

Latest Results from DESPEC Phase-0 Experiments

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for
The DESPEC Collaboration
at NuSTAR



Supplemental experiment for 'commissioning and new physics' – S480 submitted to G-PAC 22nd Oct 2019

Structure of the heaviest N=Z nuclei: Seniority Transitions and EM Transition Rates in ⁹⁴Pd

Abstract: We will exploit the unique FAIR-0 instrumental setup comprising the FRS, AIDA, bPlast, DEGAS/GALILEO and FATIMA LaBr₃ detectors to focus on the precision study of electromagnetic transition rates in the T_z=+1 nucleus ⁹⁴Pd. This will provide the first extended commissioning experiment with new physics output from the DESPEC collaboration within NUSTAR. The ⁹⁴Pd secondary nuclei will be produced using the fragmentation of a ¹²⁴Xe primary beam at an energy of 850 MeV per nucleon. Specifically, we will measure the lifetimes of the yrast I^π=6⁺ and 8⁺ states below the I^π=14⁺, T_{1/2}=499(13) ns isomer in ⁹⁴Pd. These measurements will enable precise verification of shell model calculations for the Pd isotopes approaching ¹⁰⁰Sn and the N = Z line, and provide insights on the purity of g^{9/2} configuration in the mixing of excitations from lower N = 3 pf and higher N = 4 sdg orbitals. The fragmentation products will be transported to the FRS S4 focal plane, implanted into the AIDA active stopper and will be selected event-by-event using the standard Bp-ΔE-Bp and ToF-Bp-ΔE particle identification methods. For the EM transition rate measurements, time differences between γ-rays detected in the LaBr₃ fast γ-ray scintillators of FATIMA will be analysed in coincidence with the timing signals from SC41 and bPlast, and AIDA implantation signal. The experimental set-up will also allow a search for evidence of proton radioactivity in ⁹⁷In which has been indirectly inferred in experiments at RIKEN, Japan.

GSI Darmstadt, Germany: **M. Görská**, H. M. Albers, T. Arici, A. Banerjee, P. Boutachkov, J. Gerl, H. Grawe, I. Kojouharov, A. Sharma, H. Schaffner
University of Surrey, UK: **P. H. Regan**, Zs. Podolyak, D. T. Doherty, G. Lotay, W. N. Catford, R. Canavan, S. Jazrawi, S. M. Collins, M. Brunet, T. Parry
KTH Stockholm, Sweden: **B. Cederwall**, Ö. Aktas, A. Ataç Nyberg, J. Blomqvist, T. Bäck, A. Ertoprak, A. Johnson, R. Liotta, X. Liu, C. Qi, W. Zhang, and R. Wyss
University of Cologne, Germany: **I. Jolie**, A. Blazhev, A. Esmaylzadeh, V. Karayonchev, L. Knafla, A. Petkova, J.-M. Regis, P. Reiter
TU Darmstadt, Germany: U. Ahmed, S. Alhomaidhi, N. Hubbard, P. John, H. Mayr, A. Mistry, M. Rudiger, T. Kroll, N. Pietralla, E. Sahin, V. Werner, R. Zidarova
University of Brighton, UK: A. M. Bruce, A. P. Weaver, C. E. Jones
SI Ljubljana, Slovenia: J. Vesic, M. Lipoglavsek, M. Vencelj
University of Liverpool, UK: A. J. Boston, H. C. Boston, L. J. Harkness-Brennan, D. T. Joss, D. S. Judson, R. D. Page, E. S. Paul
University of Edinburgh, UK: P. Woods, T. Davinson, C. Appleton, C. Bruno, D. Kahl, O. Hall, L. Sexton
Warsaw University, Poland: M. Palacz et al,
Jyväskylä University, Finland: P. Ruotsalainen, T. Grahn, J. Uusitalo, K. Auranen
York University, UK: R. Wadsworth et al.,
University of West Scotland, UK: B. S. Nara Singh, M. Bowry, D. O'Donnell, M. Scheck, J. F. Smith and J. Vilhena
University of Milano, Italy: G. Benzeni, M. Poletti et al.,
INFN-Legnaro, Italy: J. Valiente, G. de Angelis, M. L. Cortes, A. Gottardo, D. Napoli and E. Gregor
INFN-Padova, Italy: D. Mengoni et al.,
IFIN-HH Magurele, Romania: N. Marginean et al.,
Madrid, Spain: L. Fraile, J. Benito, J. R. Murias and J. M. Udías
GANIL, France: G. de France et al.,



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27. November 2019

S480: "Structure of the heaviest N=Z nuclei: Seniority Transitions and EM Transition Rates in ⁹⁴Pd"

Dear Colleague,

The management of GSI/FAIR would like to thank you for submitting a proposal for the Physics Run in 2020. The General Program Advisory Committee evaluated your request for 21 shifts of beam time in writing. The considerations of the G-PAC were based on their assessment of the scientific importance of the proposed research, its feasibility and its reliance on aspects of the GSI/FAIR facility that are unique.

For your proposal S480¹ the G-PAC formulated the following evaluation with which I concur:

Regarding the proposal "Structure of the heaviest N=Z nuclei: Seniority Transitions and EM Transition Rates in ⁹⁴Pd" (Proposal S480), the G-PAC recommends this proposal with 21 shifts of main beamtime be allocated for this measurement.

Further Steps

- For scheduling your experiment, please contact your local contact person.
- The department "Safety and Radiation Protection" is to be informed on the planned set-up of the experiment and their consent is required before running an experiment. Your local contact person might help you with this.
- The form "F.14 Safety at GSI" attached to this letter needs to be completed by the spokesperson and the external participants of the experiment and sent to the secretary of Safety and Radiation Protection, Mrs. Andrea Brühne. The form is also available at the GSI guest-office.

Geschäftsführung:
Professor Dr. Paolo Giubellino
Ursula Weyrich
Jörg Blaurock

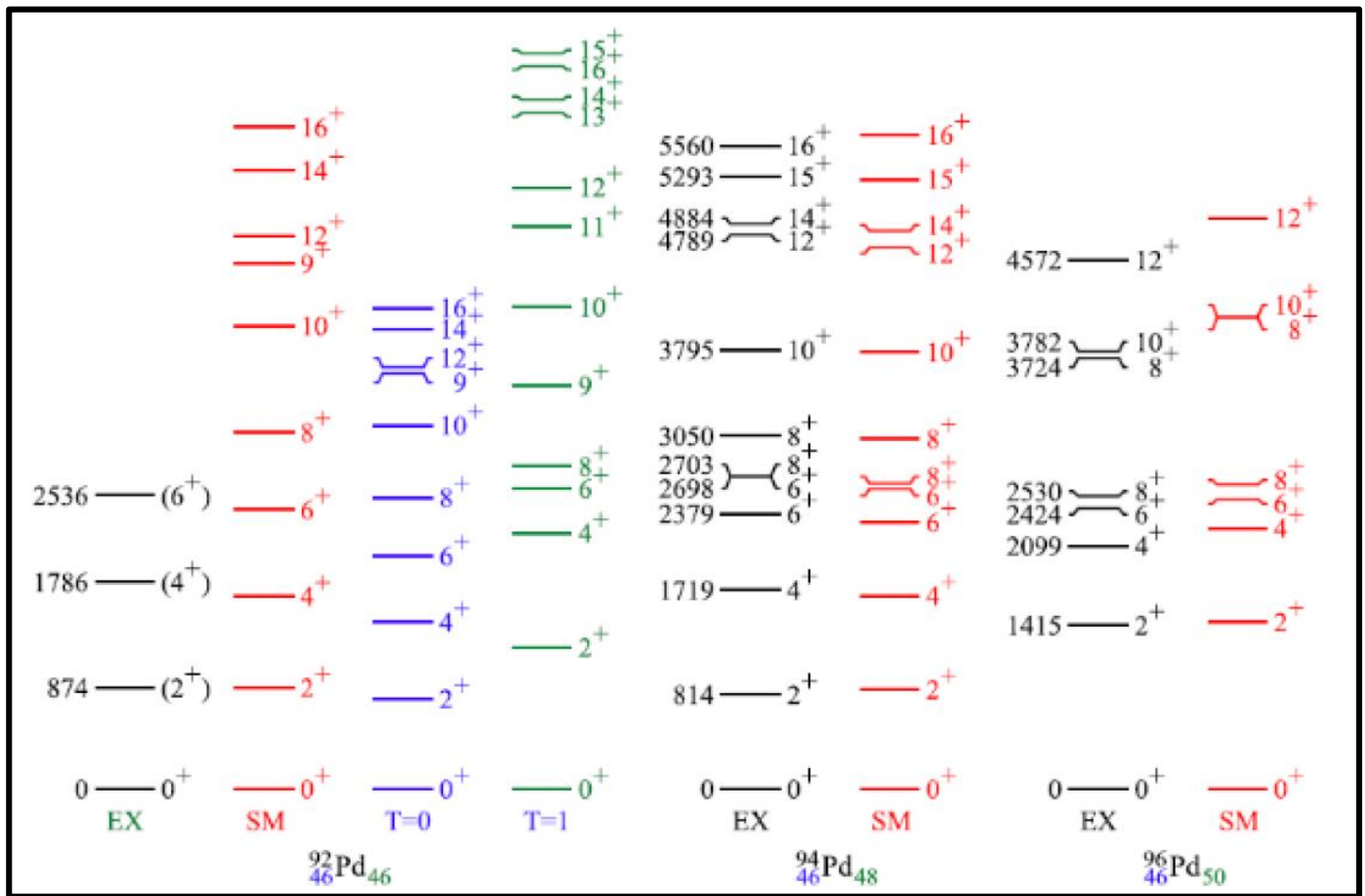
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Amtsgericht Darmstadt HRB 89372
US-IDNr.: DE 275 595 927

Commerzbank Darmstadt
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BIC COBADE33HAN

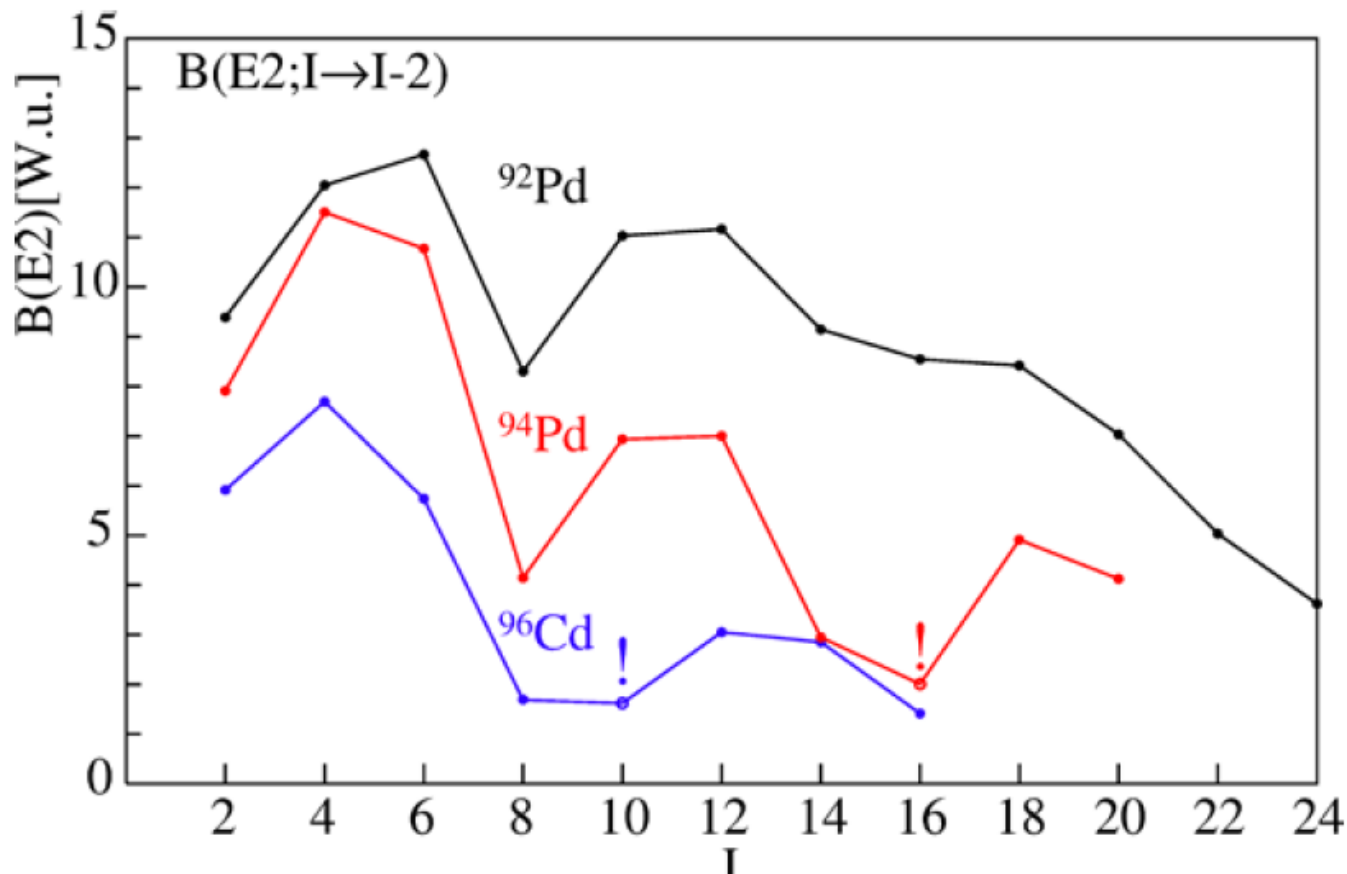
GSI:
Vorsitzender des Aufsichtsrates:
Ministerialdirektor Dr. Volkmar Dietz

Sitz: Darmstadt
Amtsgericht Darmstadt HRB 1528
US-IDNr.: DE 111 671 917

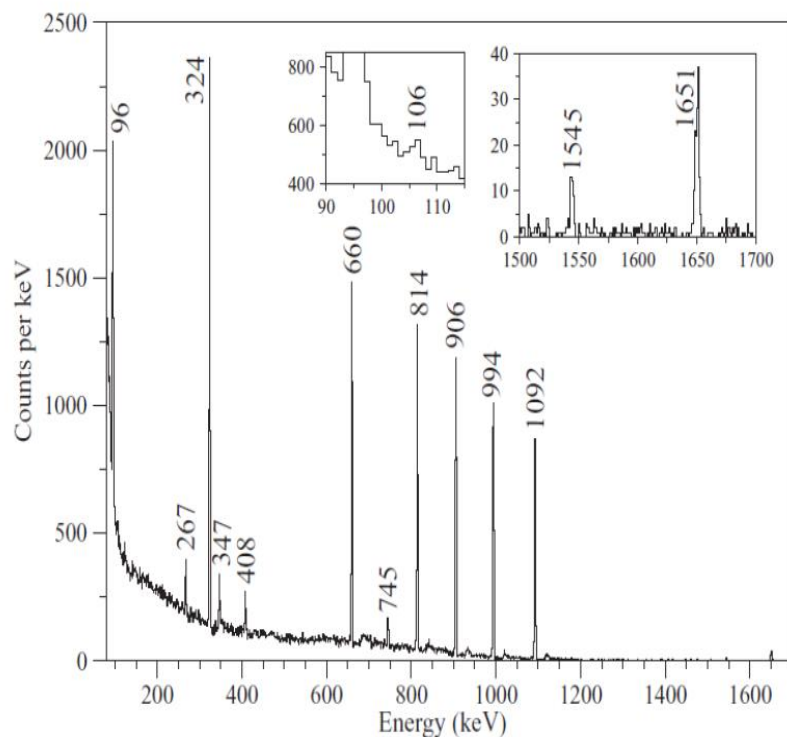
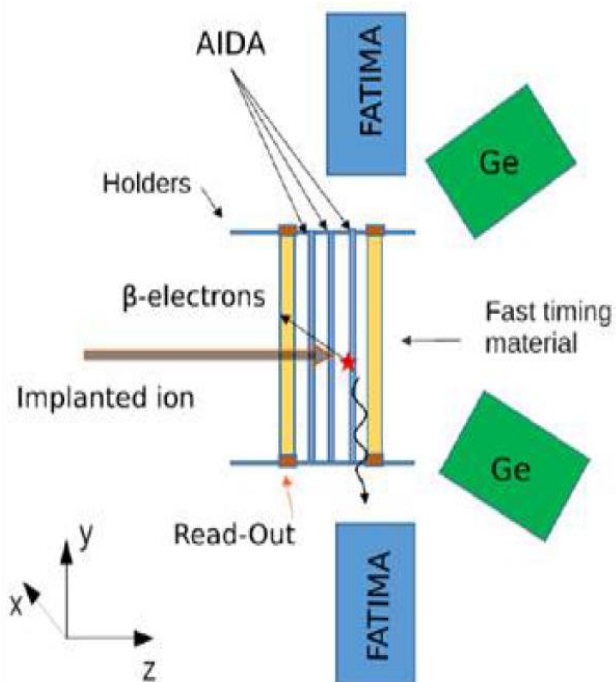
Landesbank Hessen/Thüringen
IBAN DE56 5005 0000 5001 8650 04
BIC HELADEF333



State (I ^π)	T _{1/2}	G9 B(E2)	GDS B(E2)	F5G9 B(E2)	γ rays (keV)	ε _γ Efficiency (FATIMA)	FATIMA-ΔT coinc events per day / per 7 day expt.
6 ⁺	>10 ps	10.77	25.06	12.09	324 ; 660	0.08 ; 0.04	330 / 2.3x10 ³
8 ⁺	~1 ns	4.19	7.94	6.90	1092 ; 324	0.02 ; 0.08	160 / 1.1x10 ³



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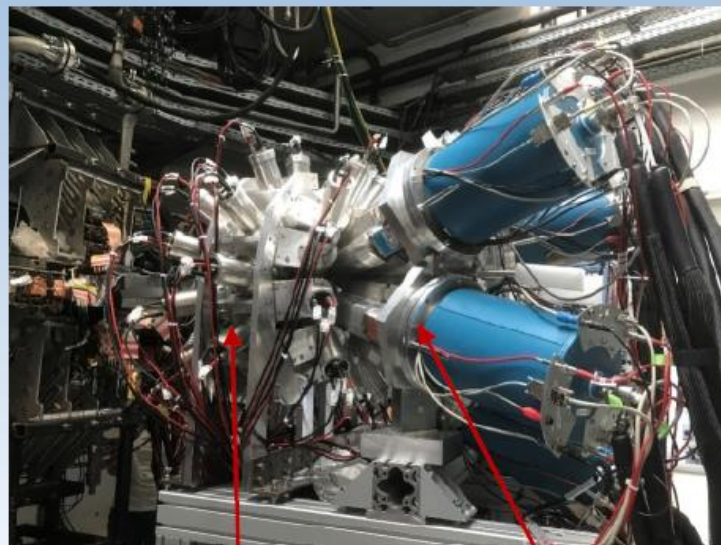
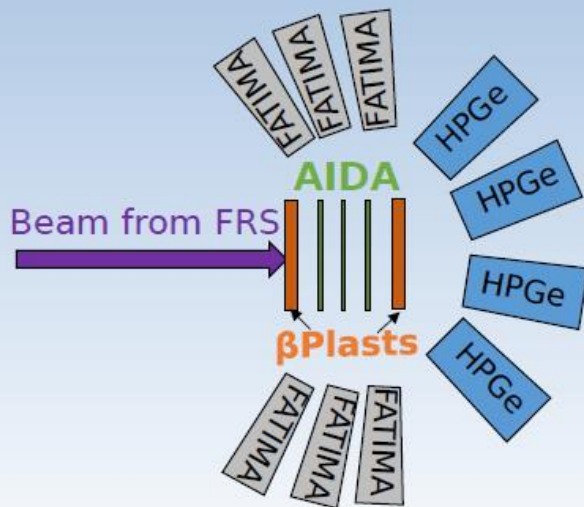
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Physics commissioning 2020

- S480 Physics Commissioning March 2020
- Fragmentation of ^{124}Xe beam @ 850 MeV/u
- Carried out just before COVID-19 lockdown

First results from S480 experiment:
talk of **S. Jazrawi**

- Implantation array **AIDA**: 3 highly-segmented DSSD layers
- AIDA sandwiched by two **β Plasts**: fast plastic scintillators
- 36 **FATIMA** $\text{LaBr}_3(\text{Ce})$
- 6 **GALILEO** triple clusters
- New EDAQ

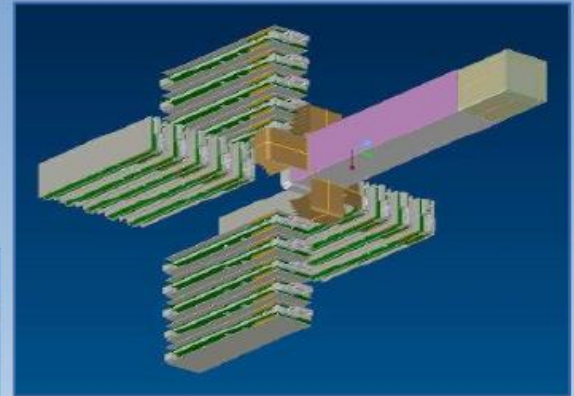


FATIMA modules

GALILEO triple clusters

Current setup - AIDA

- The **A**dvanced **I**mplantation **D**etector **A**rray (Edinburgh, Daresbury, Liverpool)
- Stack of three, $8 \times 8 \text{ cm}^2$, 1-mm thick DSSDs

