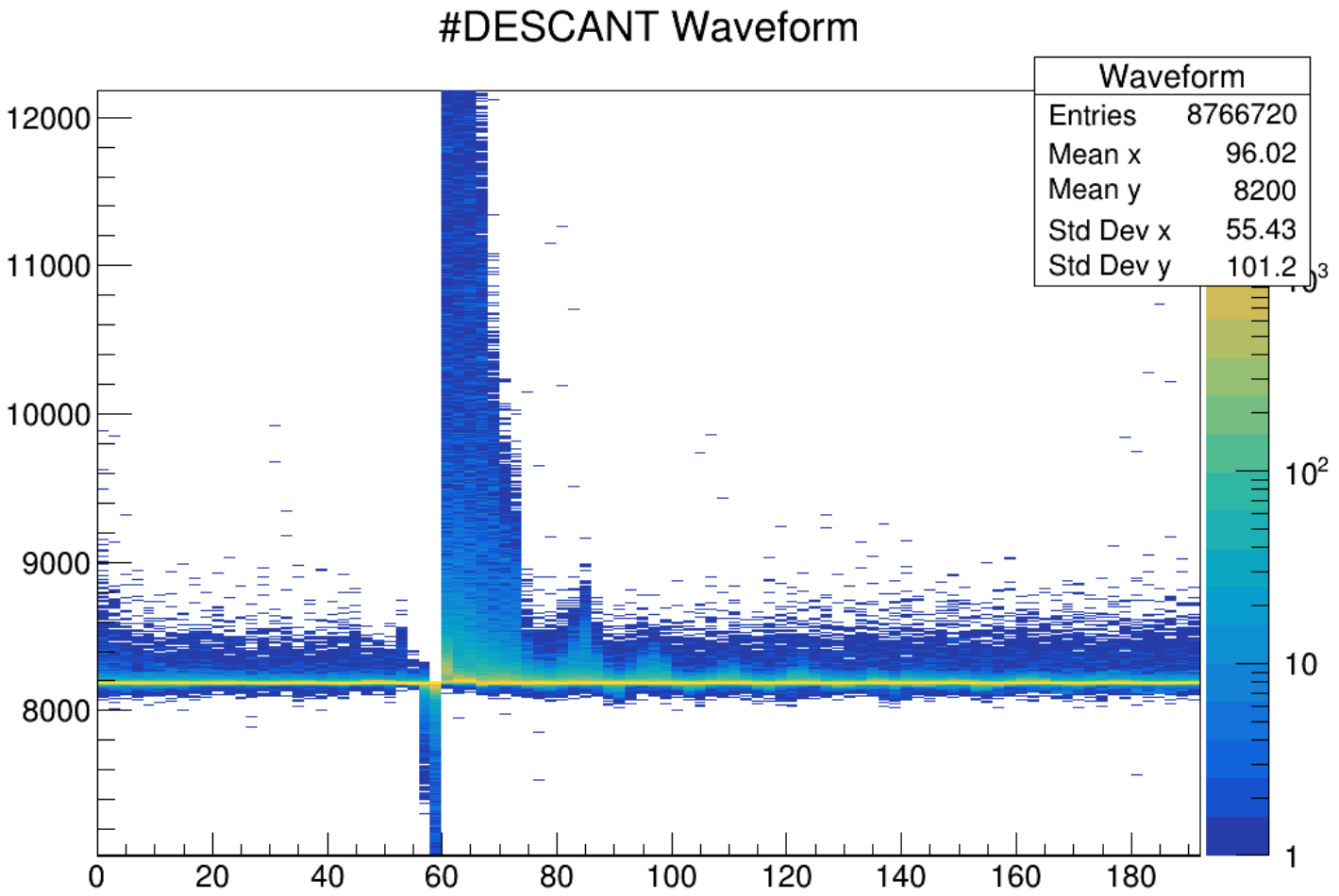
Neutron Selection

Time of Flight

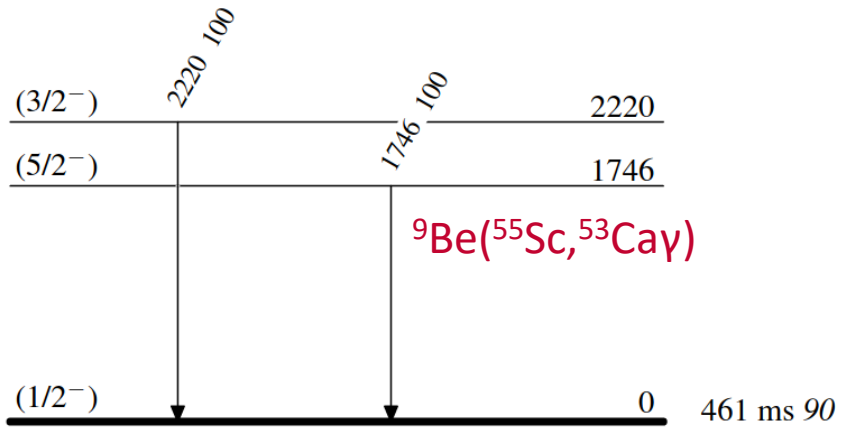
- ZDS starts the clock

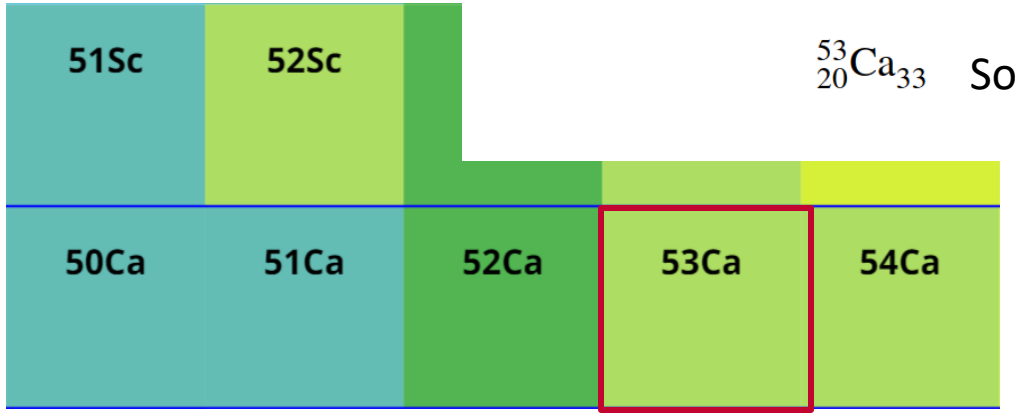
Pulse Shape Discrimination



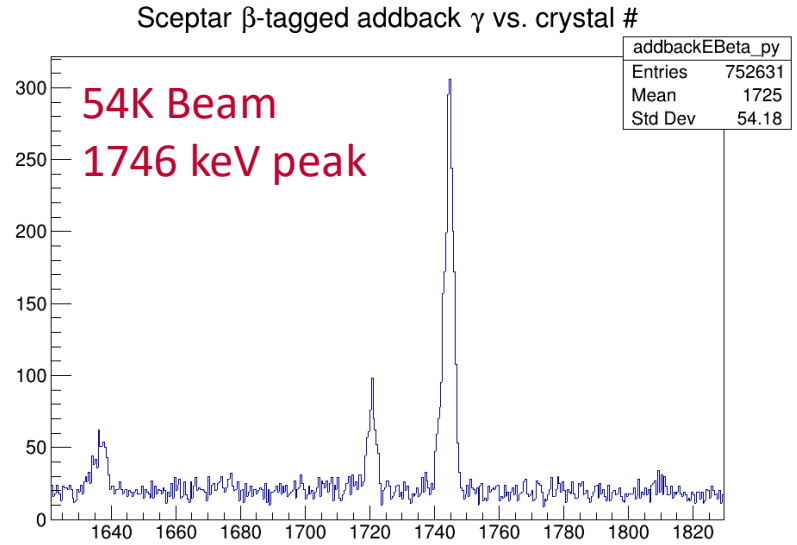


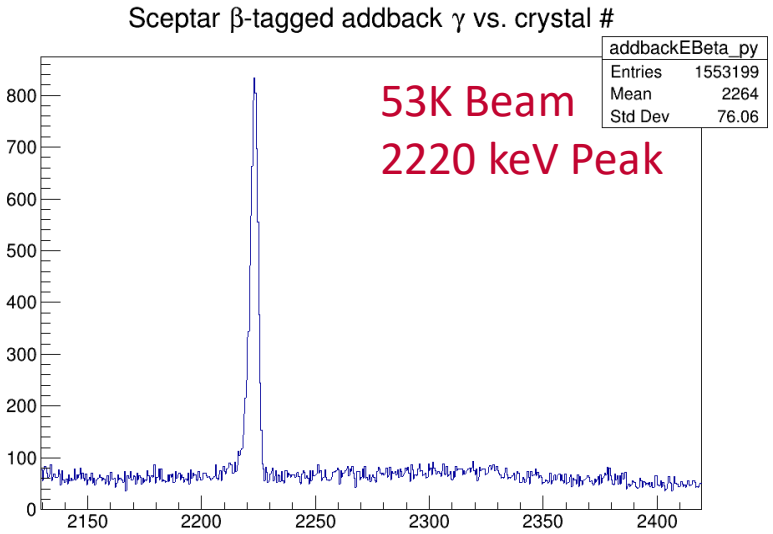
Level Schemes





$^{53}_{20}Ca_{33}$ Source: ENSDF





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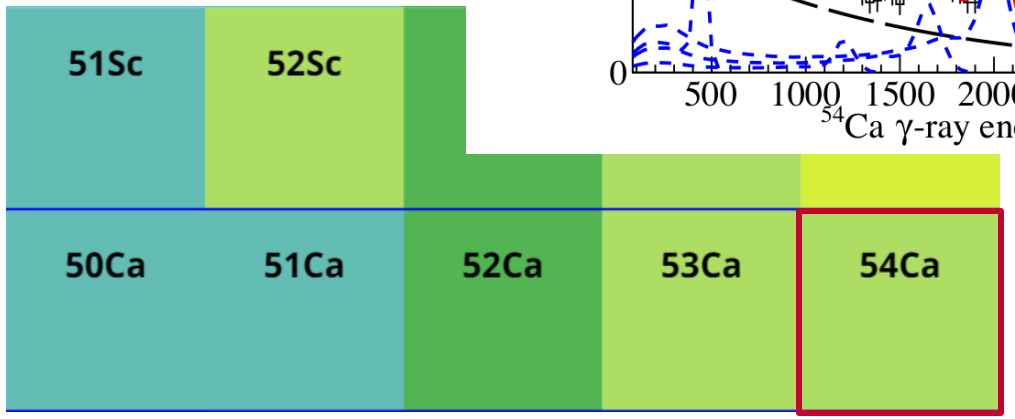

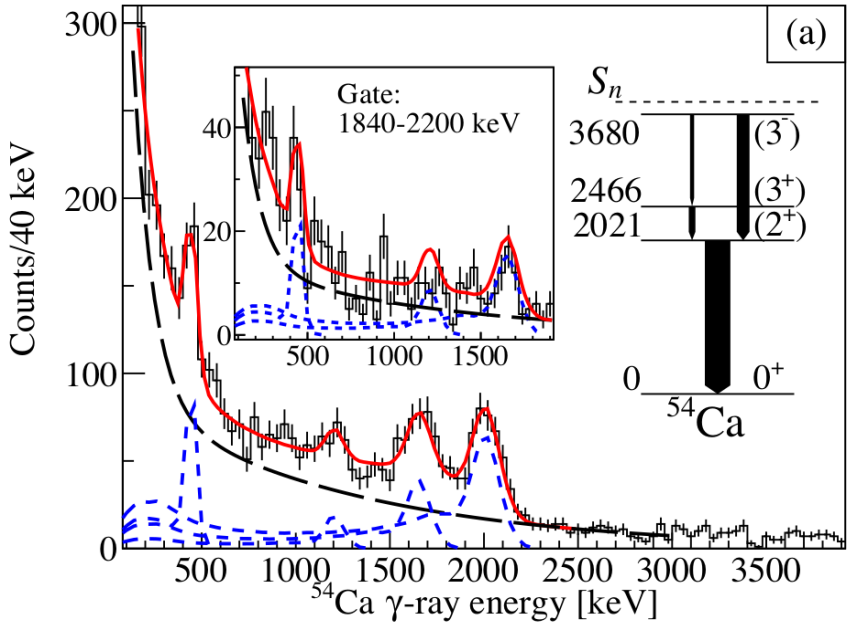

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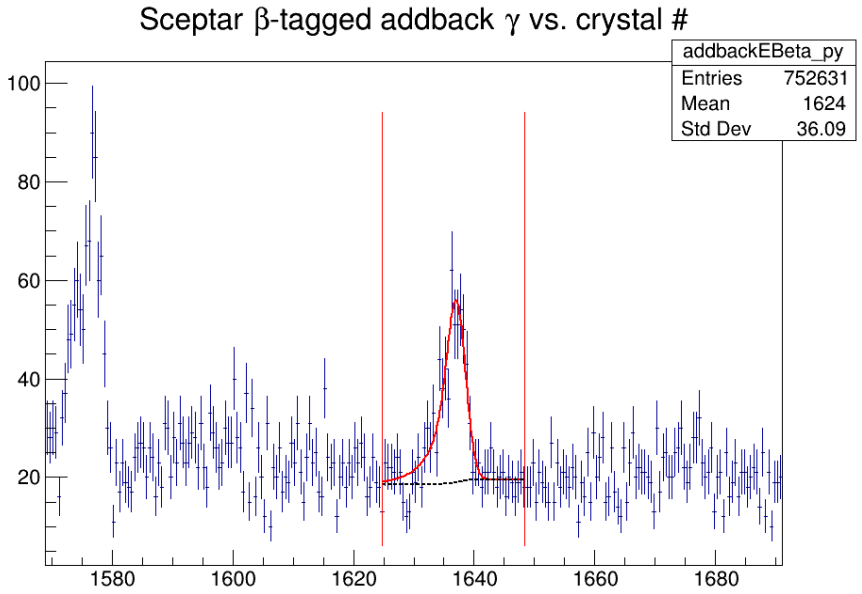
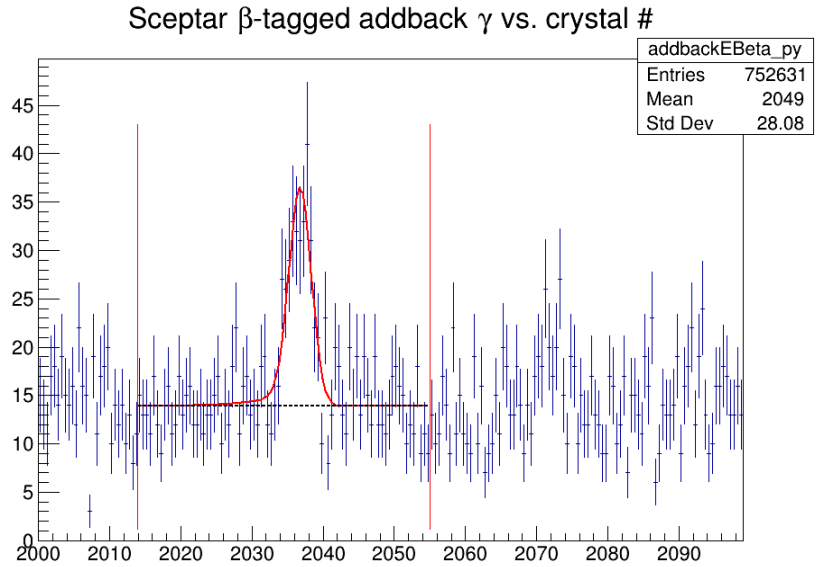