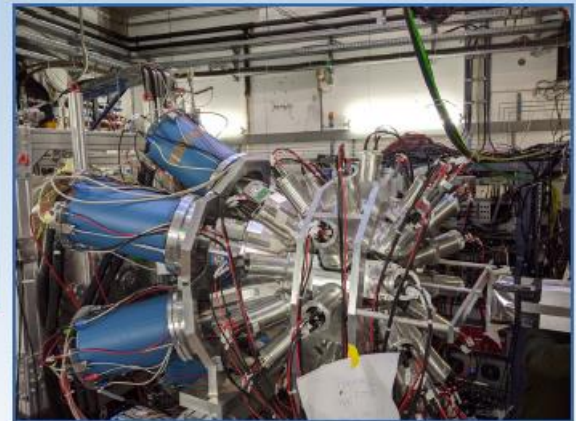
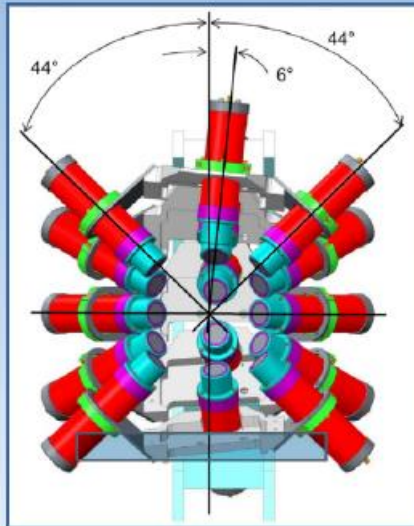
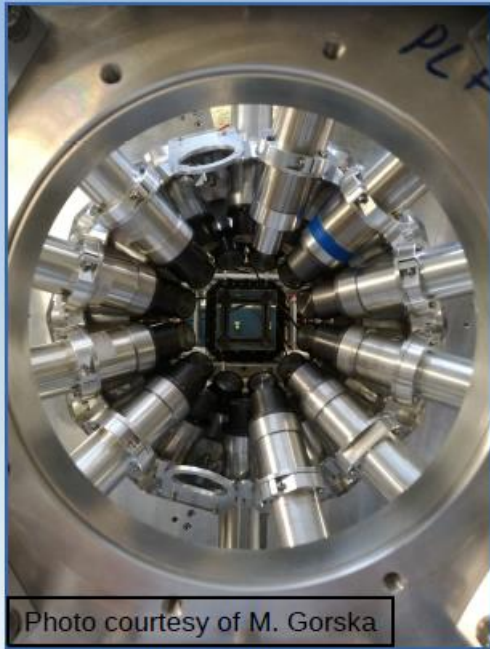


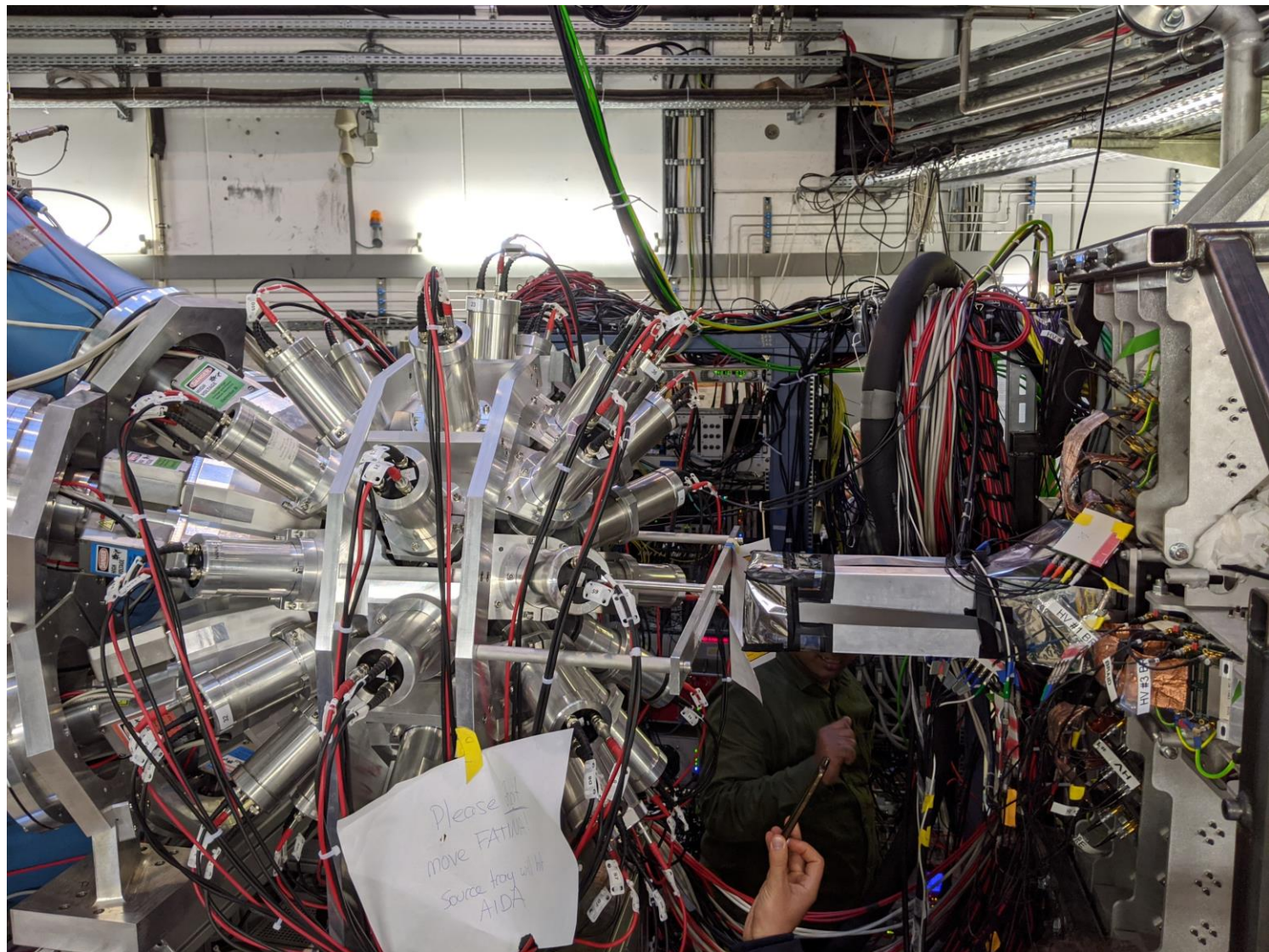
- Dedicated ASIC chips allow **large dynamic range**
- **Implants**: multi-GeV; **Decays**: tens-of-keV $\rightarrow$ MeV
- Triggerless DAQ, high data throughput
- Fast recovery time $< 40 \mu\text{s}$



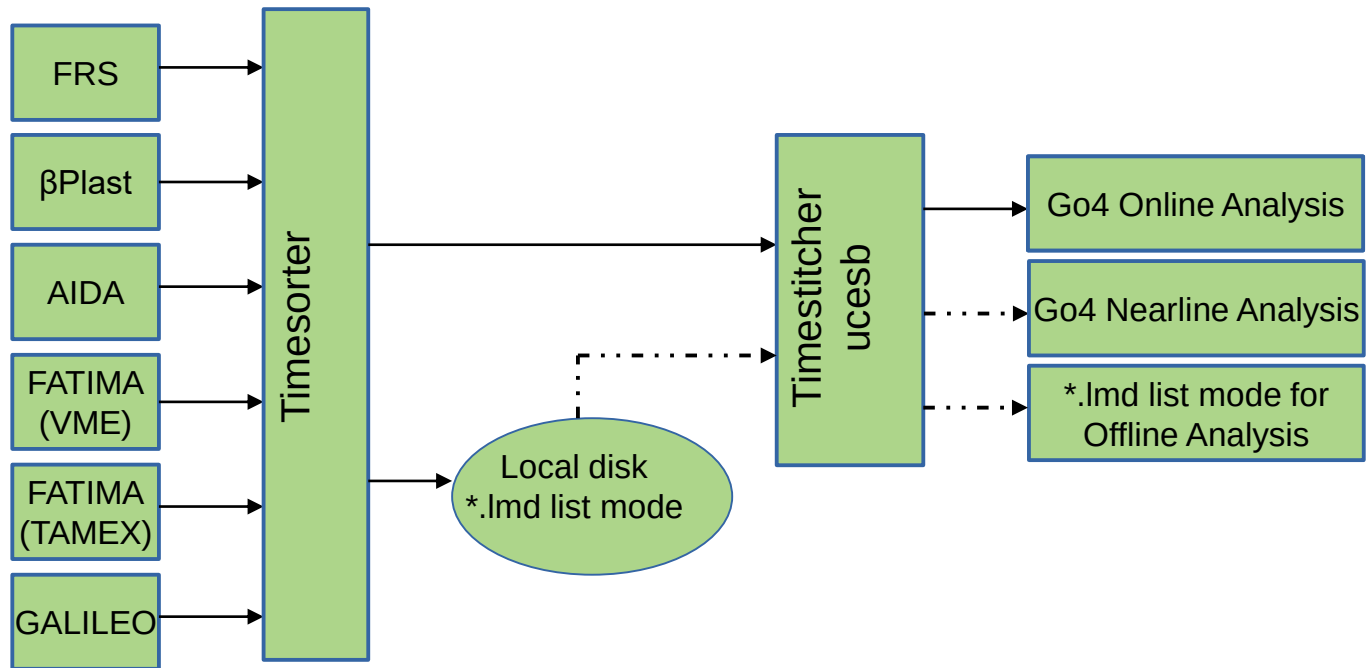
Current setup - FATIMA

- **FA**st **TIM**ing **A**rray of 36 $\text{LaBr}_3(\text{Ce})$ crystals
- Brighton, Surrey, IFIN-HH, Cologne, Daresbury, Madrid, Manchester...
- 6 IFIN-HH modules at GSI
- Extremely stable VME electronics > 1yr





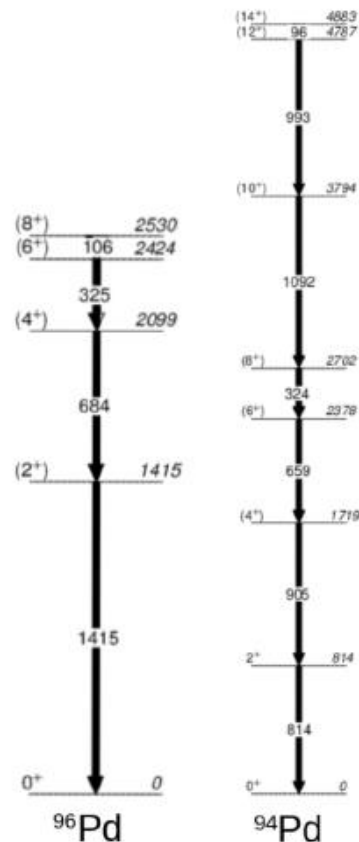
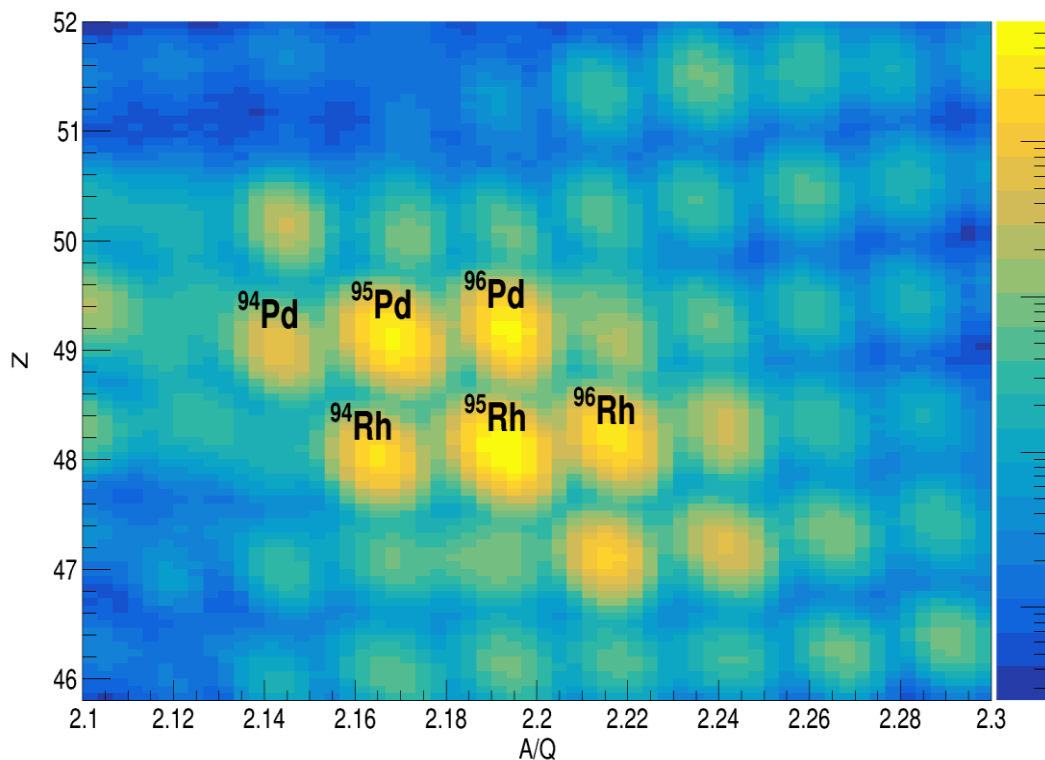
Data Acquisition Outline for DESPEC-0



- Key DAQ features:
- *White Rabbit (WR) timestamping (correlations)*
- *2 Hz pulser (data throughput and synchronisation)*
- *Time Machine for synchronisation**
- *SC41 (FRS) signal into subsystem DAQs*
- *Prompt flash trigger suppression ➔ new for 2021*

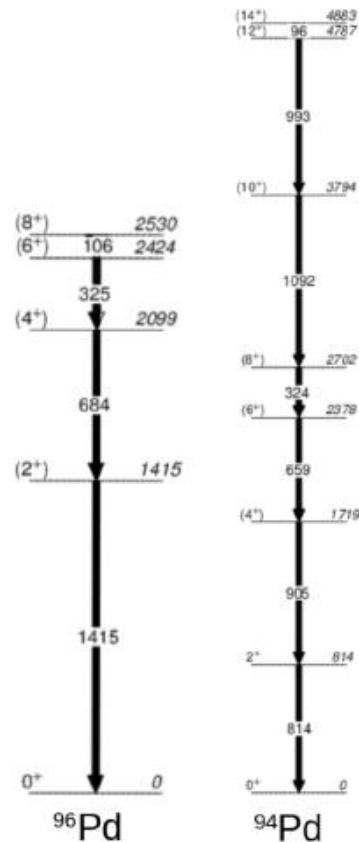
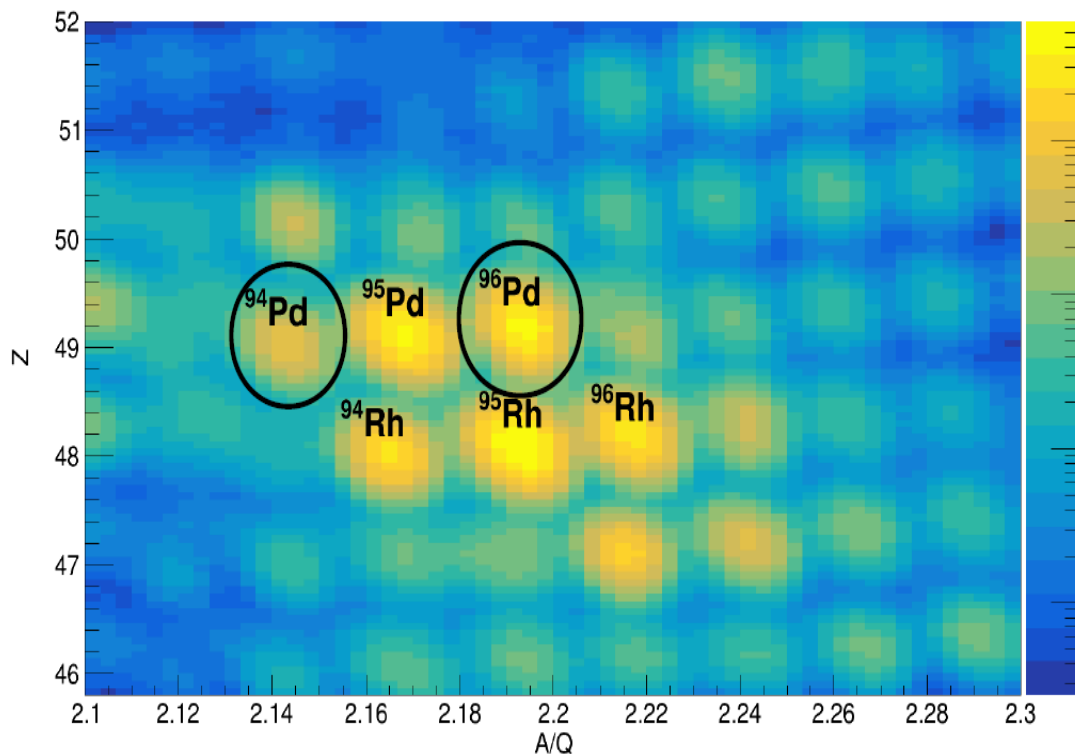
S480 experiment: March 2020, 850 MeV/u ^{124}Xe beam.

Main objective, tagged isomer fast-timing coincidence spectroscopy,
Measure the $B(E2:8^+ \rightarrow 6^+)$ in ^{94}Pd as test for p-n pairing vs seniority
couplings in this $N=Z+2$ ($T_z=+1$) nucleus.

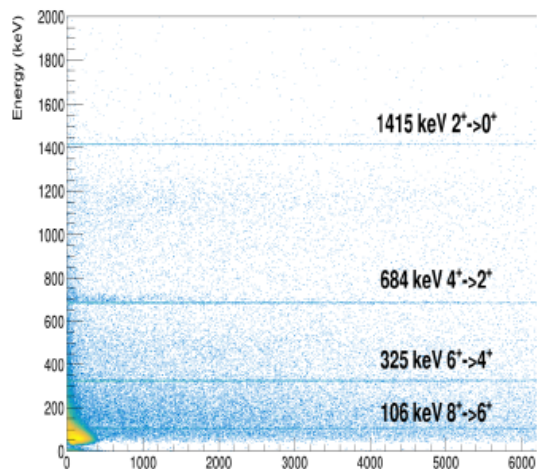


S480 experiment: March 2020, 850 MeV/u ^{124}Xe beam.

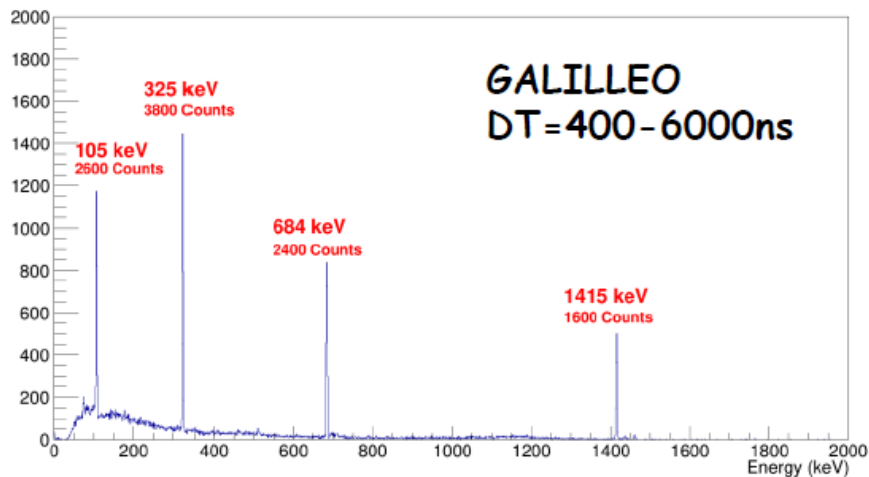
Main objective: tagged isomer fast-timing coincidence spectroscopy,
Extract $^{94}\text{Pd}_{48}$ B(E2: $8^+ \rightarrow 6^+$) as test for p-n vs seniority couplings.