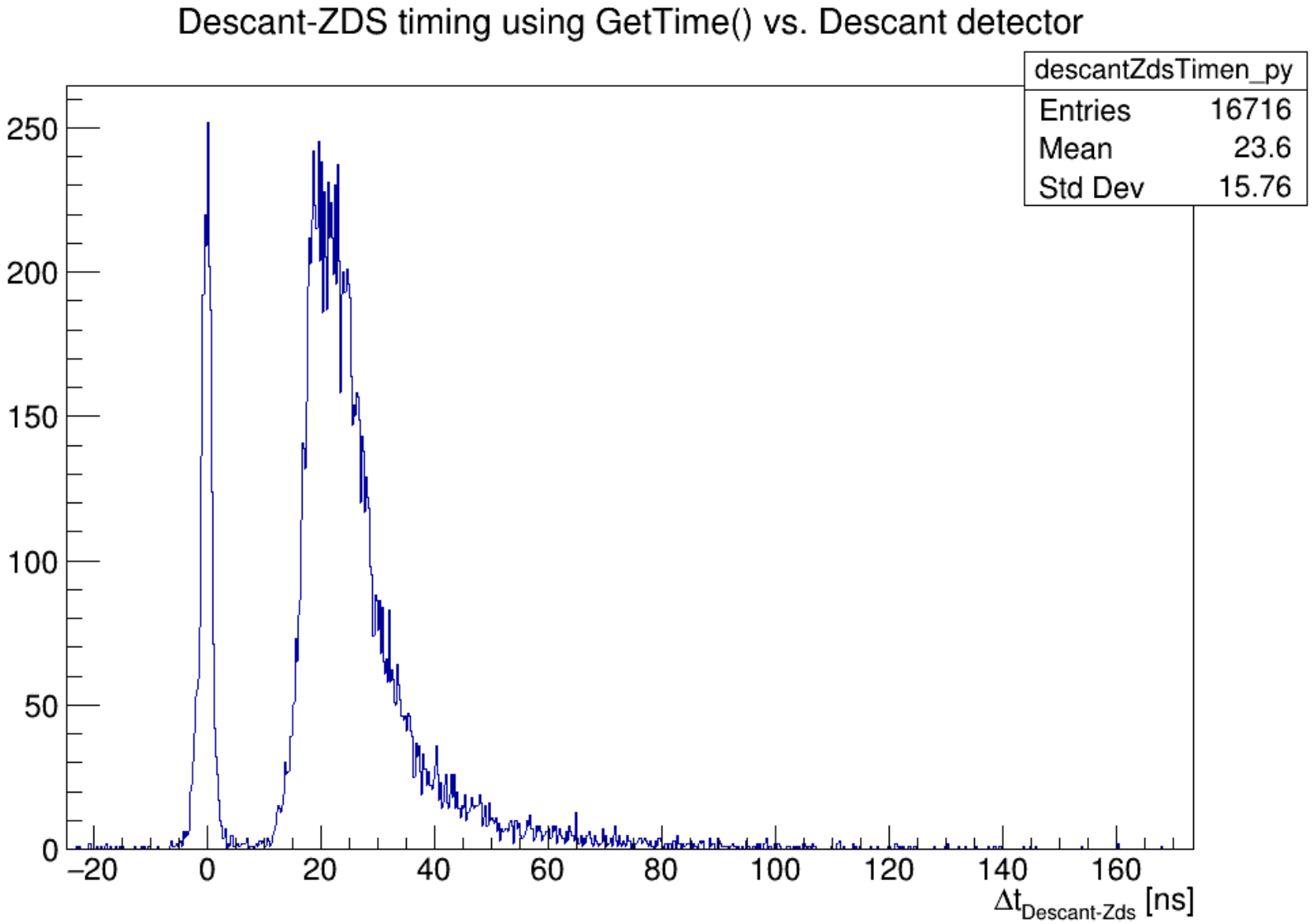




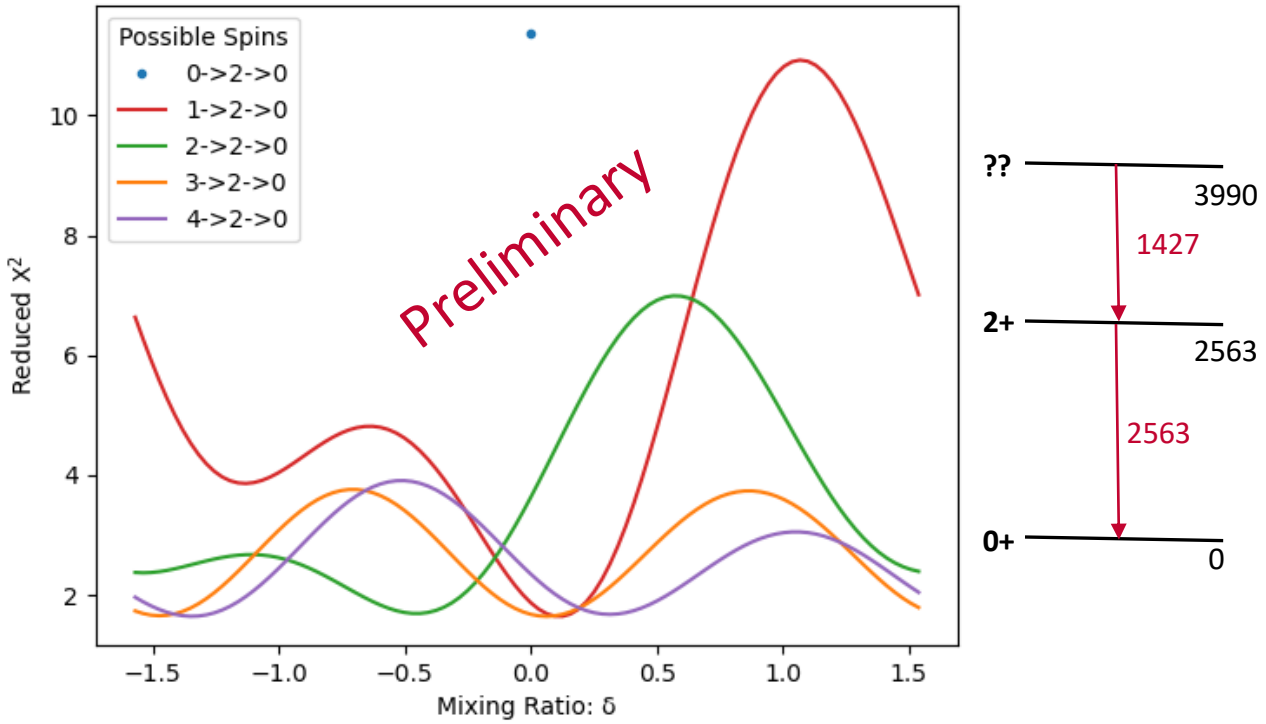
DESCANT ToF

53K Data
Target to Detector
Distance: 50cm
18 ns ~ 4 MeV
24 ns ~ 2.5 MeV
40 ns ~ 0.8 MeV
Qβ-Sn = 9.1 MeV