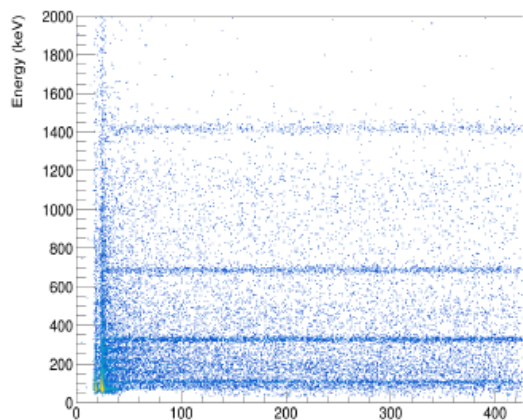
^{96}Pd E vs dt



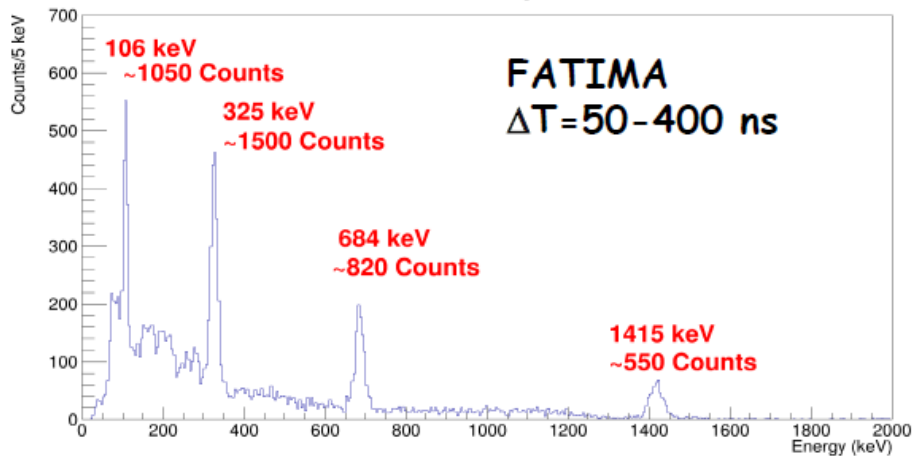
^{96}Pd E vs dt Projection

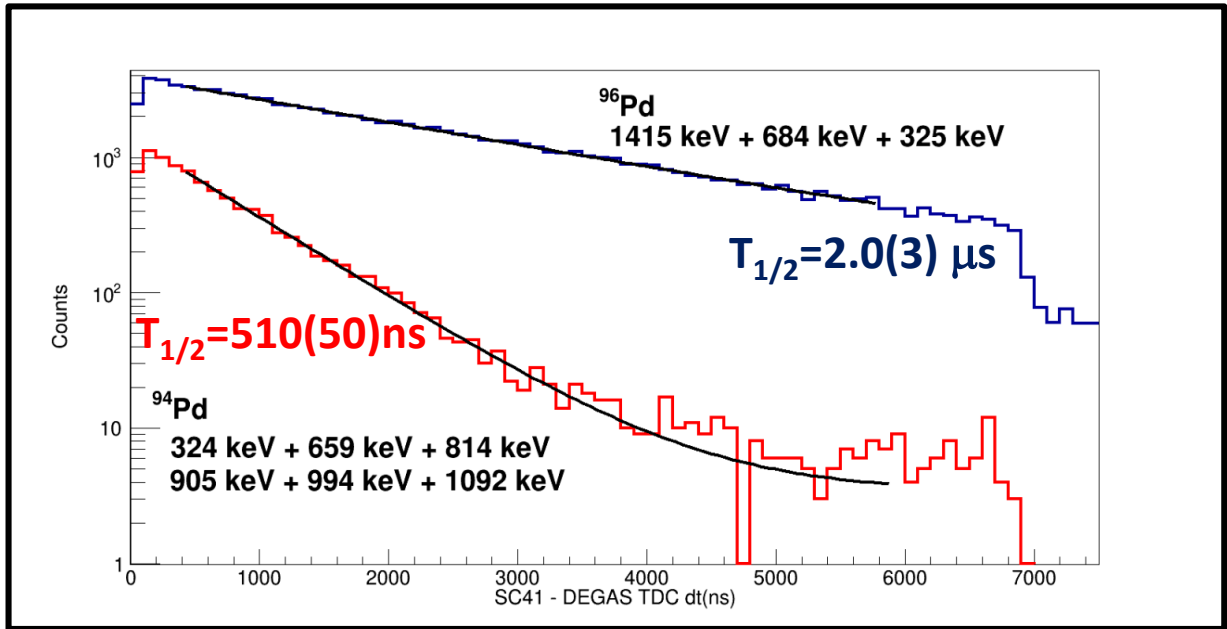
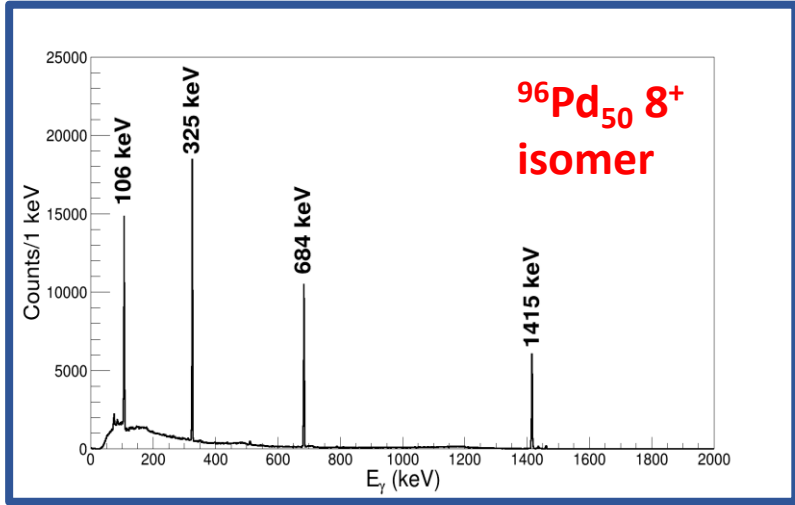
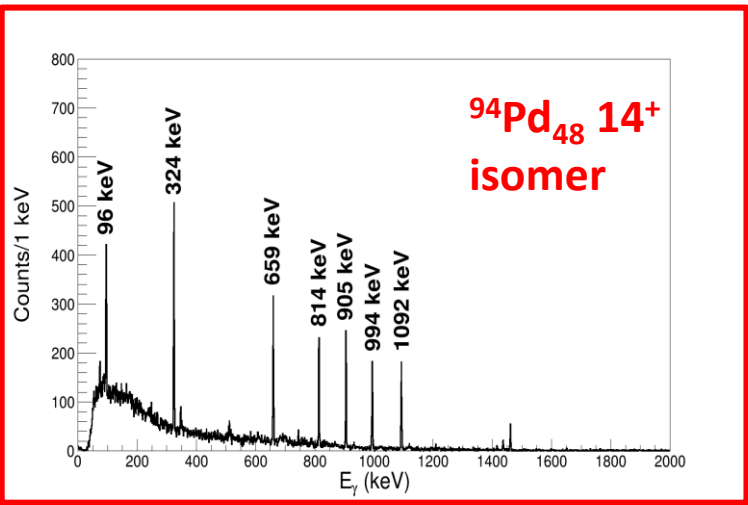


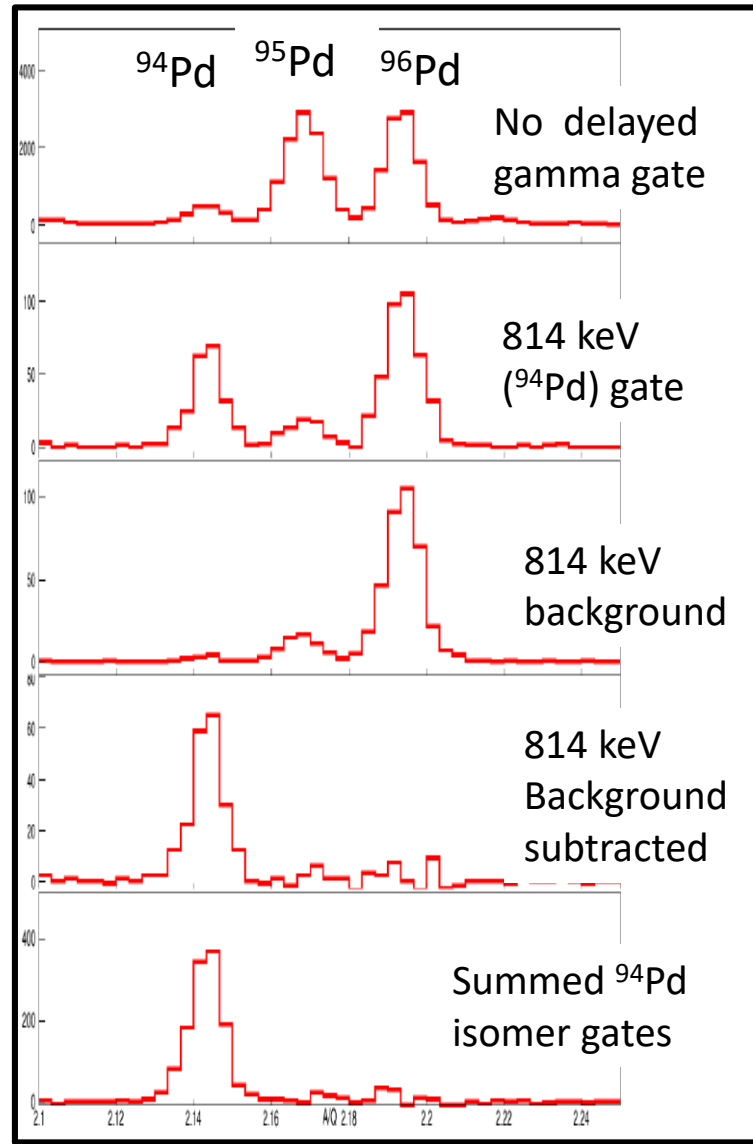
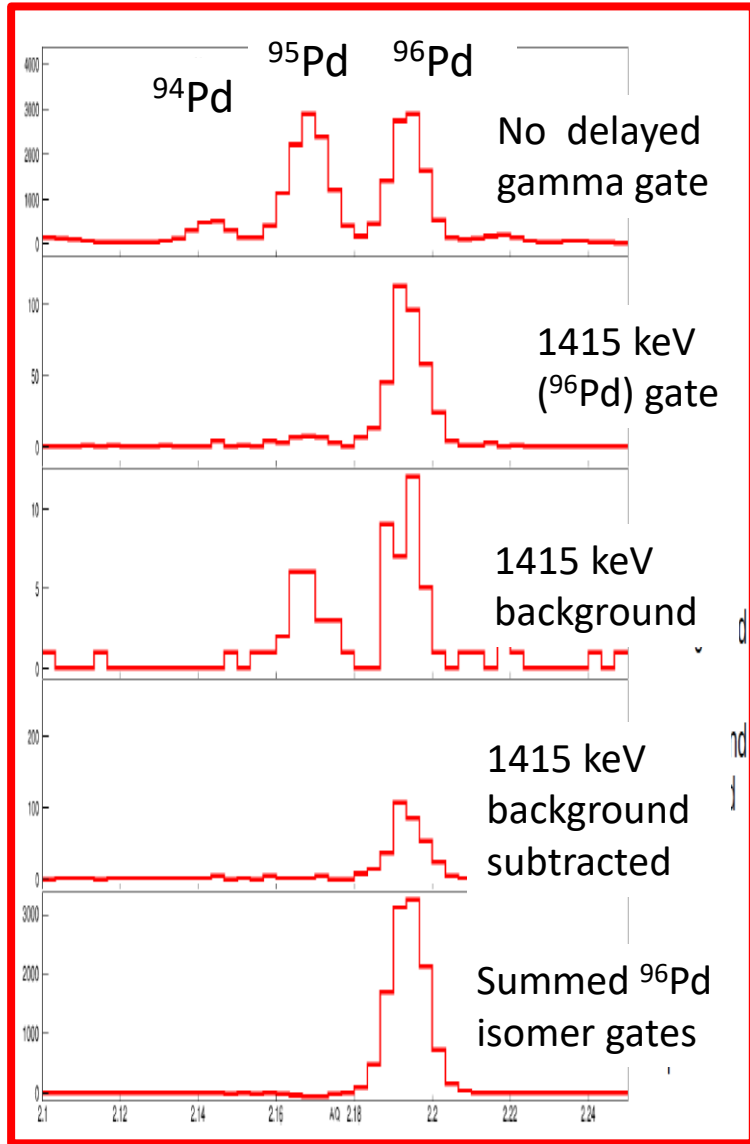
^{96}Pd E vs dt



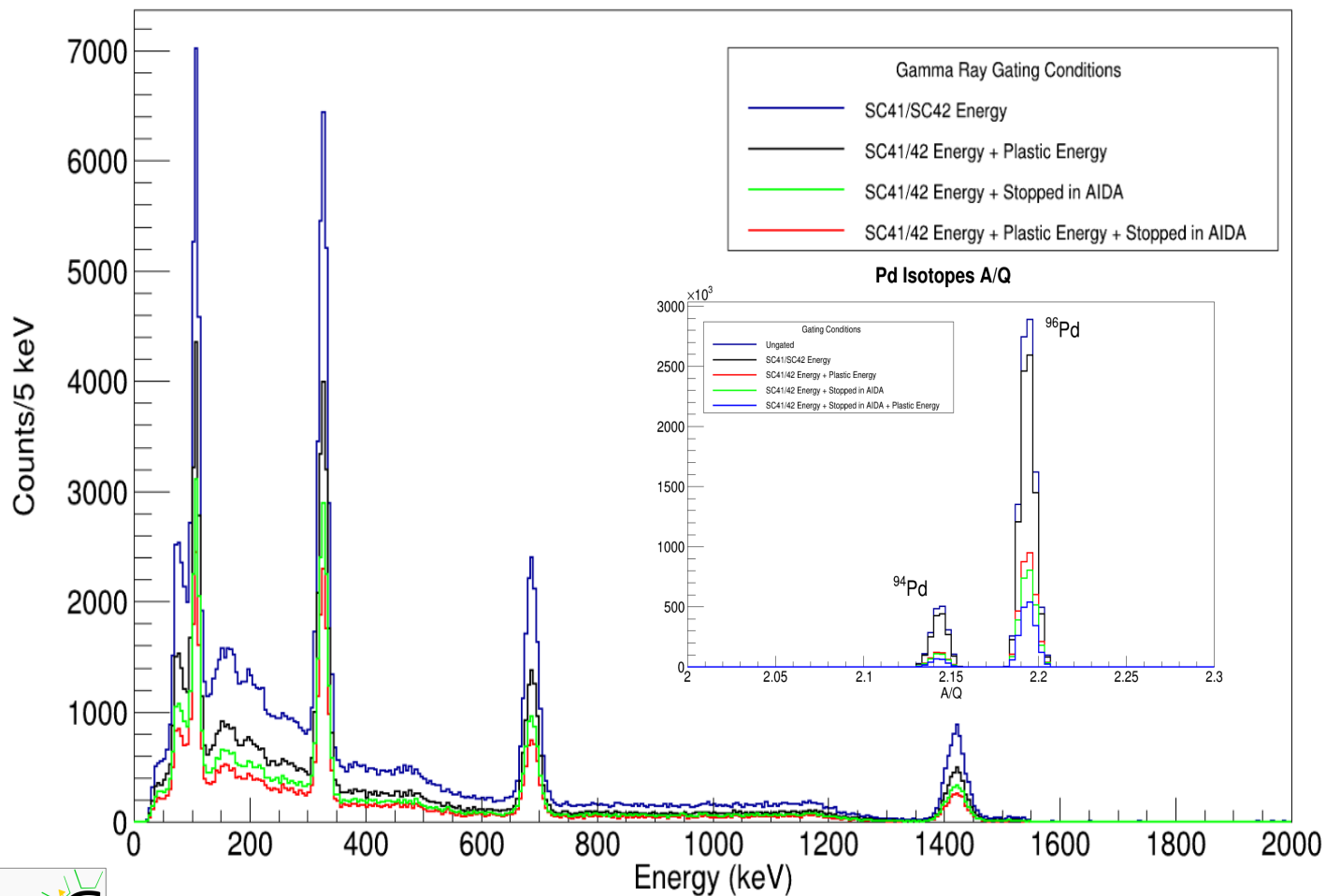
^{96}Pd E vs dt Projection



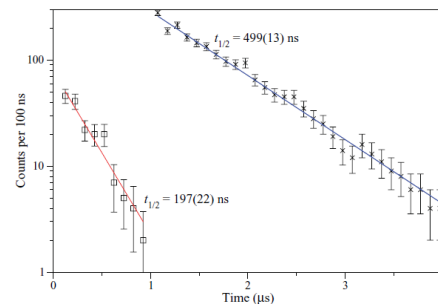
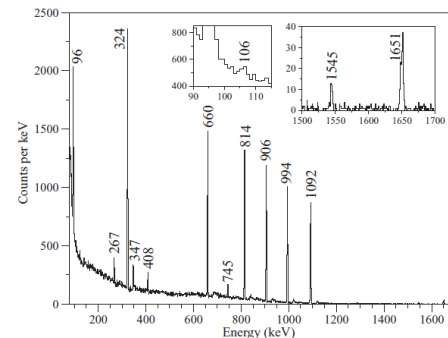
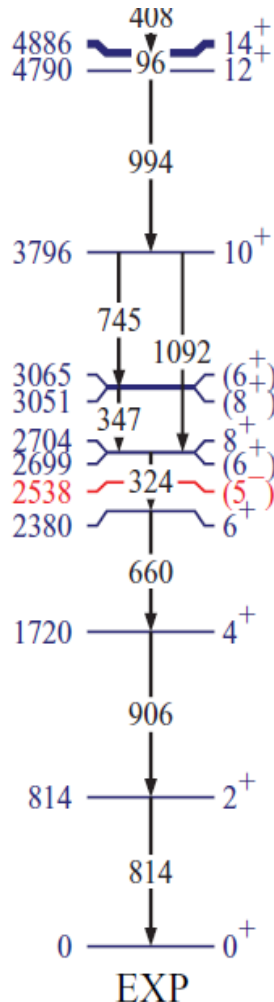
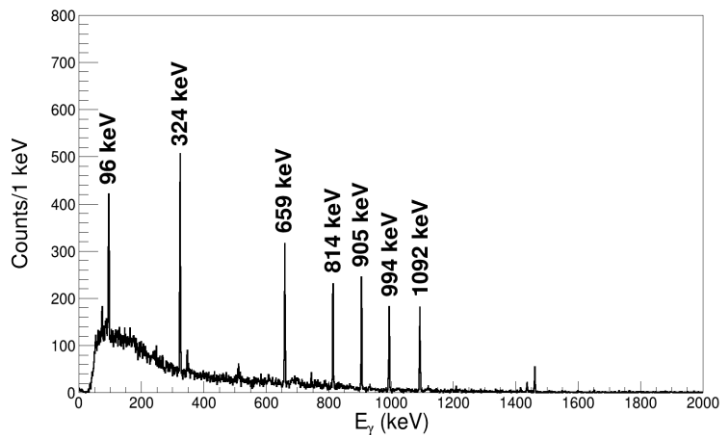
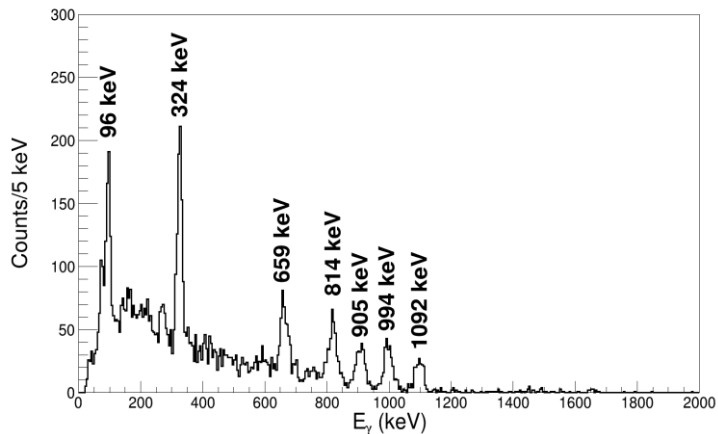




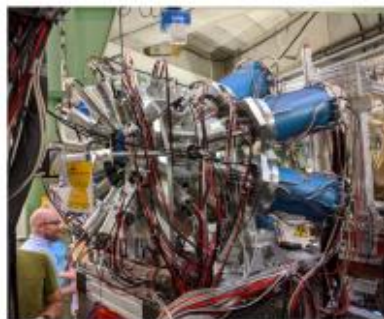
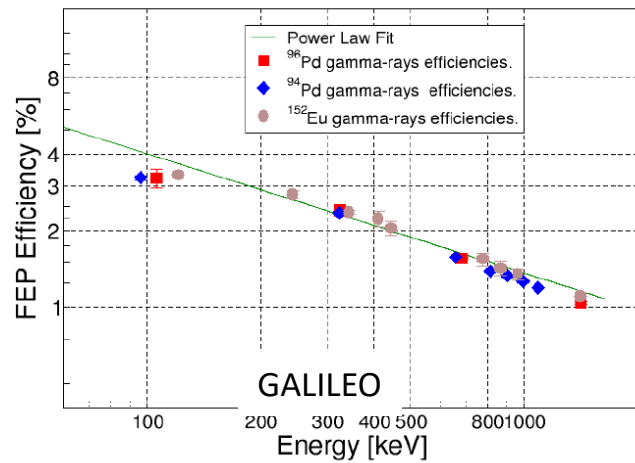
^{96}Pd E vs dt Projection



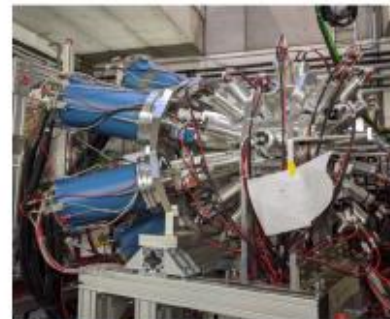
$^{94}\text{Pd } I^\pi = 14^+$ Isomer



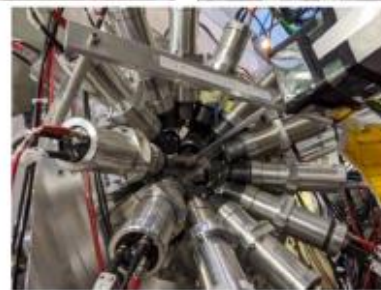
$^{94}\text{Pd } (N=Z+2), I^\pi=14^+$ isomer,
 $T_{1/2}=499(13)$ ns via RISING,
 Phys. Rev. C82 061309(R)
 (2010)



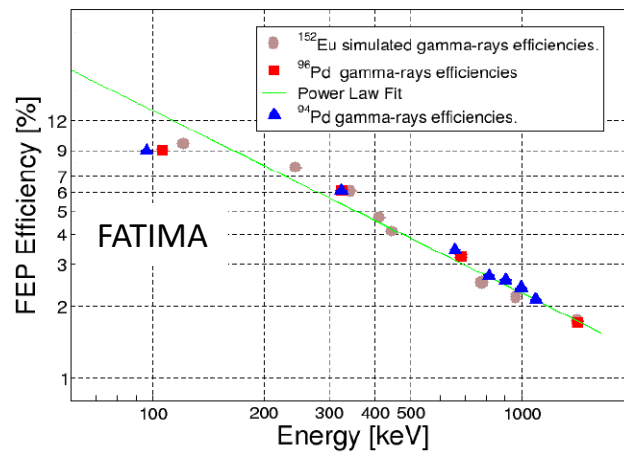
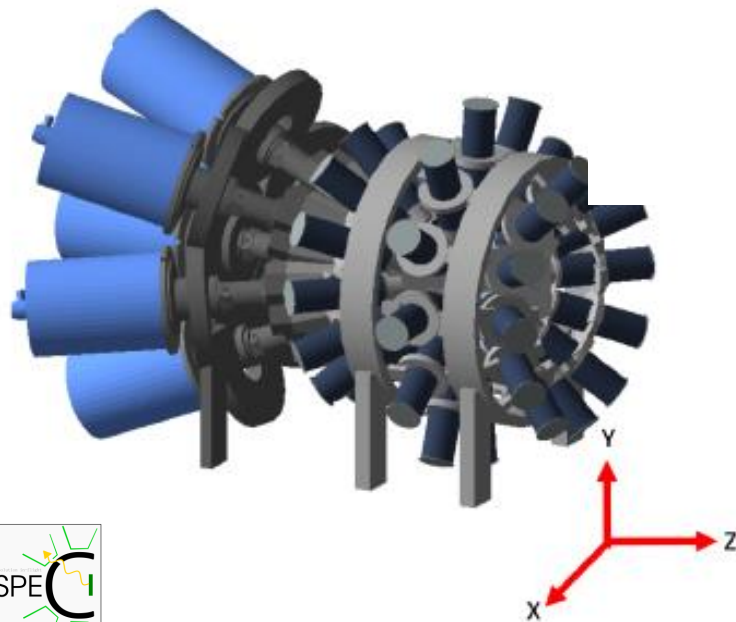
(a)

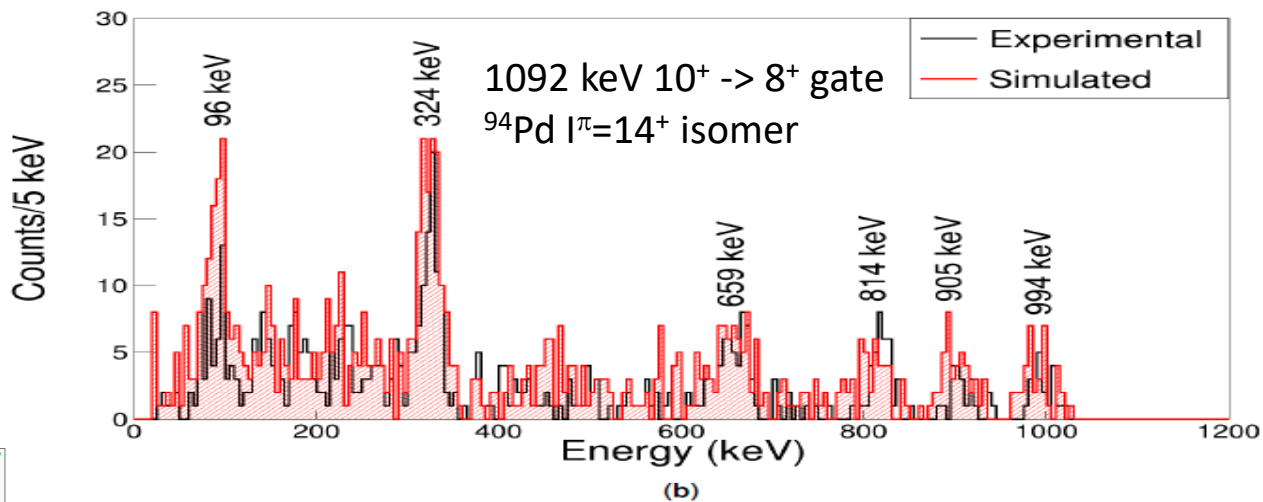
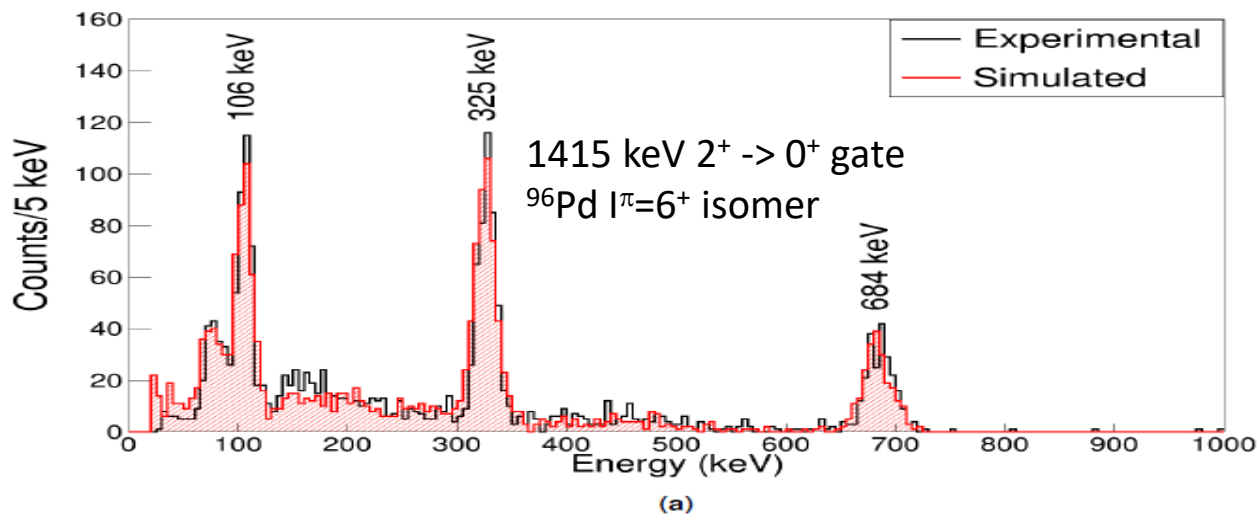


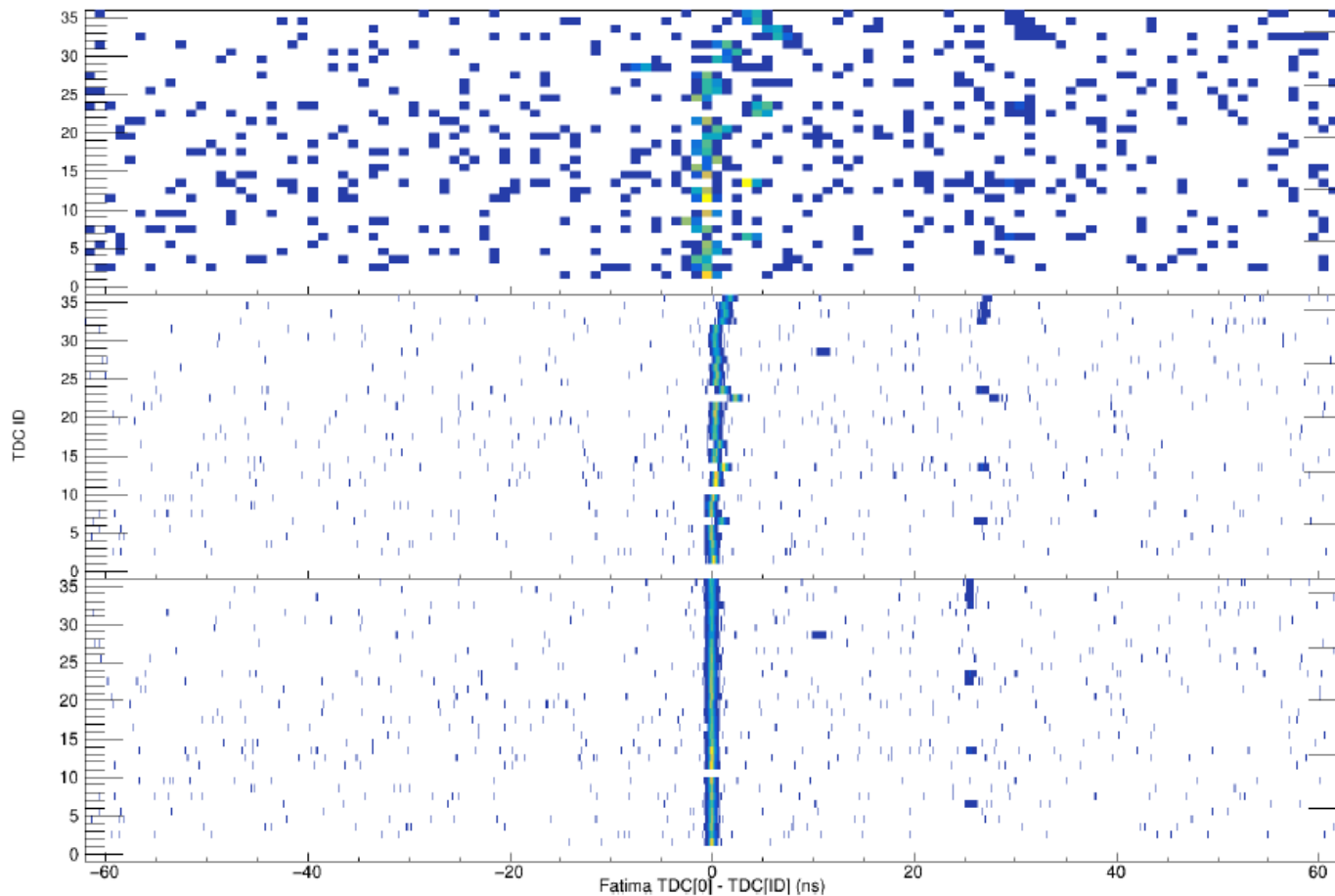
(b)



(c)

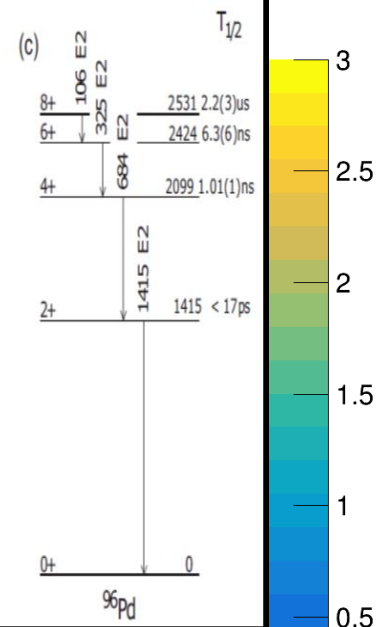
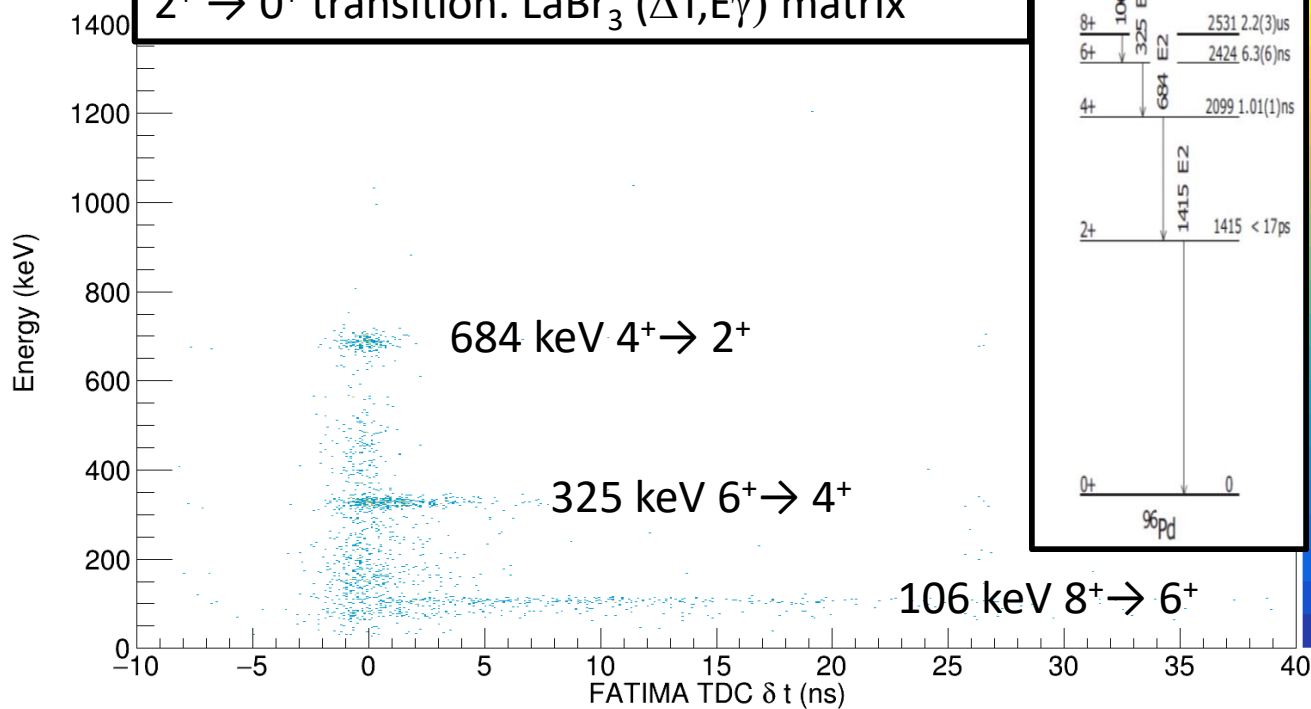




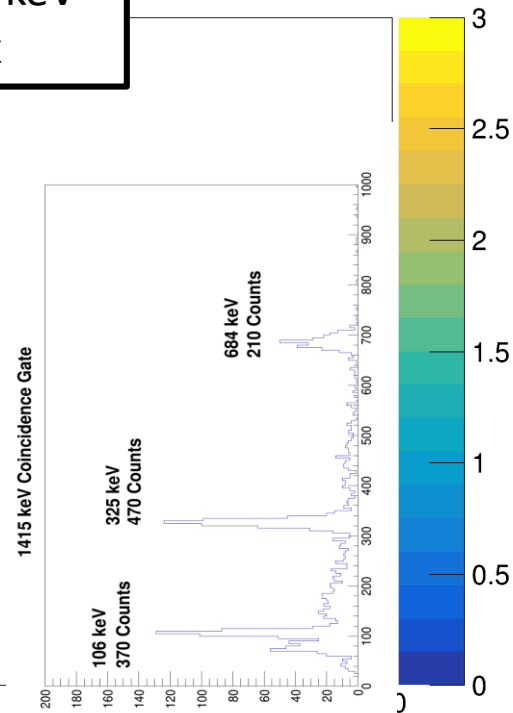
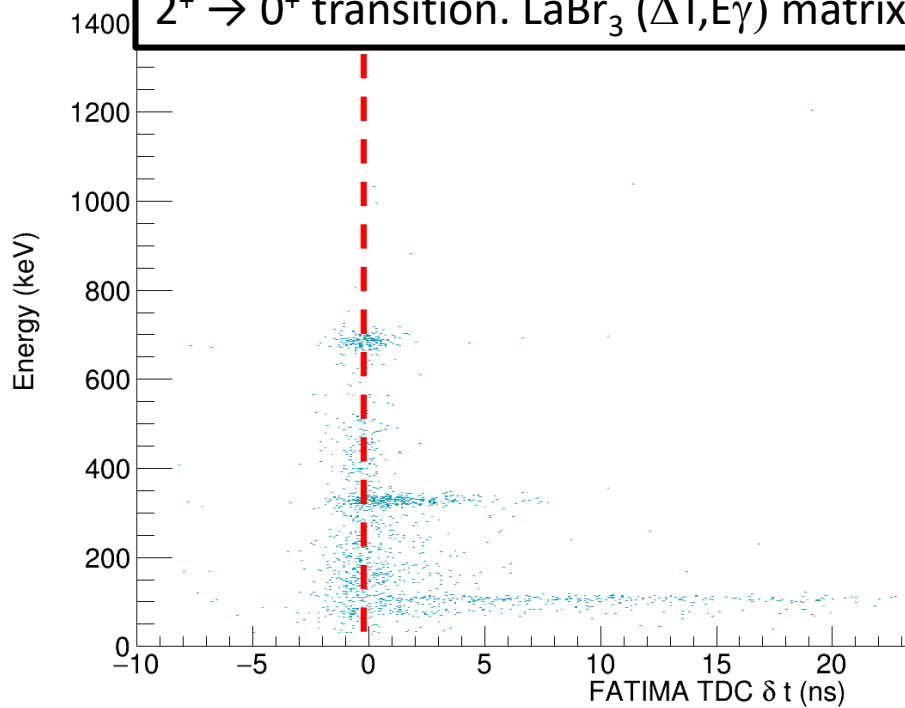


FATIMA LaBr_3 TDCs lined up using prompt flash and source γ - γ coins
FWHM < 1 ns without position correction for ToF for distributed source

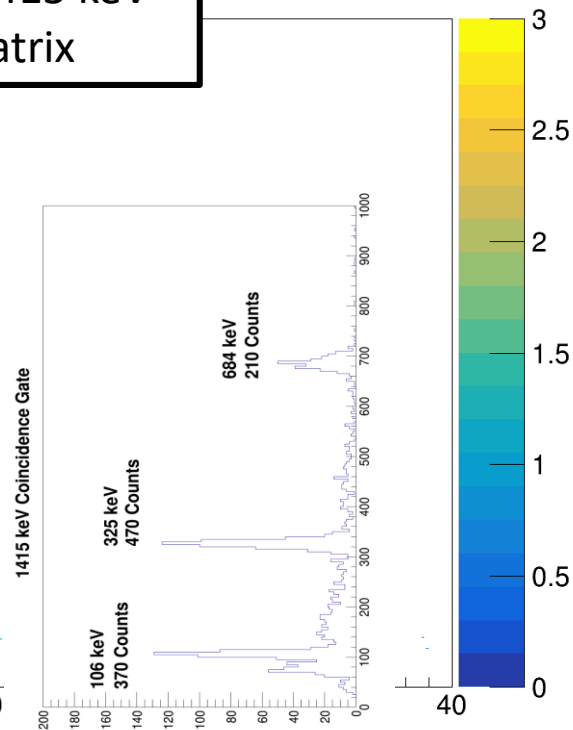
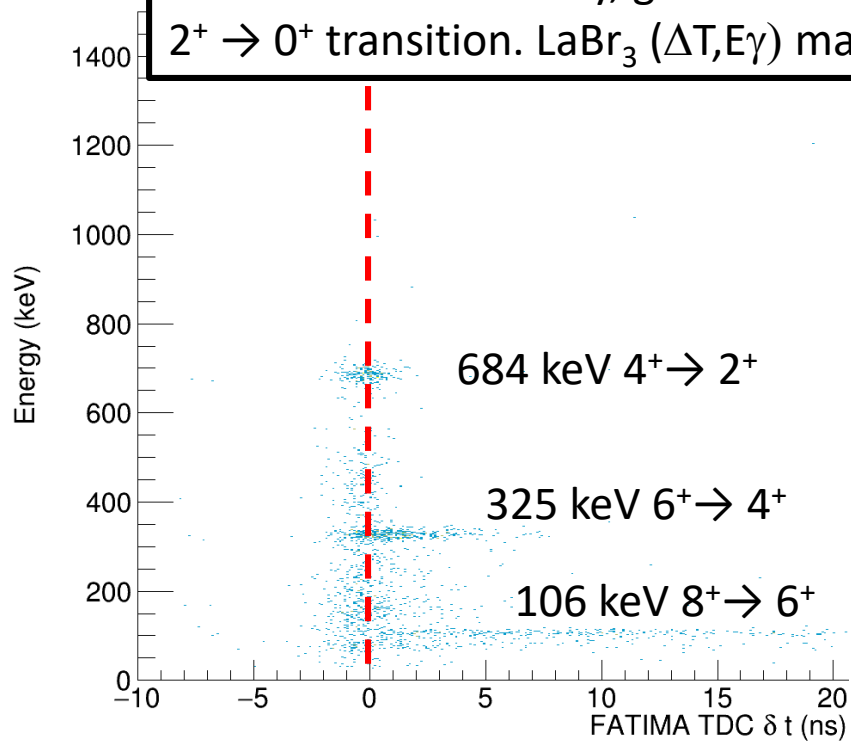
^{96}Pd $I^\pi=8^+$ isomer decay, gated on 1415 keV
 $2^+ \rightarrow 0^+$ transition. LaBr_3 ($\Delta T, E_\gamma$) matrix