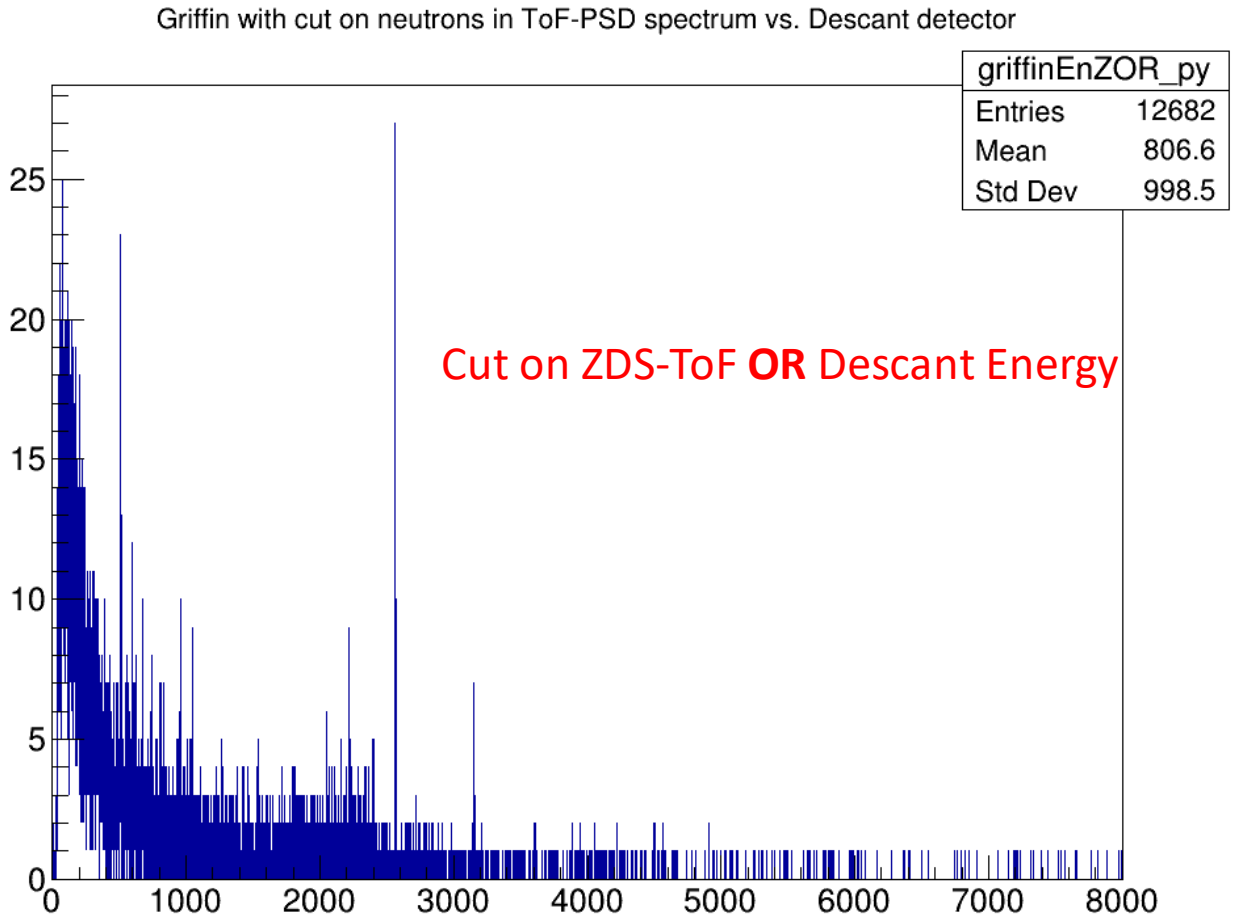


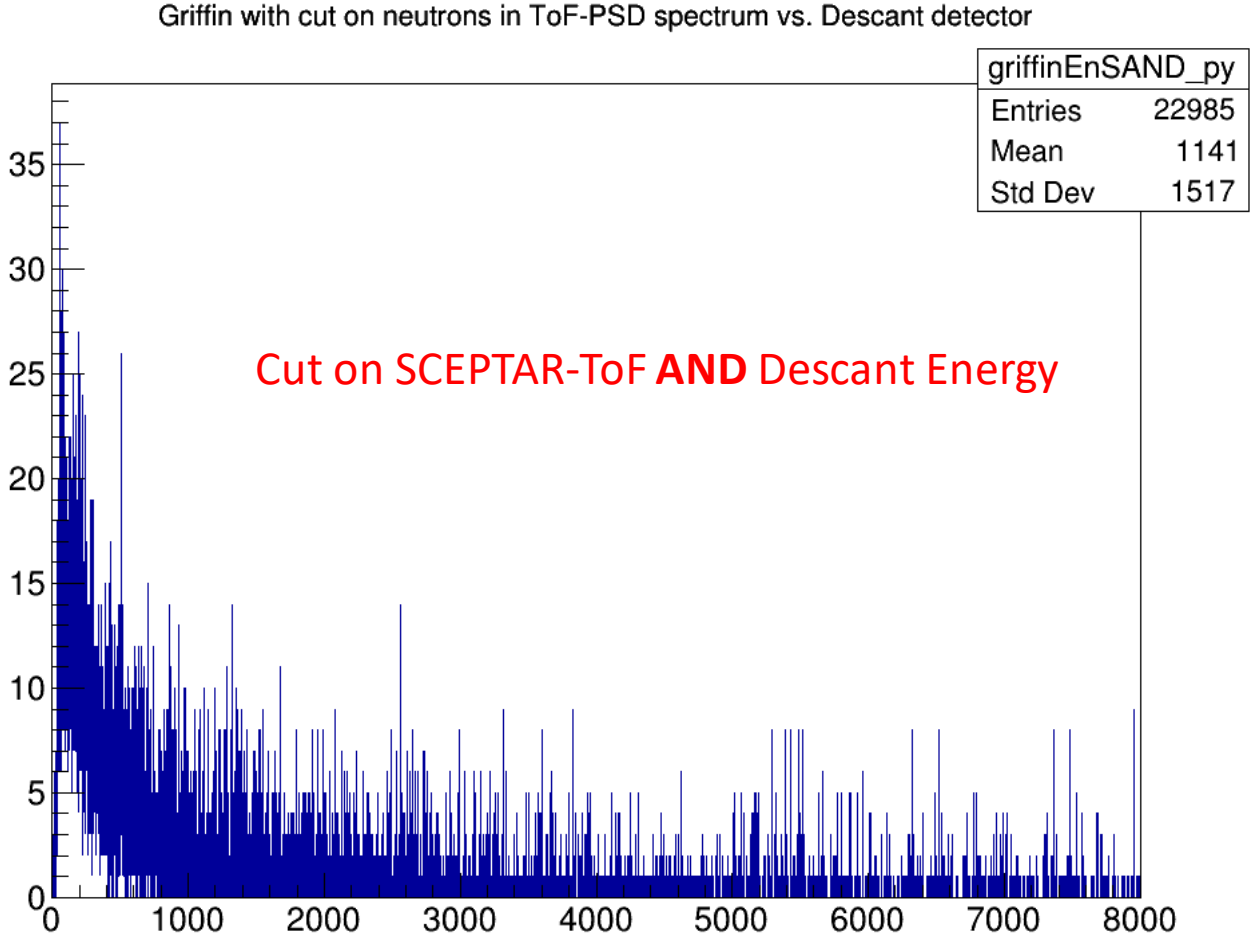
Angular Correlations

Angular correlation between coincident gamma rays



DESCANT


Griffin with cut on neutrons in ToF-PSD spectrum vs. Descant detector
griffinEnZOR_py
Entries 12682
Mean 806.6
Std Dev 998.5
Cut on ZDS-ToF **OR** Descant Energy
0
5
10
15
20
25
0
1000
2000
3000
4000
5000
6000
7000
8000