$^{96}\text{Pd } I^{\pi}=8^+$ isomer decay, gated on 1415 keV
 $2^+ \rightarrow 0^+$ transition. $\text{LaBr}_3 (\Delta T, E\gamma)$ matrix

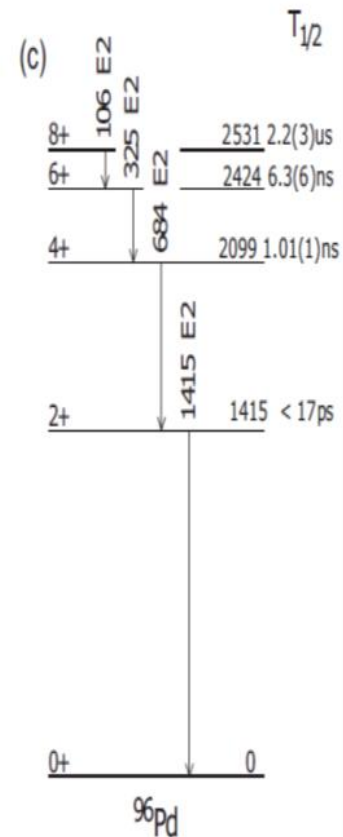
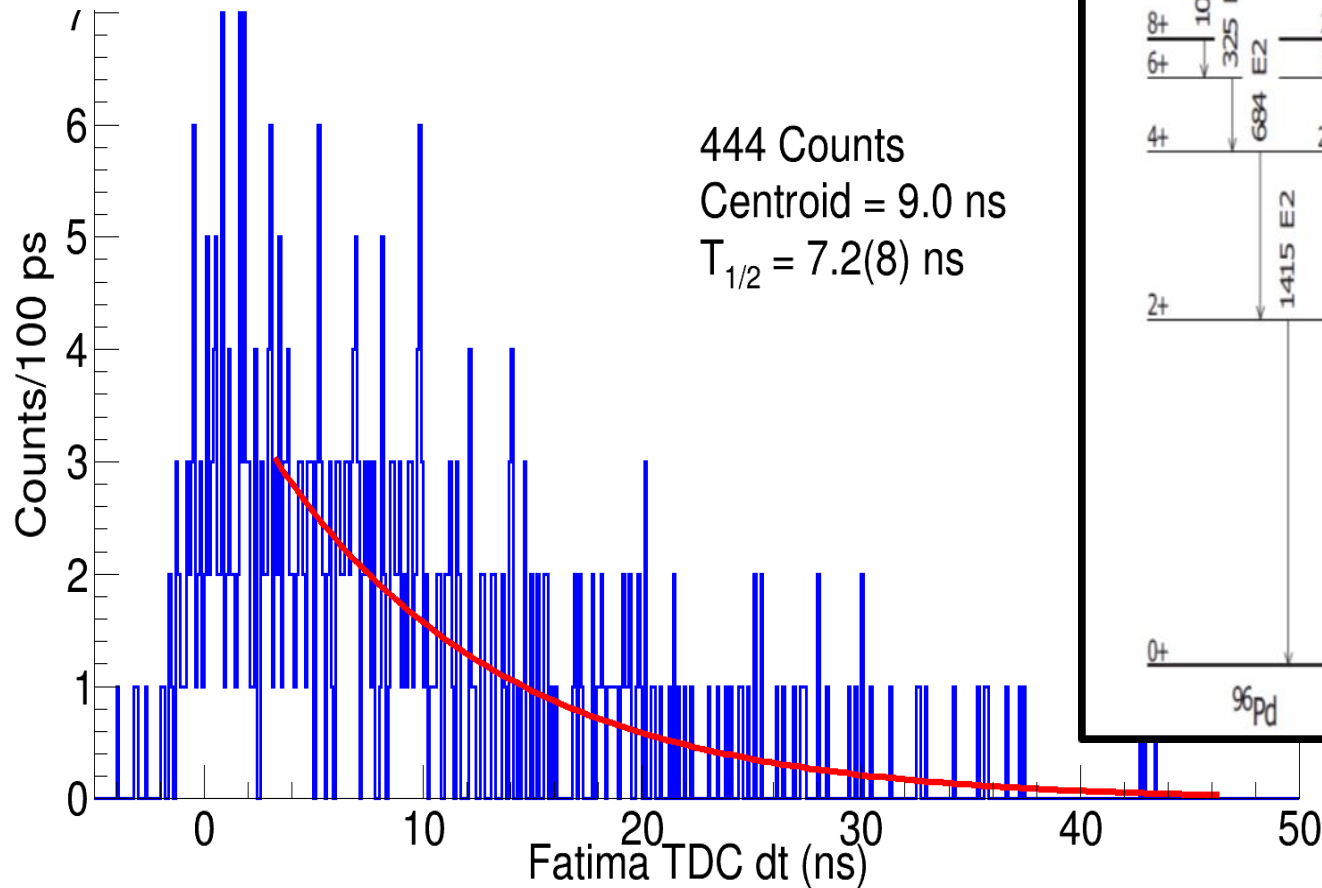


$^{96}\text{Pd } I^\pi=8^+$ isomer decay, gated on 1415 keV
 $2^+ \rightarrow 0^+$ transition. $\text{LaBr}_3 (\Delta T, E\gamma)$ matrix

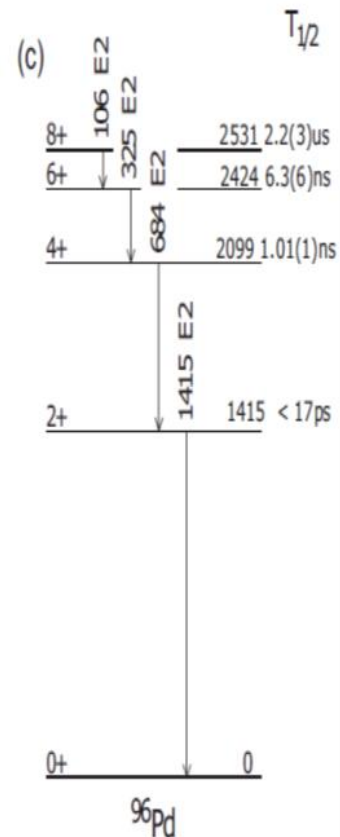
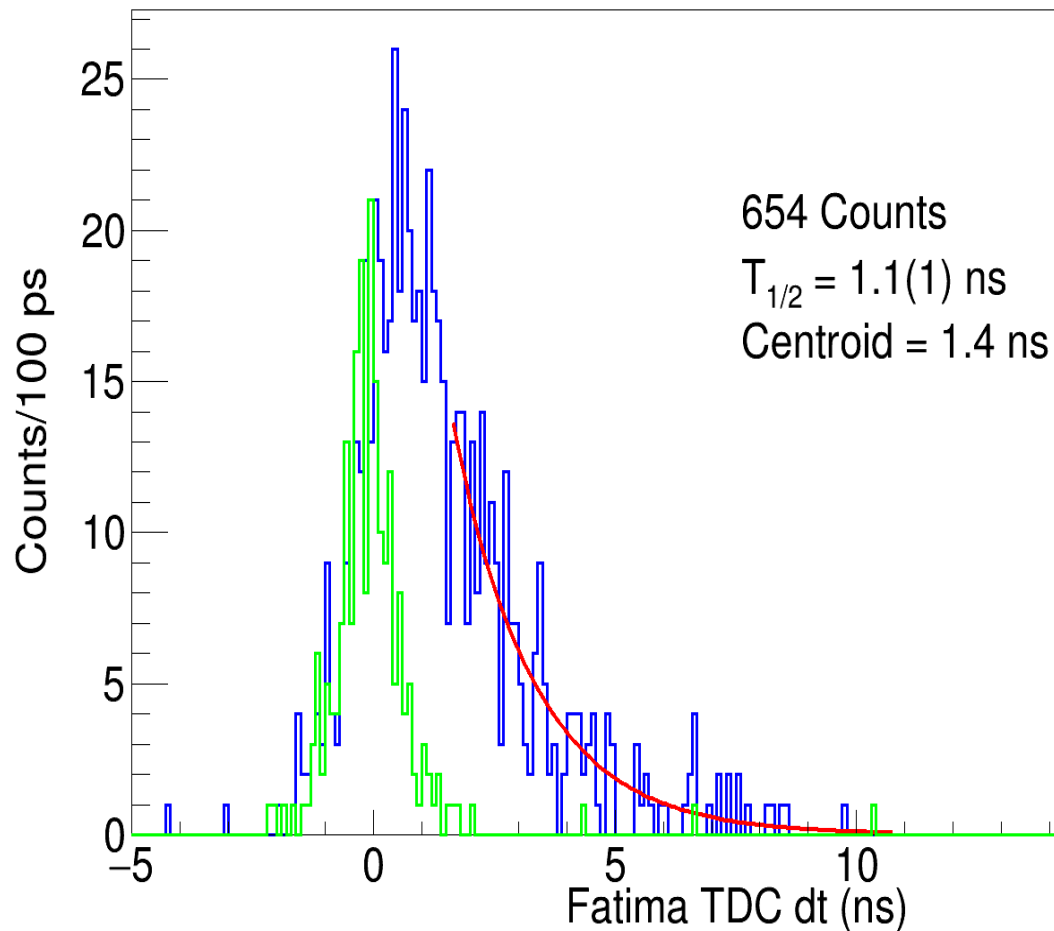


Delated ^{96}Pd , $\Delta\text{T-LaBr}_3\text{-LaBr}_3$

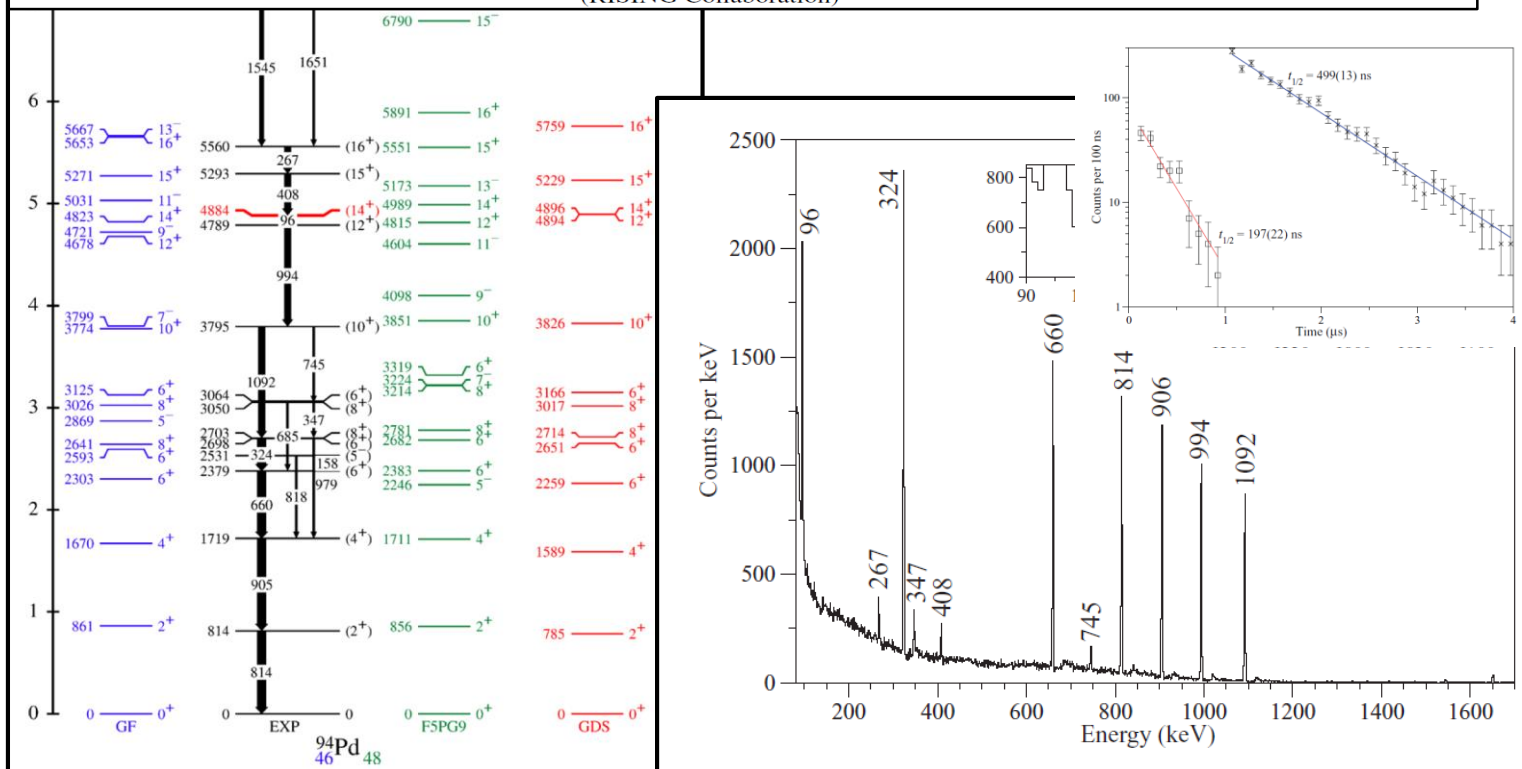
{106 keV} x {325 keV}, fitted to $N(t)=A\exp(-\lambda t)+B$



^{96}Pd 4⁺ Lifetime



T. S. Brock,¹ B. S. Nara Singh,¹ P. Boutachkov,² N. Braun,³ A. Blazhev,³ Z. Liu,⁴ R. Wadsworth,¹ M. Górska,² H. Grawe,² S. Pietri,² C. Domingo-Pardo,² D. Rudolph,⁵ S. J. Steer,⁶ A. Ataç,⁷ L. Bettermann,³ L. Cáceres,² T. Engert,² K. Eppinger,⁸ T. Faestermann,⁸ F. Farinon,² F. Finke,³ K. Geibel,³ J. Gerl,² R. Gernhäuser,⁸ N. Goel,² A. Gottardo,⁴ J. Grębosz,⁹ C. Hinke,⁸ R. Hoischen,^{2,5} G. Ilie,³ H. Iwasaki,³ J. Jolie,³ A. Kaşkaş,⁷ I. Kojuharov,² R. Krücken,⁸ N. Kurz,² E. Merchán,¹⁰ C. Nociforo,² J. Nyberg,¹¹ M. Pfützner,¹² A. Prochazka,² Zs. Podolyák,⁶ P. H. Regan,⁶ P. Reiter,³ S. Rinta-Antila,¹³ H. Schaffner,² C. Scholl,³ P.-A. Söderström,¹¹ N. Warr,³ H. Weick,² H.-J. Wollersheim,¹⁴ and P. J. Woods⁴
(RISING Collaboration)



^{94}Pd E vs dt

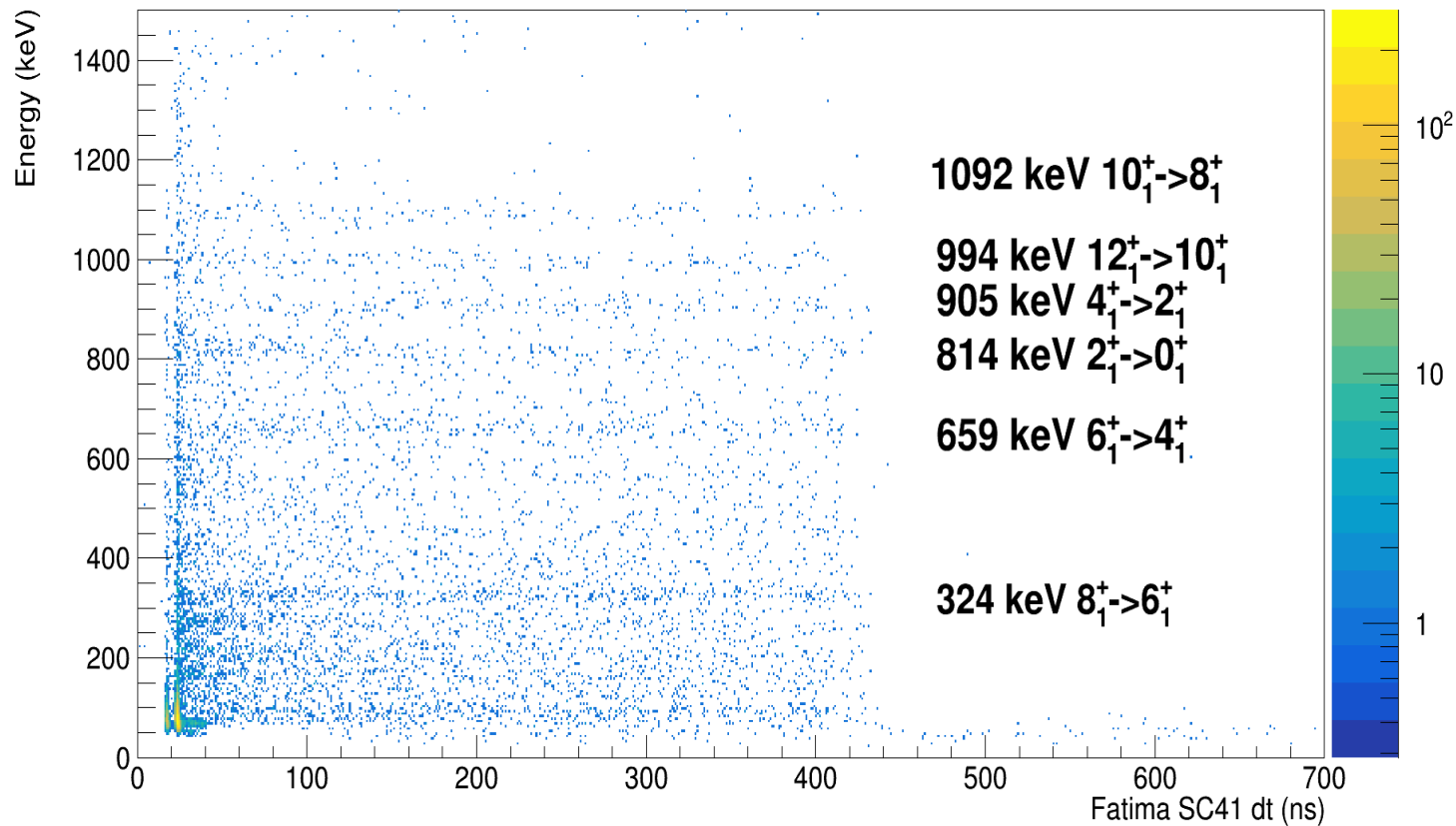


Figure S.Jazrawi, A. Yaneva et al.,

^{94}Pd $I^\pi=14^+$ isomer decay, gated on 814 keV
 $2^+ \rightarrow 0^+$ transition. LaBr_3 ($\Delta T, E_\gamma$) matrix

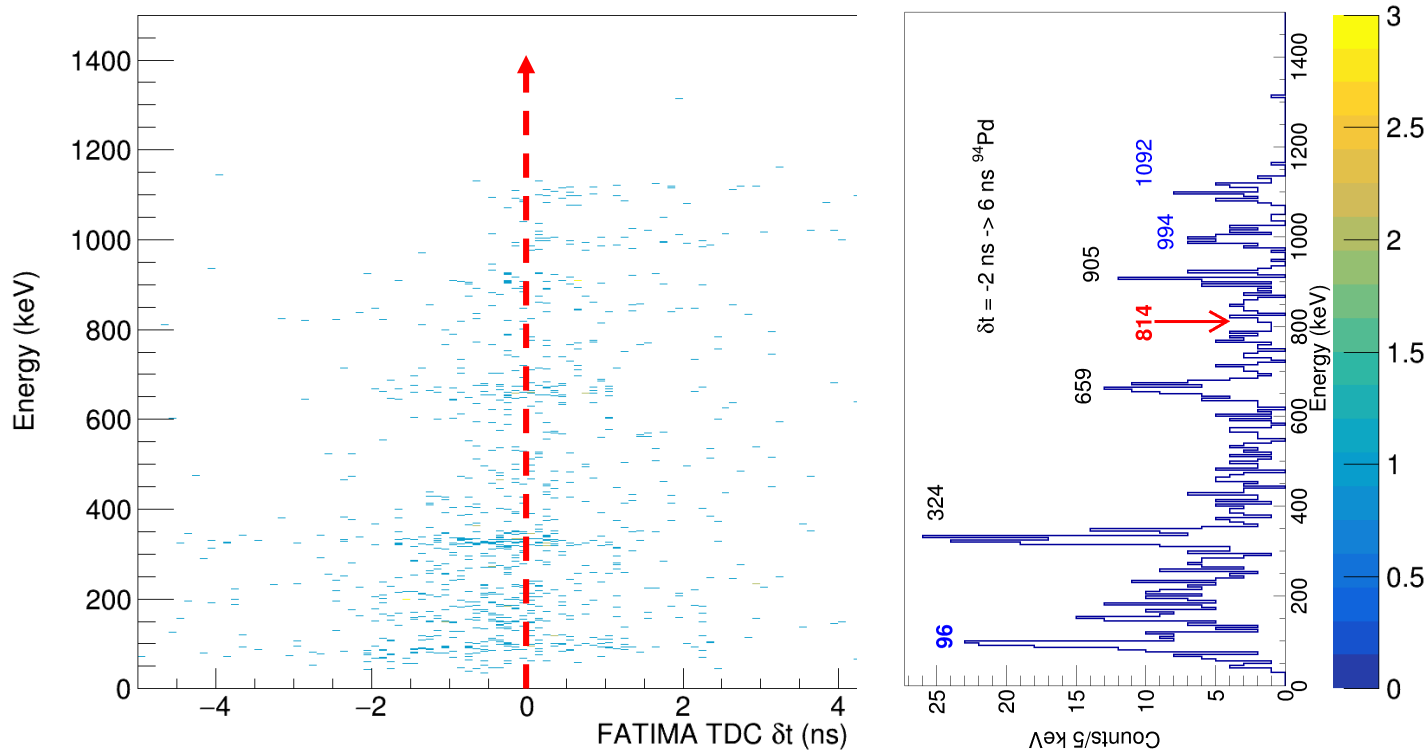
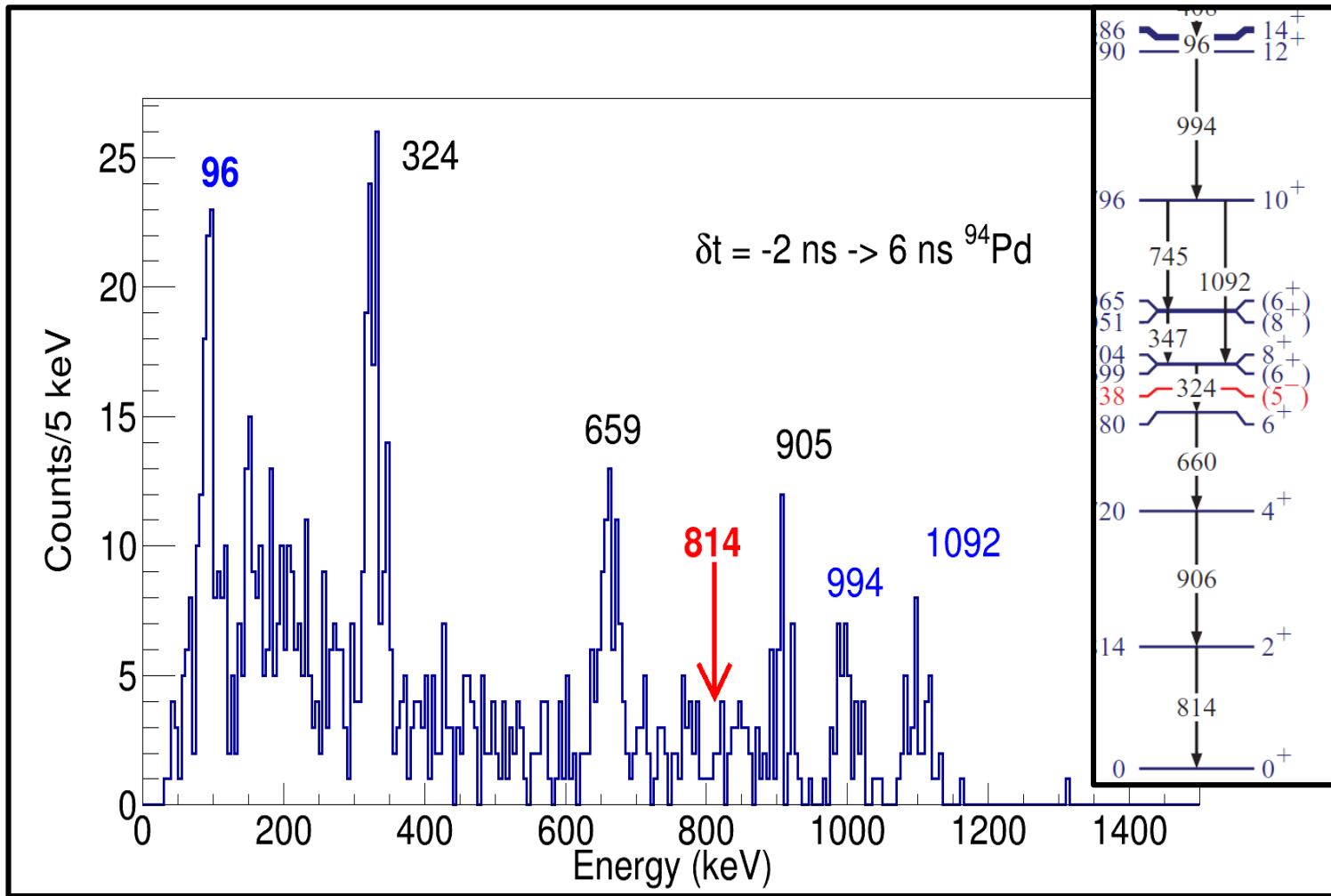


Figure S.Jazrawi, A. Yaneva et al.,



^{94}Pd $I^\pi=14^+$ isomer decay, gated on 814 keV
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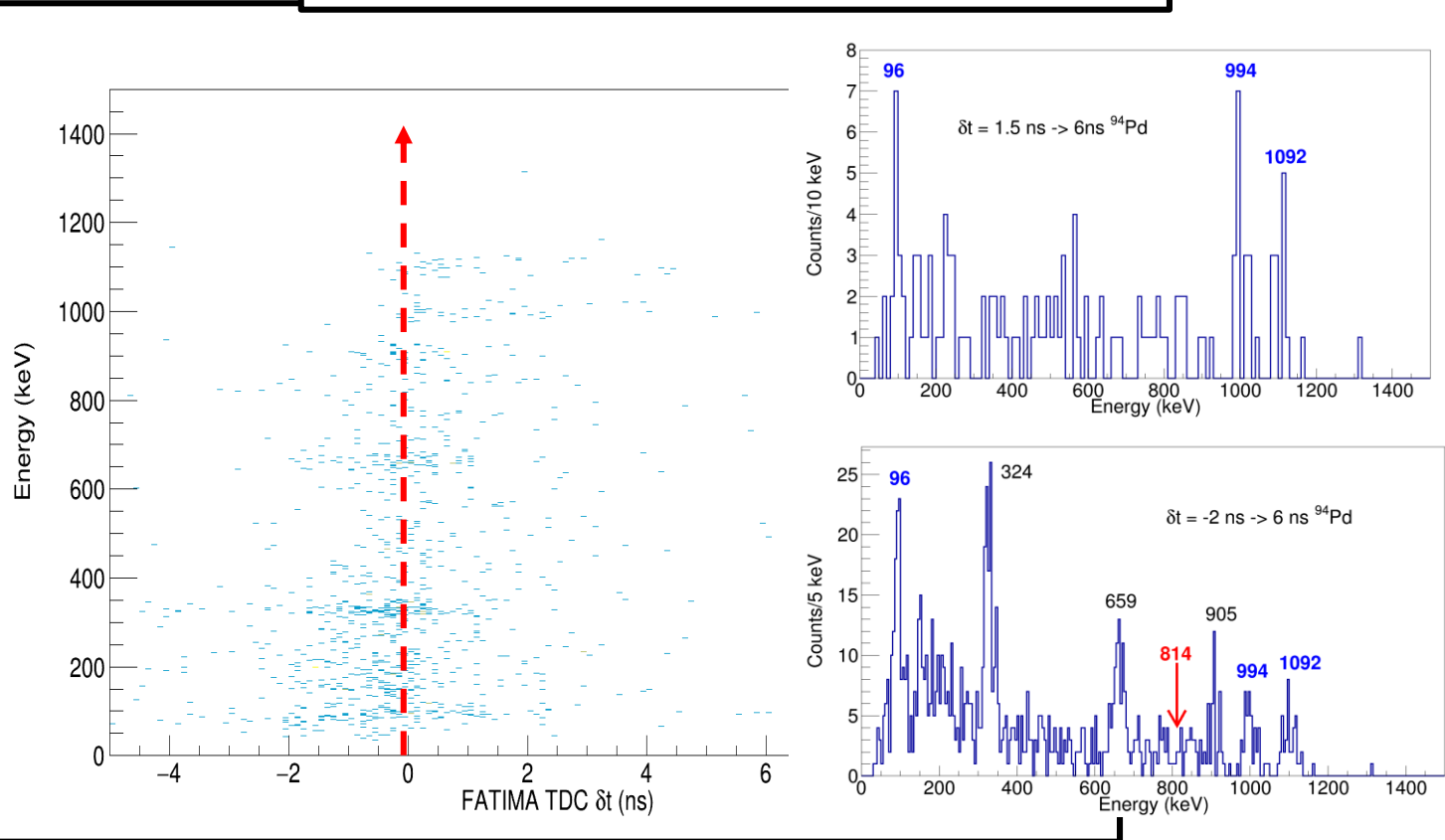
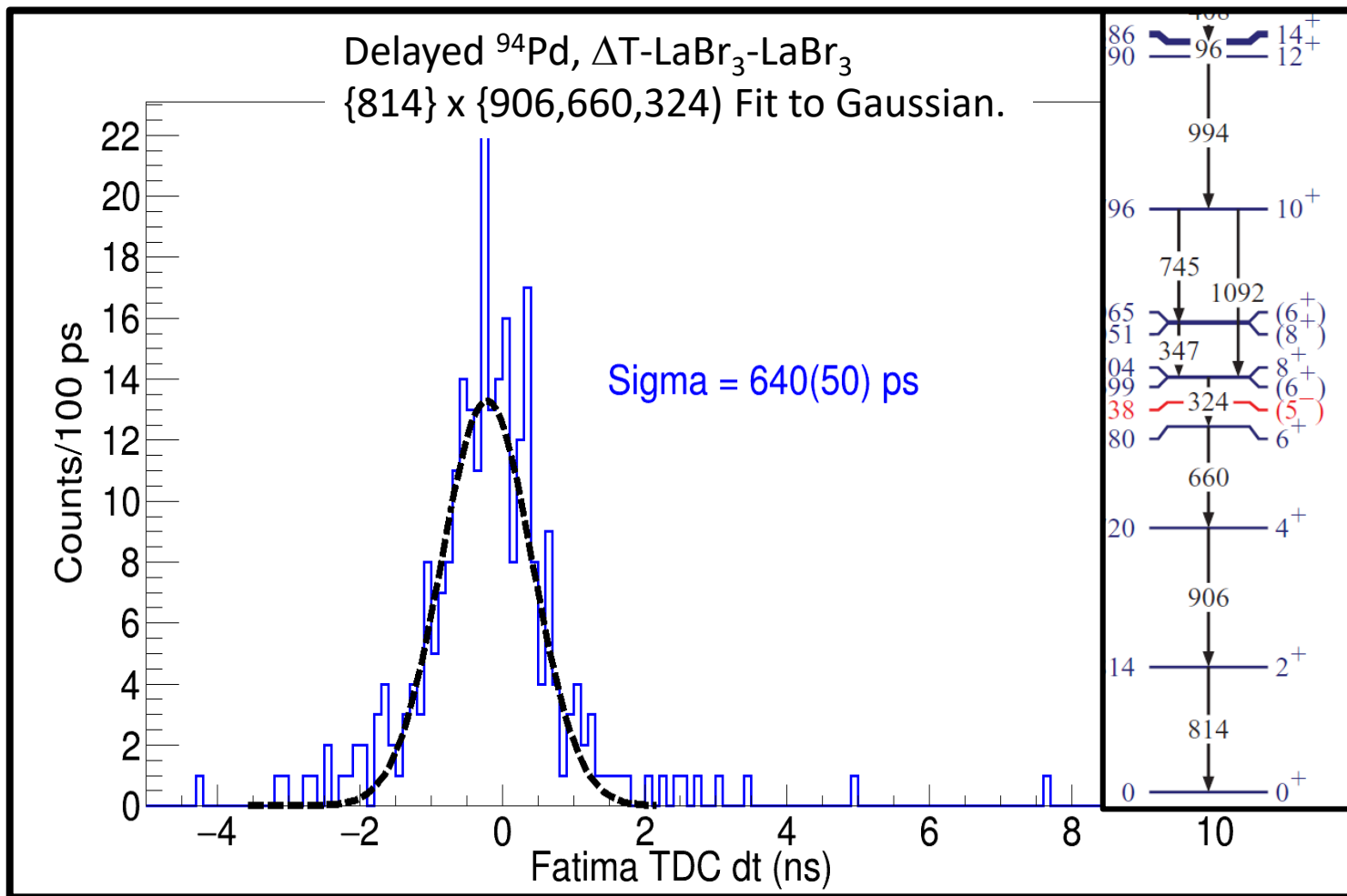


Figure S.Jazrawi, A. Yaneva et al.,



Delated ^{94}Pd , $\Delta\text{T-LaBr}_3\text{-LaBr}_3$

$\{814,906,660,325\} \times \{1092,994\}$ Fit $N(t)=A\exp(-\lambda t)+B$

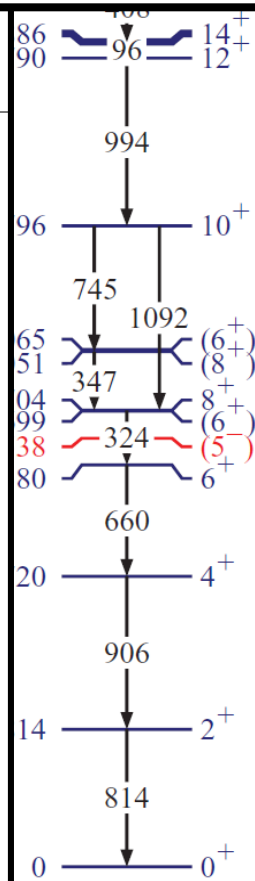
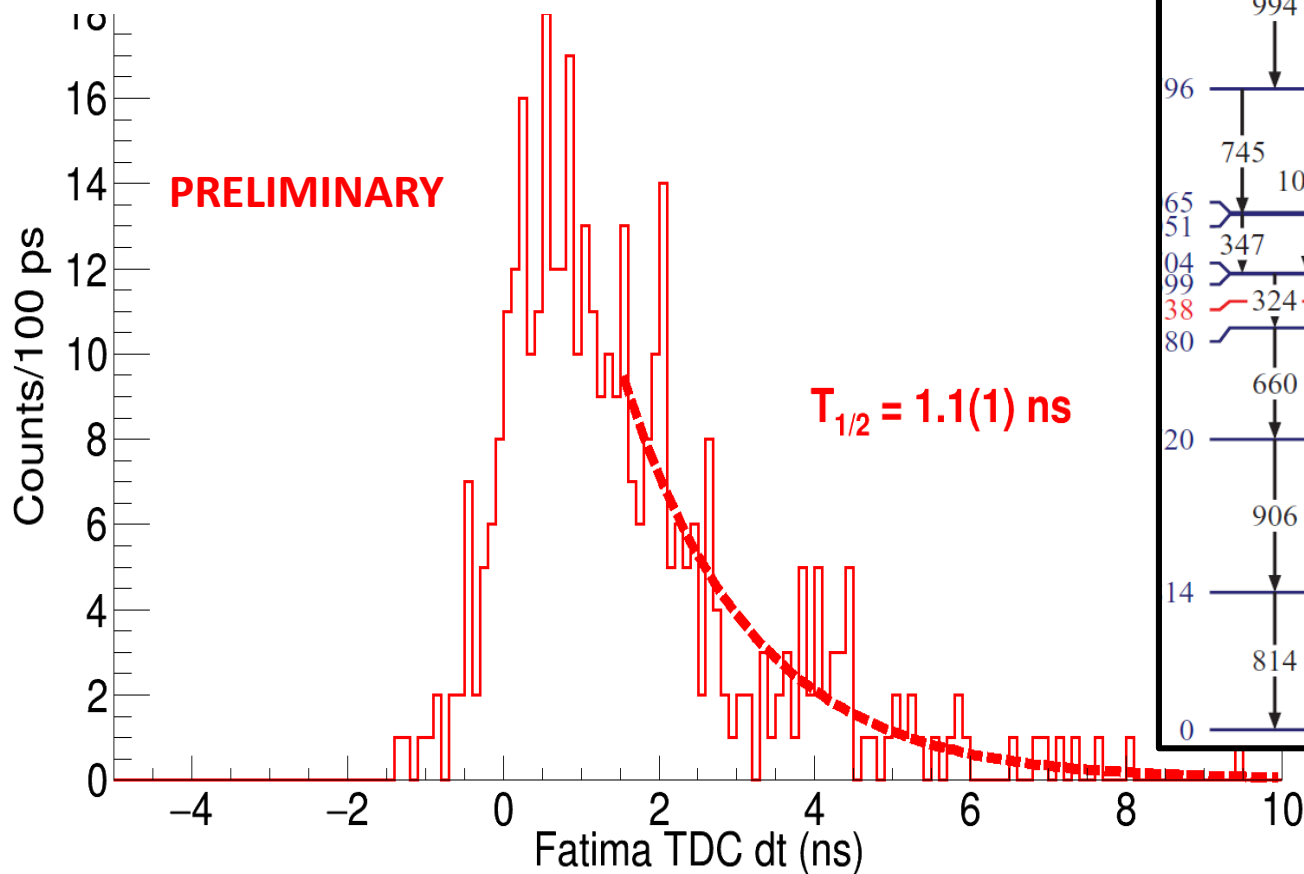


Figure S.Jazrawi, A. Yaneva et al.,

$^{94}\text{Pd } 8^+$ Half-life

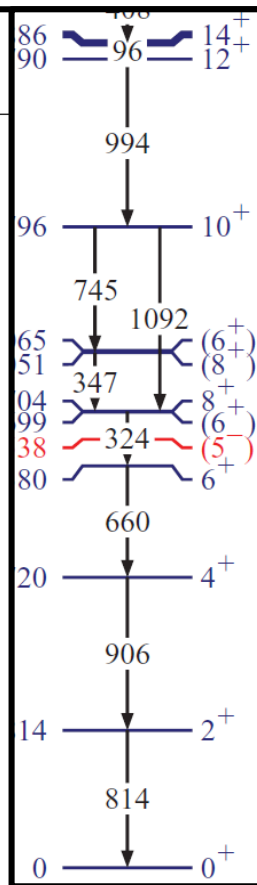
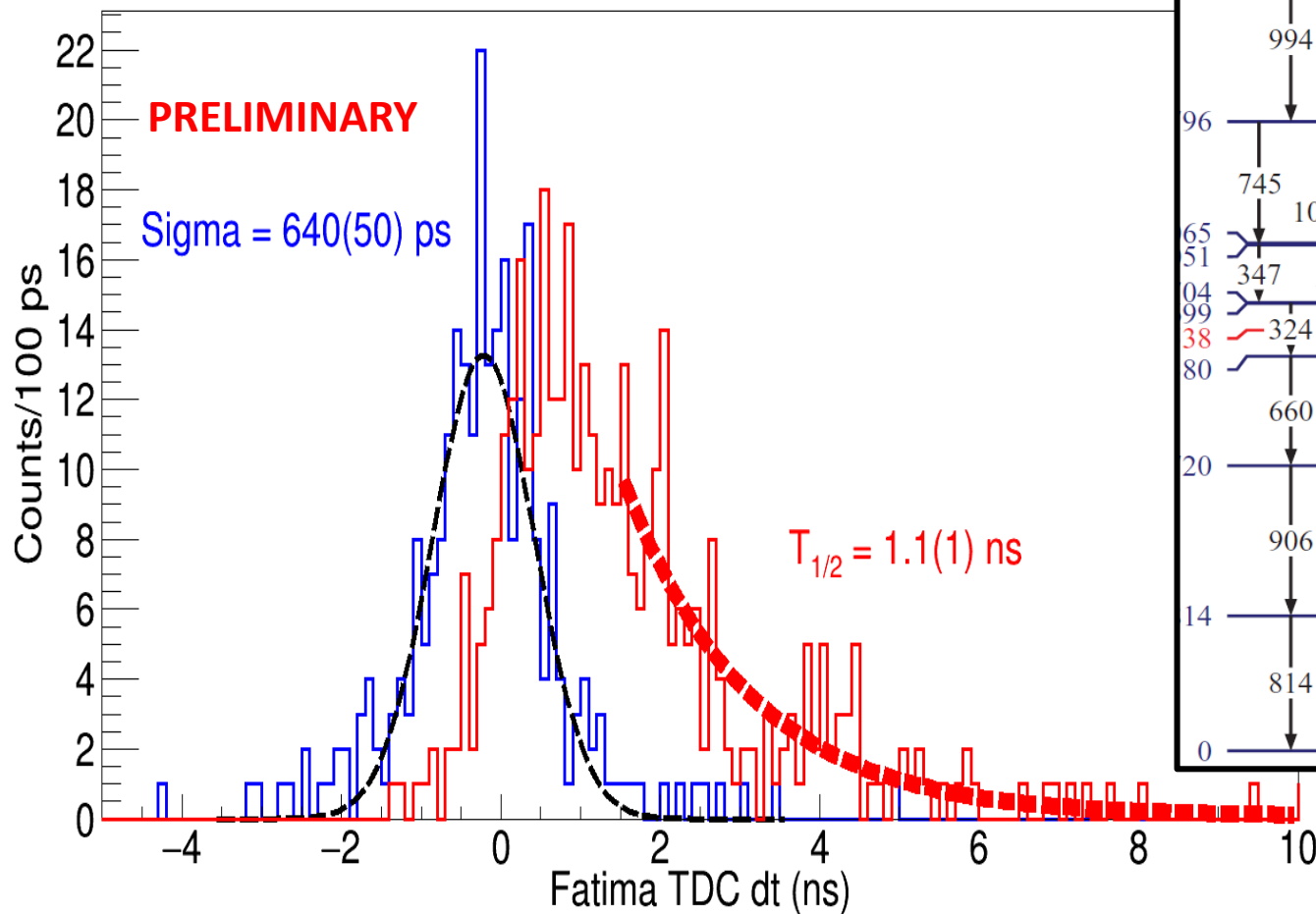