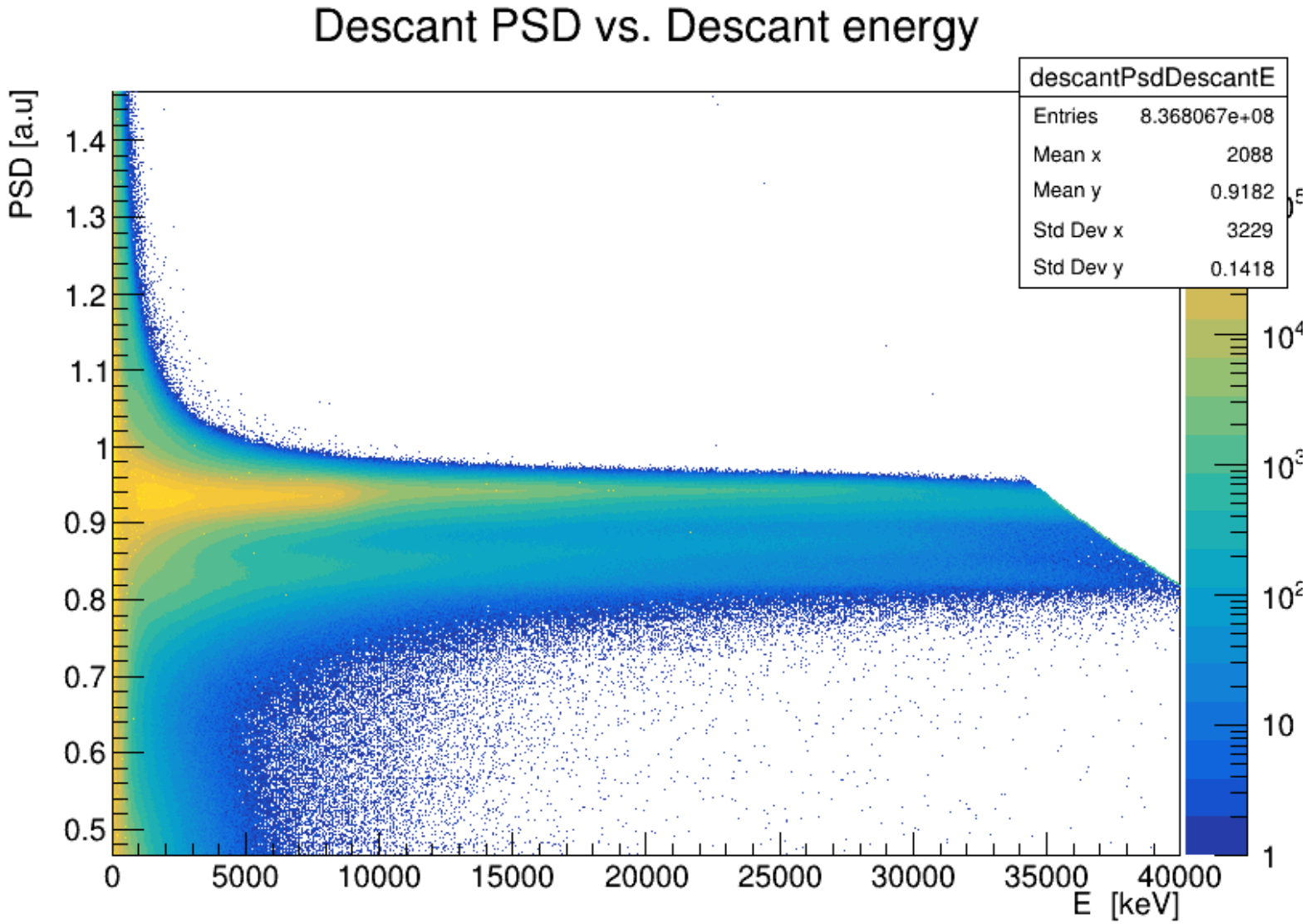

Griffin with cut on neutrons in ToF-PSD spectrum vs. Descant detector
griffinEnSAND_py
Entries 22985
Mean 1141
Std Dev 1517
Cut on SCEPTAR-ToF **AND** Descant Energy
0
5
10
15
20
25
30
35
0
1000
2000
3000
4000
5000
6000
7000
8000