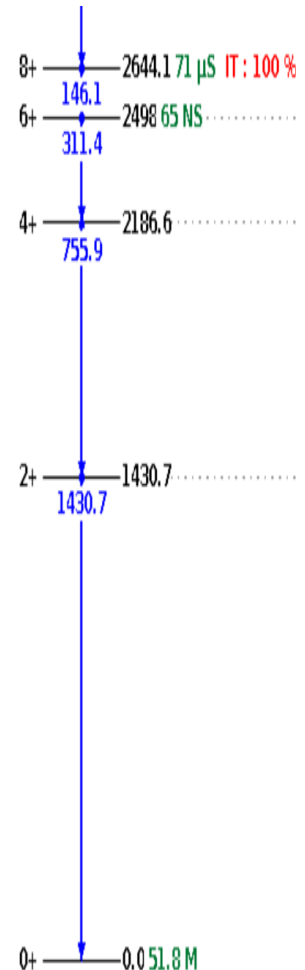
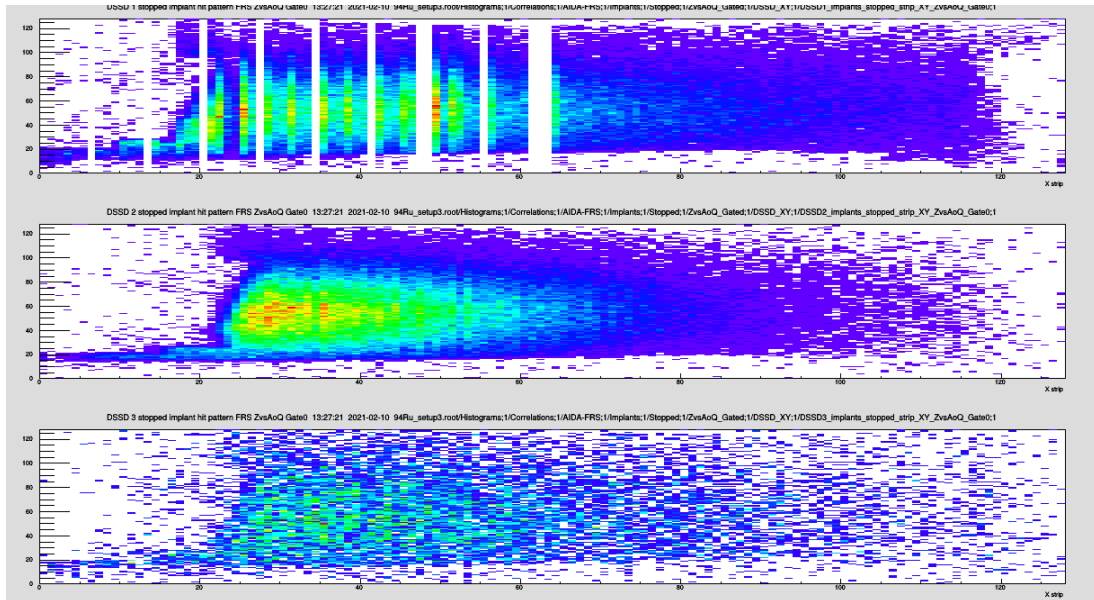
Figure S.Jazrawi, A. Yaneva et al.,

^{94}Ru isomer S480 ($T_{1/2}=71\text{ }\mu\text{s}$ isomer decay)

0-700 μs correlation time (WR FRS, WR Germanium/Fatima)

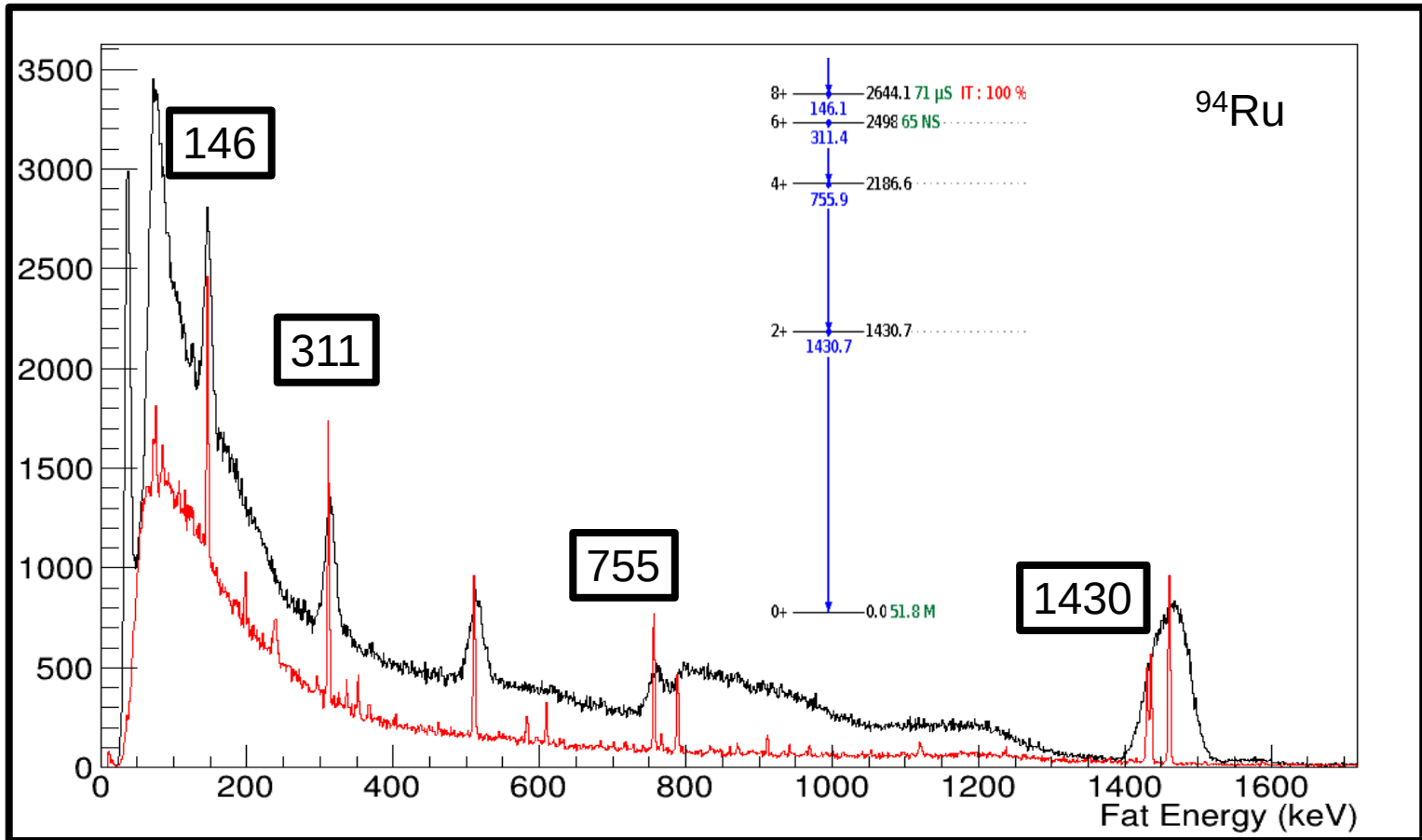
Full S480 data set

^{94}Ru Z vs A/Q: total $1.3\text{E}6$ ions in PID gate



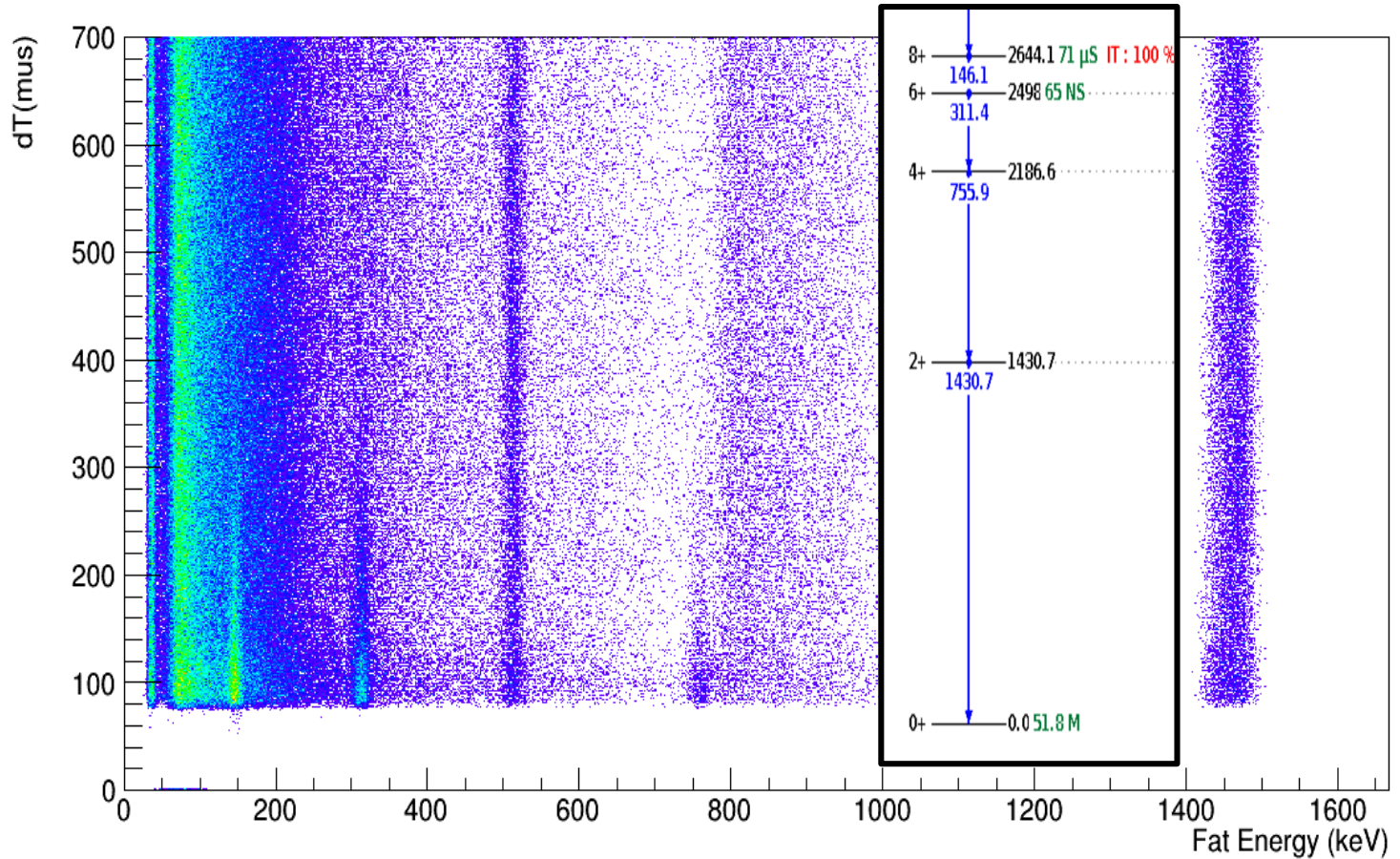
AIDA DSSD distribution ($3.4\text{E}5$ ions total stopped)

Germanium and Fatima: (Z,A/Q Gated on ^{94}Ru ions)
Gamma-ray **Energy Projection, PID- γ WR 0-350 μs range**

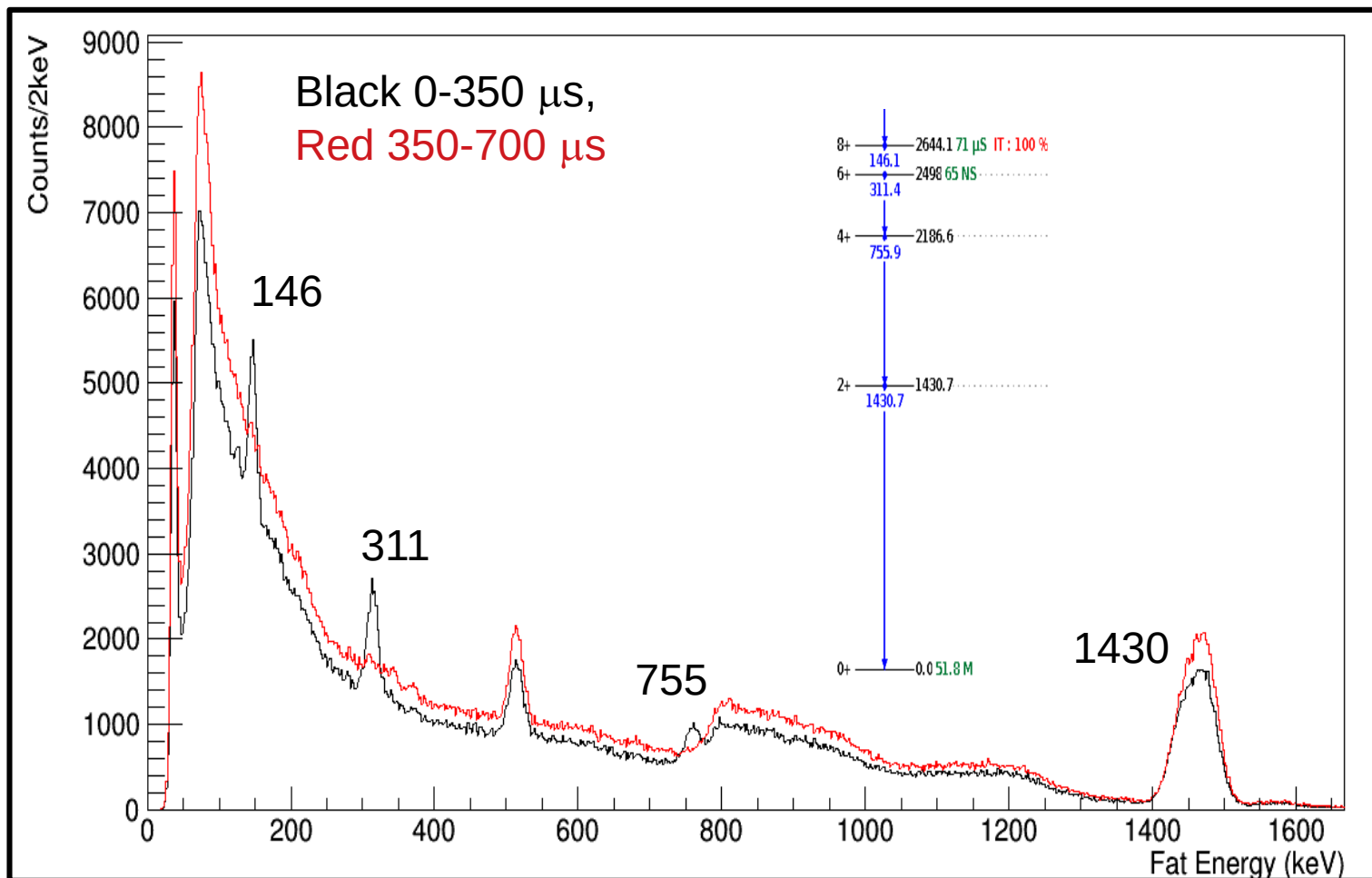


Courtesy of A.Mistry, H. Albers et al.,

Longer Time Correlations: ^{94}Ru



^{94}Ru $T_{1/2}=77\ \mu\text{s}$, $I^\pi=8^+$ isomer in FATIMA Extended Energy range,
A.K.Mistry, H. Albers, N.Hubbard, A.Bannerjee et al., From S480.