DESCANT

DESCANT PSD vs Energy

Selects higher energy neutrons than time-of-flight vs. PSD cut

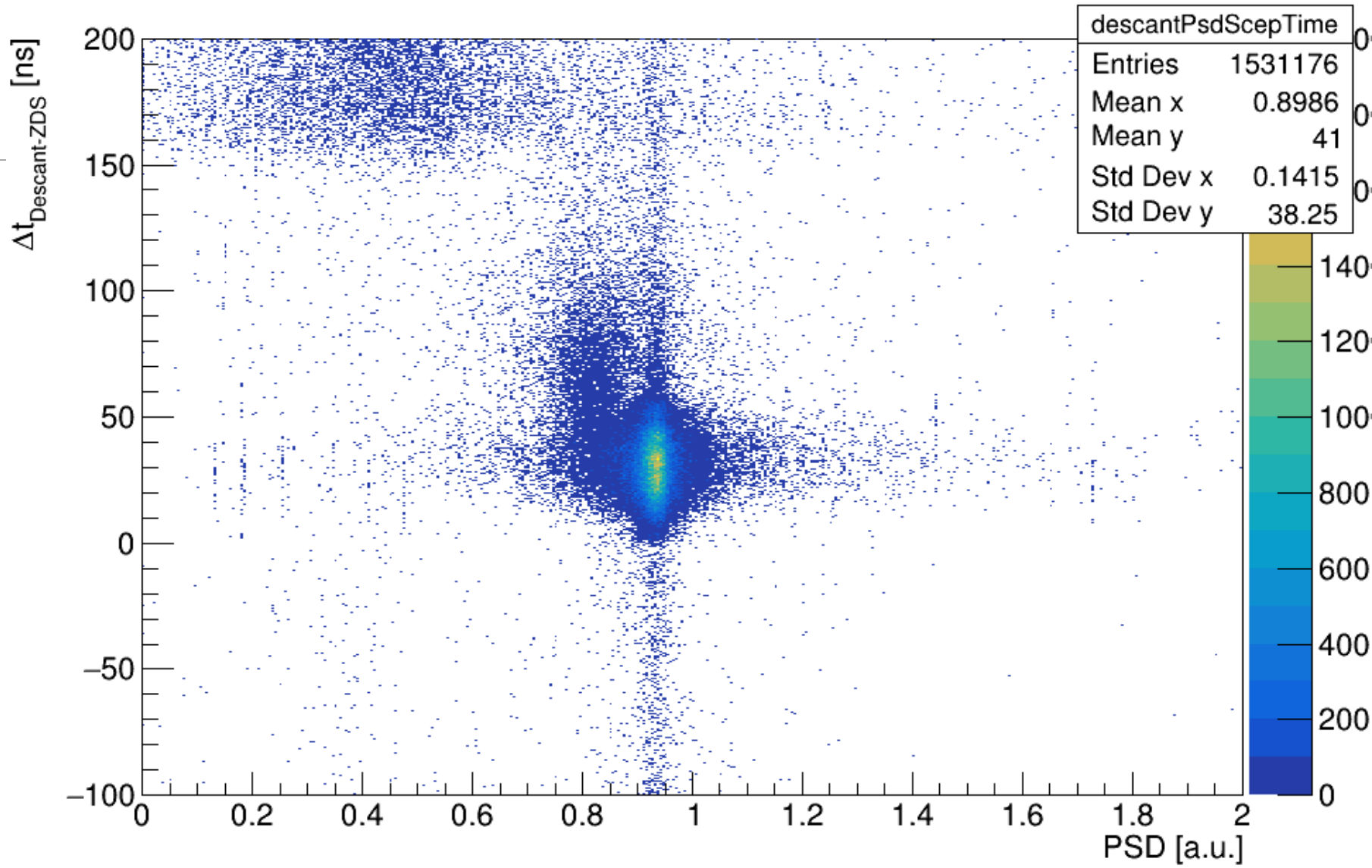
Removes any inherent timing selection



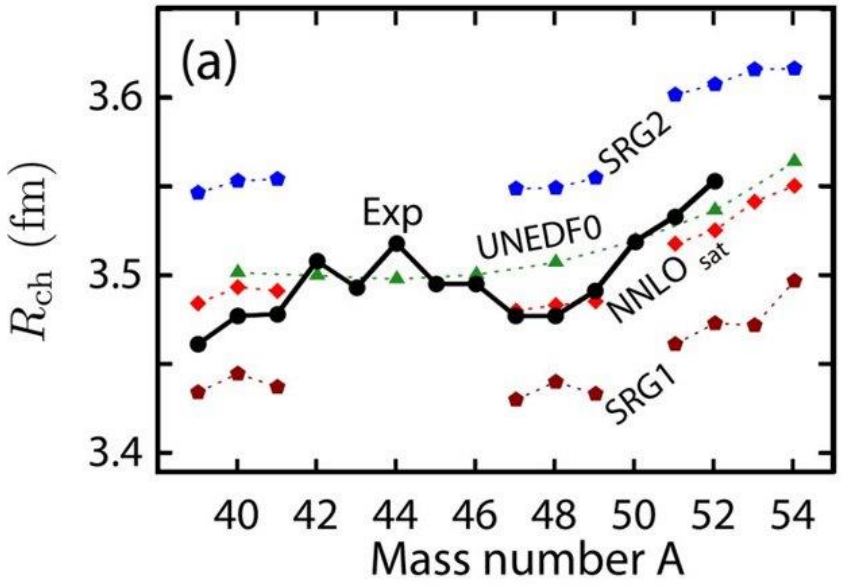
DESCANT

Tof vs PSD with SCEPTAR

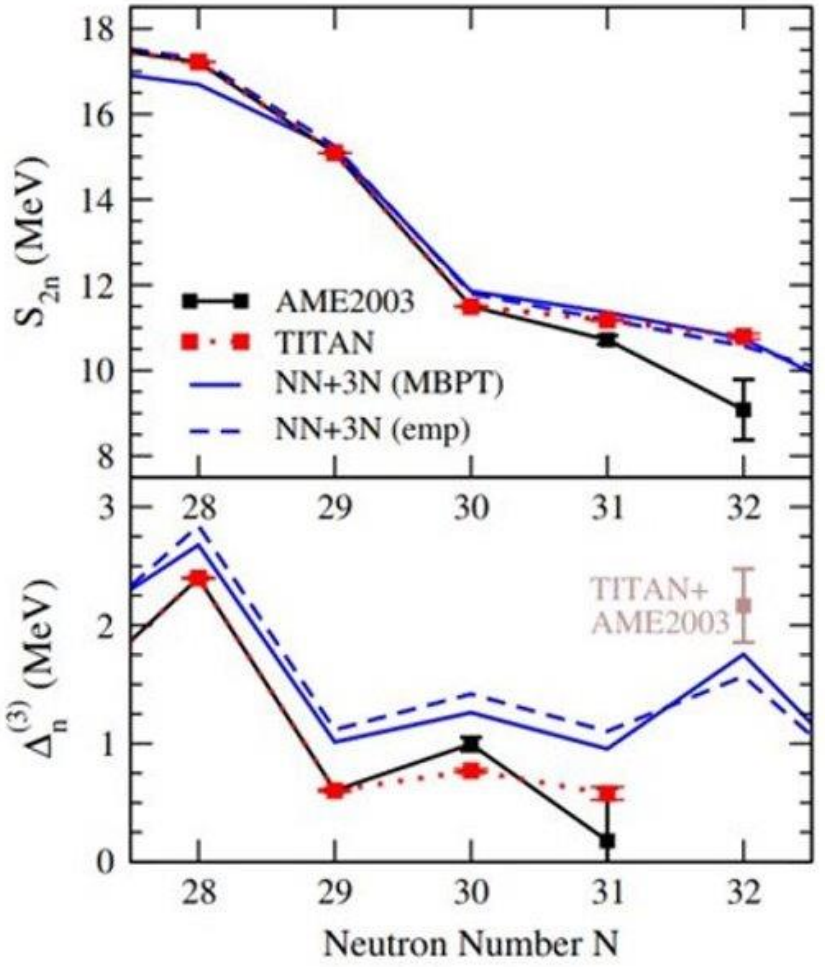
Much worse timing resolution



Observables



R.F. Garcia Ruiz et al., Nature **12**, 594 (2016).

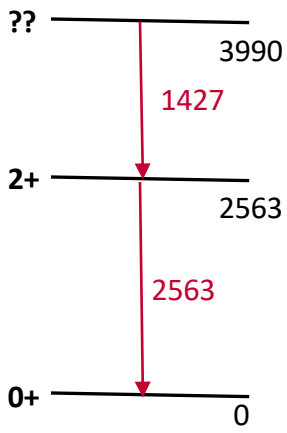


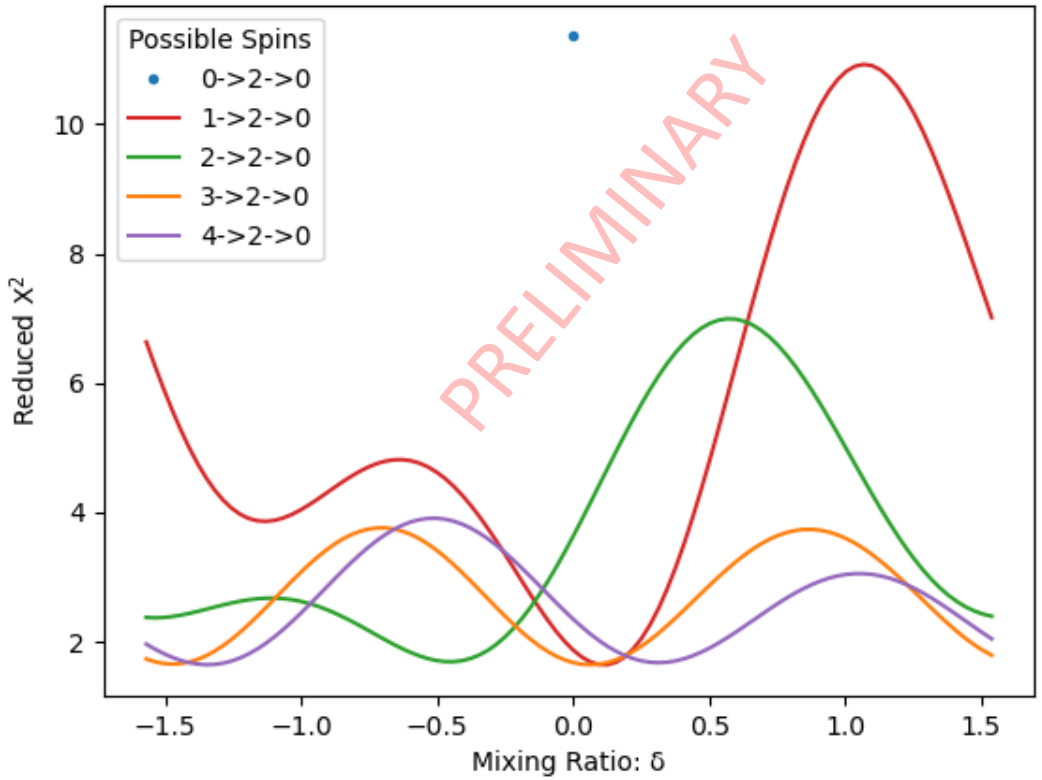
A. T. Gallant et al. Physical Review Letters **109,** 032506 (2012)

Angular Correlations

Angular correlation between coincident gamma rays

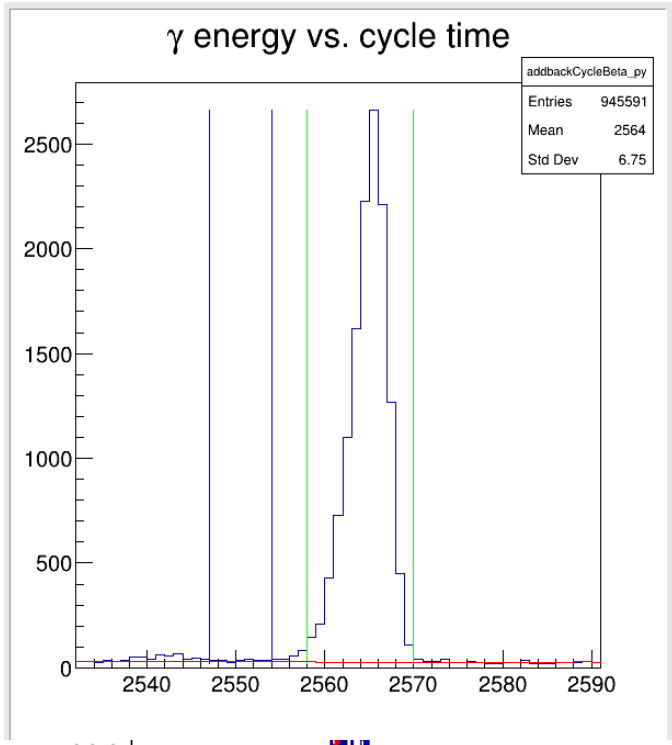
Illustrates spin assignments of the states in the cascades

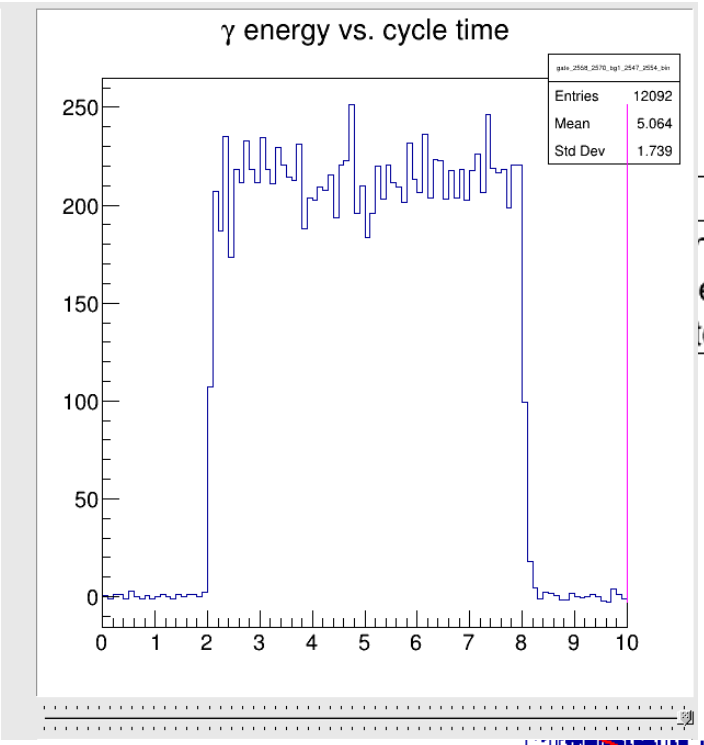


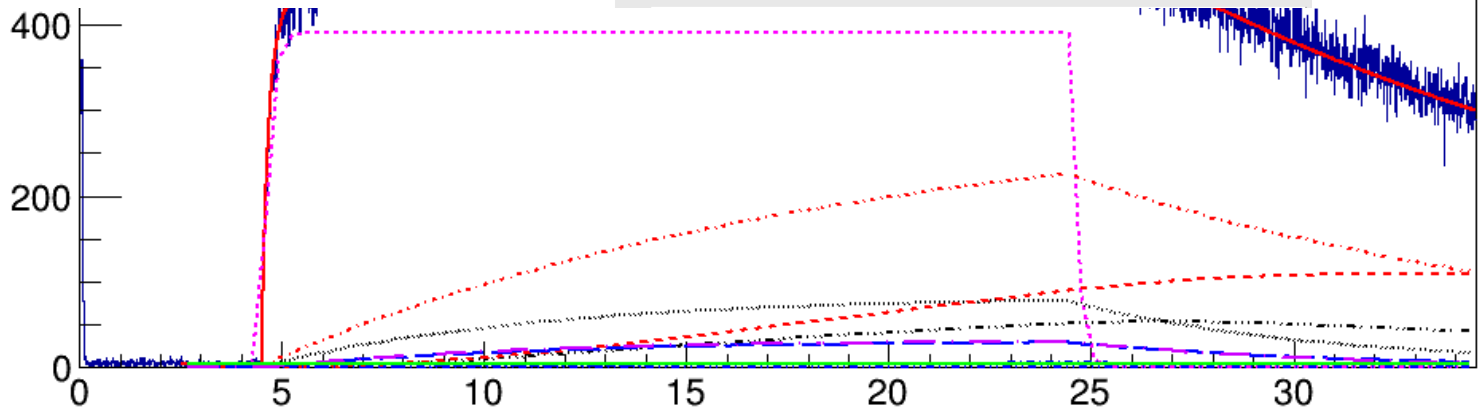


Beta Data

- Dependent on
  - Half lives
  - β-n probabilities
  - Relative efficiencies for nuclei

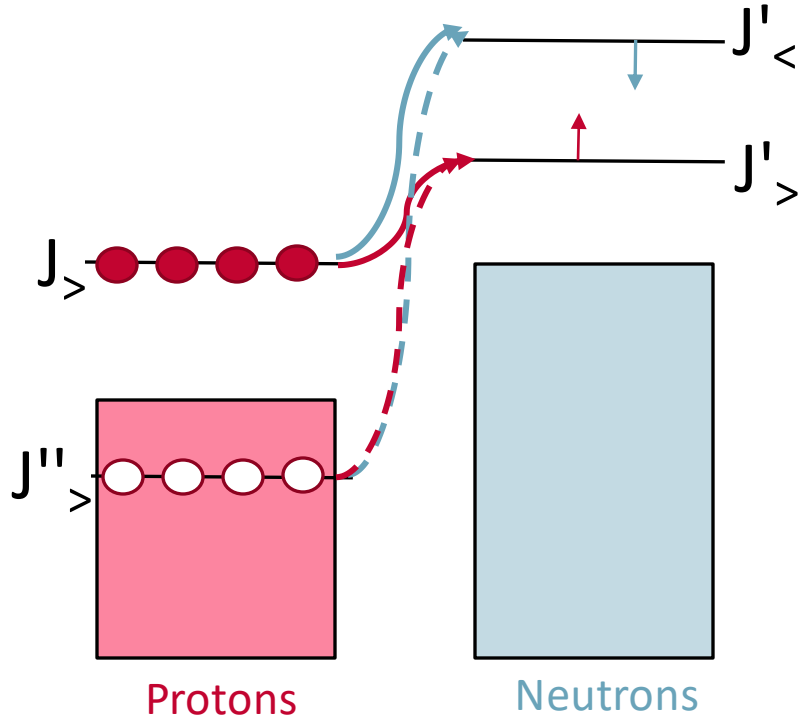






Nuclear Shell Model

- Particle Hole excitations create type II shell evolution which can alter the shell structure



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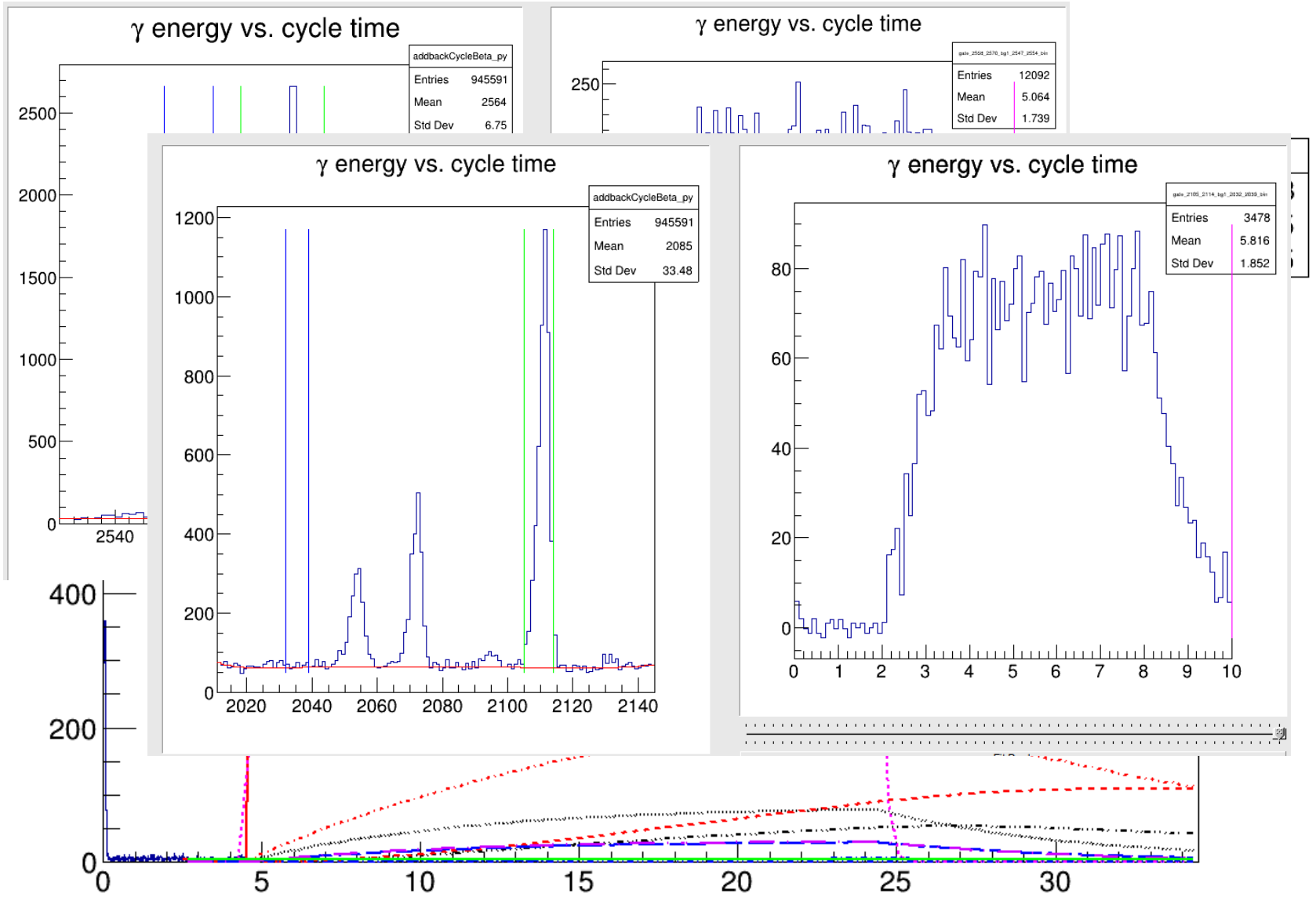
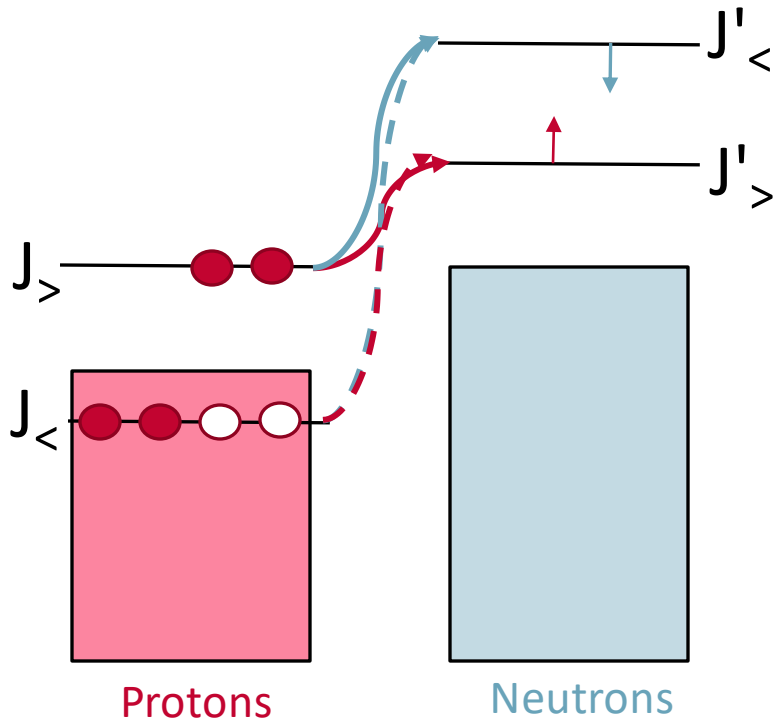


Nuclear Shell Model

- Tensor force of occupied proton shells attract/repel corresponding neutron orbital
- Particle-Hole excitations create Type-II shell evolution



Beta Data

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