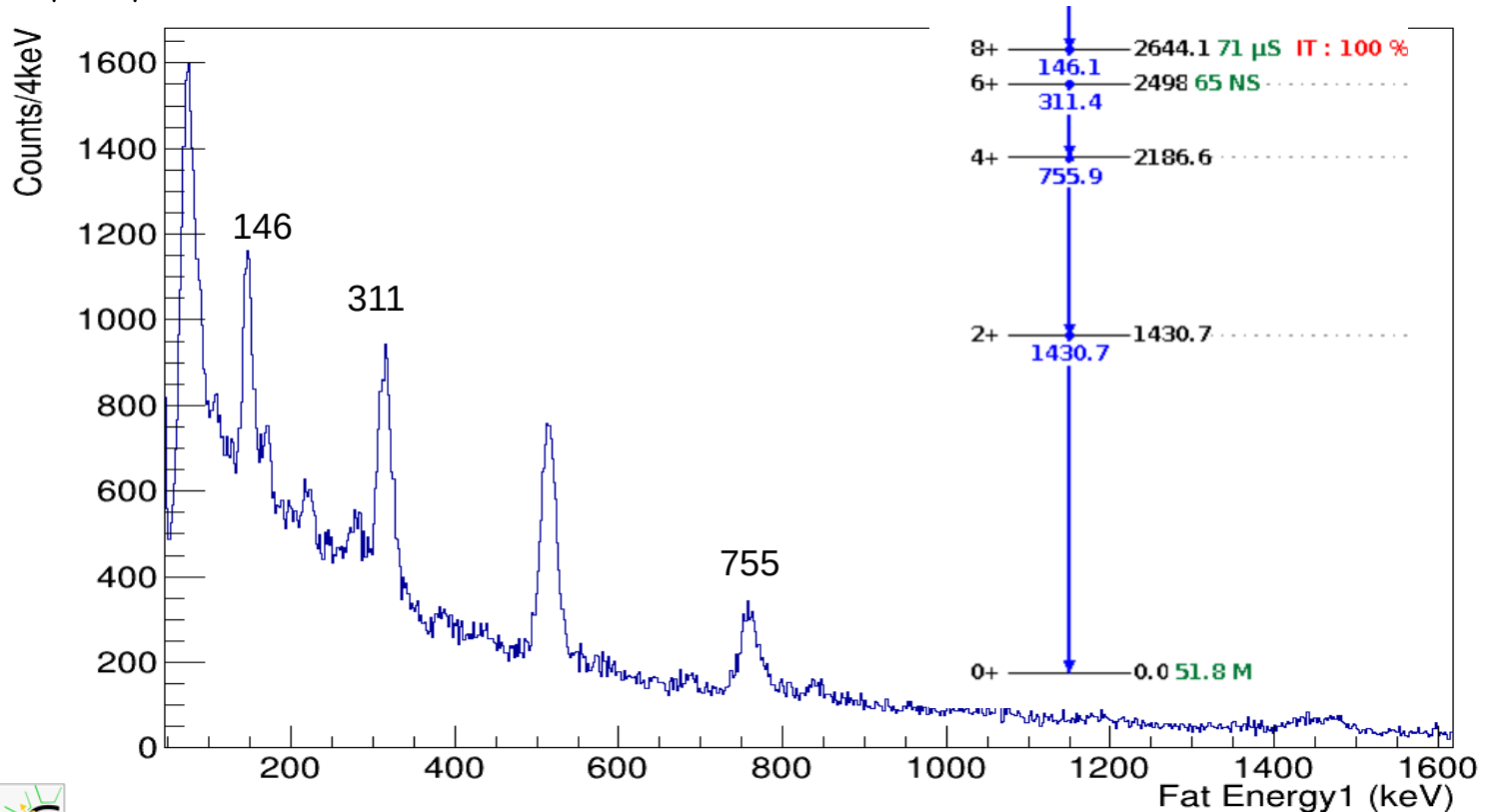


Courtesy of A.Mistry, H. Albers et al.,

Fatima coincidence spectra, (Z,A/Q) gated on ^{94}Ru

E_{γ} gate 1430 keV Projection 0-350 μs range

$$E_{\gamma} - E_{\gamma} \Delta T = \pm 500 \text{ ns}$$

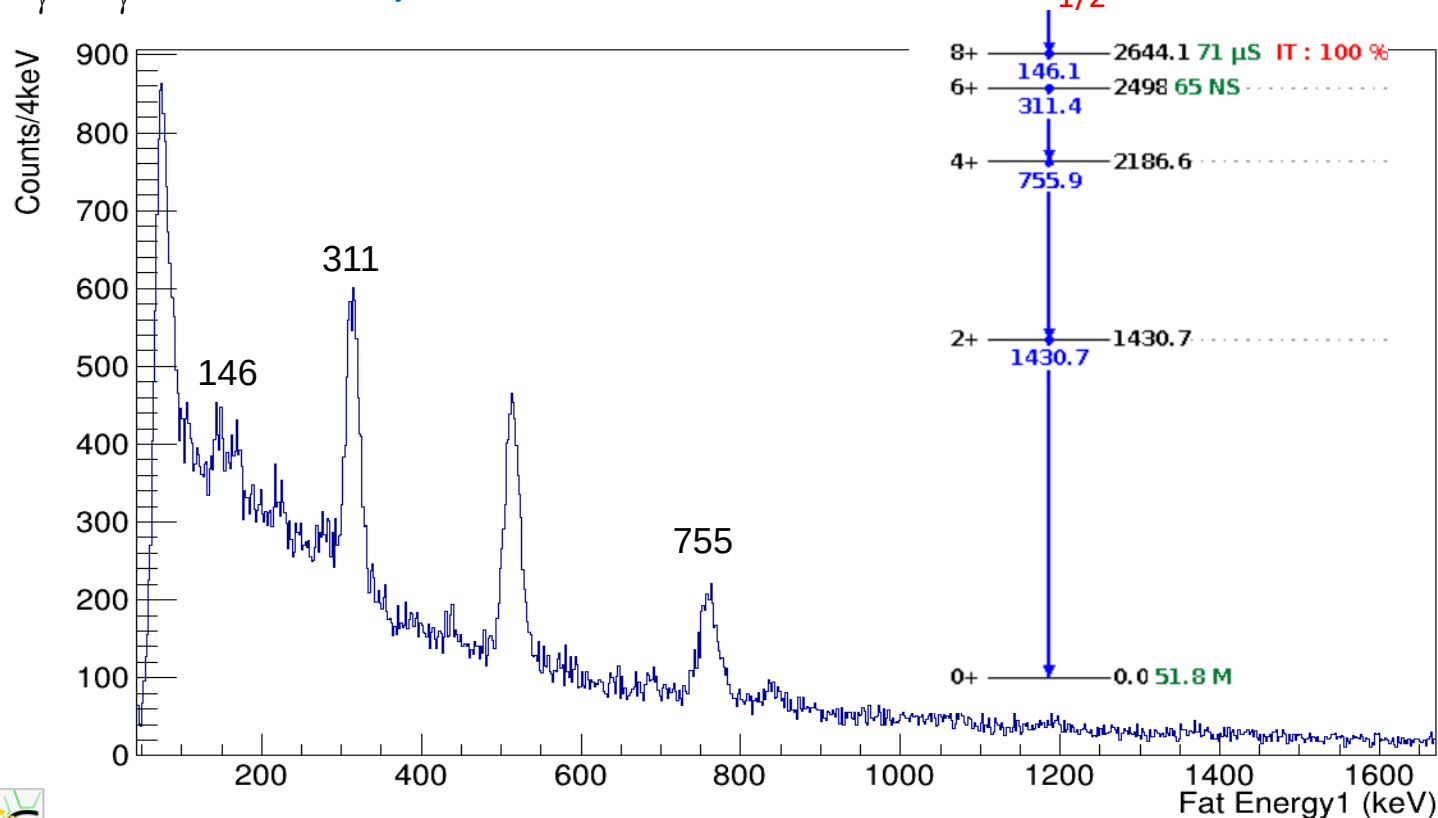


Courtesy of A.Mistry, H. Albers et al.,

Fatima coincidence spectra, (Z,A/Q) gated on ^{94}Ru

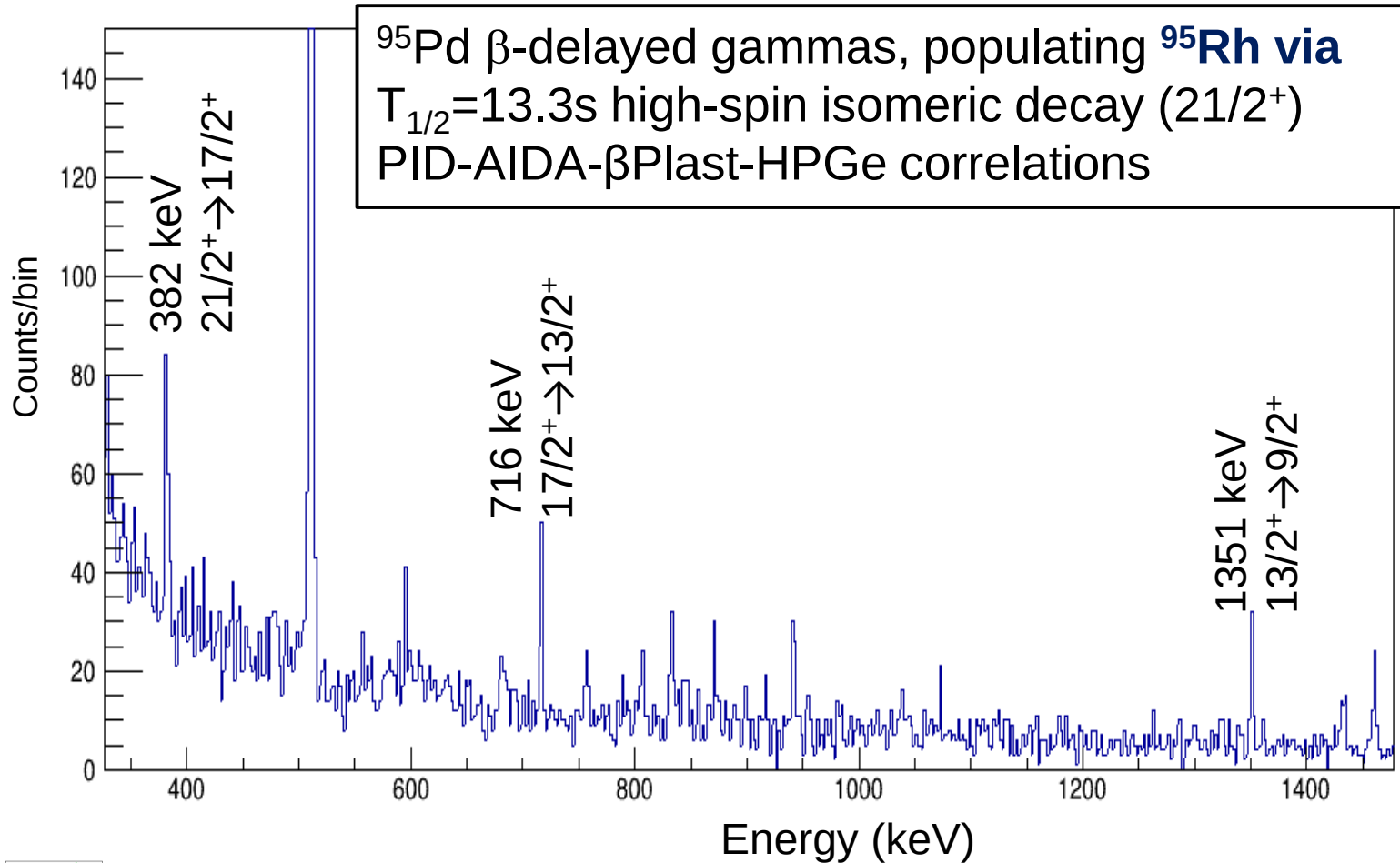
E_γ gate 1430 keV Projection 0-350 μs range

$E_\gamma - E_\gamma \Delta T = \pm 10\text{ns}$, reduction in 146 keV due to $T_{1/2}=65\text{ ns}$ for 6^+

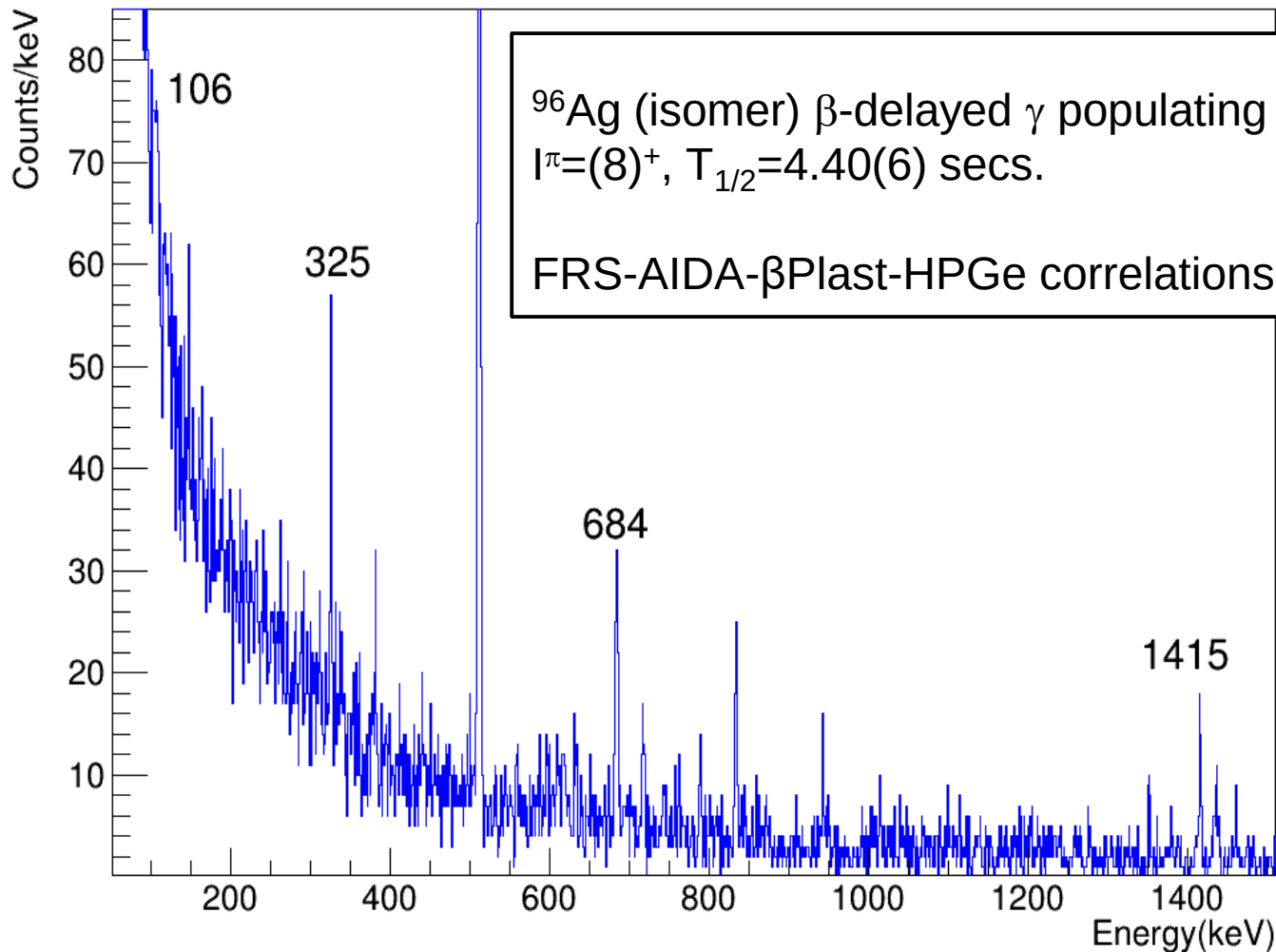


Courtesy of A.Mistry, H. Albers et al.,

β -delayed Spectroscopy with AIDA + β Plast



Courtesy of A.Mistry, H. Albers, B.Das et al.,



Courtesy of A.Mistry, H. Albers et al.,

Summary of S480 Results so Far – to Feb 2021.

- First new physics experiment for DESPEC@FAIR-0 - March 2020.
- $^{94}\text{Pd} (I^\pi=14^+)$ and $^{96}\text{Pd} (I^\pi=8^+)$ isomers measured with FATIMA + HpGe hybrid array + AIDA + β Plast active stopper.
- Isomeric ratios for $^{94,6}\text{Pd}$ used to validate DESPEC-0 DAQ and Monte Carlo simulations for system response.
- PID gated, isomerLaBr₃-LaBr₃- ΔT data used to isolate states.
 - Measured $I^\pi=8^+$ cascade in $^{96}\text{Pd}_{50}$, $T_{1/2}(6^+)=7.2(8) \text{ ns}$; $T_{1/2}(4^+)= 1.1(1) \text{ ns}$.
 - Measured $I^\pi=14^+$ cascade in $T_z=+1$ ^{94}Pd , $T_{1/2}(8^+)=1.1(1) \text{ ns}$ (prelim).
- **White rabbit – PID – FATIMA** correlations demonstrated ia selection of $^{94}\text{Ru}_{50} I^\pi=8^+$, $T_{1/2}=77 \mu\text{s}$ isomeric cascade.
- B-delayed gamma spectroscopy of daughters demonstrated using $^{96}\text{Ag} \rightarrow ^{96}\text{Pd}$ ($T_{1/2}=4.4 \text{ s}$) and $^{95}\text{Pd} \rightarrow ^{95}\text{Rh}$ ($T_{1/2}=13.3 \text{ s}$) decays.

Acknowledgements:

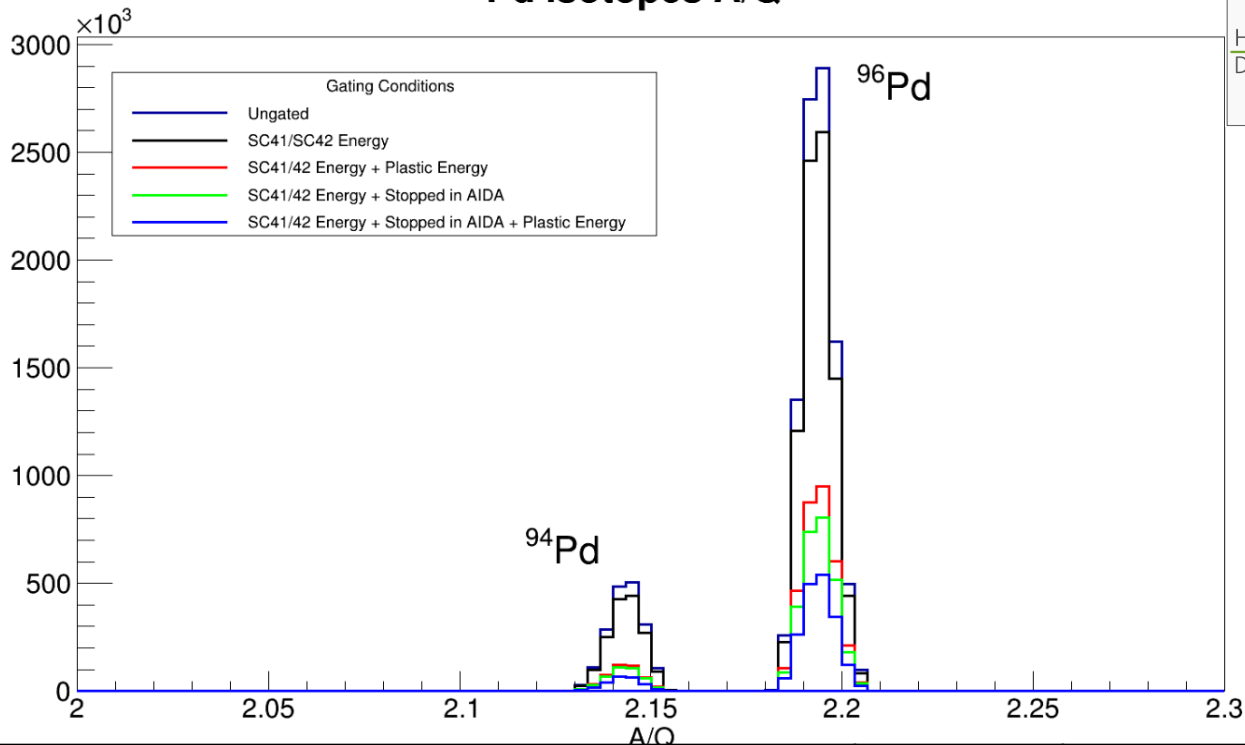
The local GSI DESPEC Team and whole collaboration including:

- **Shaheen Jazrawi**, **Majid Chishti**, Zsolt Podolyak, Rob Shearman, Rhian Canavan et al., (Surrey & NPL UK)
- **Helena Albers**, **Akashrup Banerjee**, **Andrew Mistry**, **Nic Hubbard**, Juergen Gerl, **Magda Gorska**, **Tugba Arici**, Henning Schaffner, Nick Kurz, Ivan Kojouharov, Stephane Pietri et al., (GSI-FAIR-0)
- **Aleks Yaneva**, **Jan Jolie**, Andrey Blazhev et al.,
- **Marta Polettini**, Giovanna Benzoni et al., (Milano)
- Matthias Rudigier, Philip John, Sultan Alhomaidhi, Norbert Pietralla, Volker Werner et al., (TU Darmstadt)
- Biswarup Das, **Bo Cederwall** (KTH Stockholm)
- Tom Davinson, Oscar Hall et al., (Edinburgh)
- Luis Fraile et al. (Madrid)
- BS Nara Singh et al., (U. West of Scotland)
- Alison Bruce et al., (U. Brighton)
- Robert Page et al, (U. Liverpool)



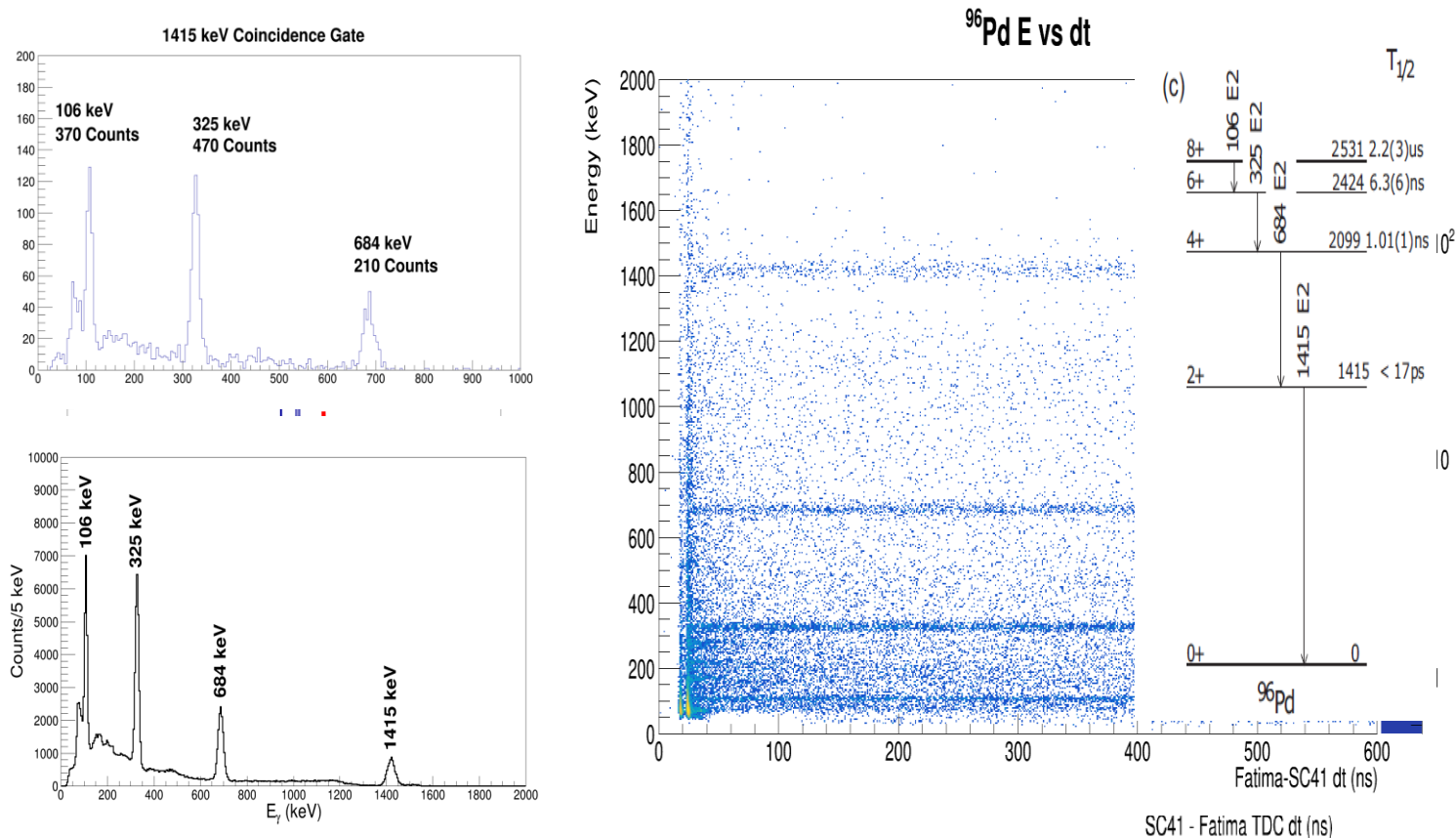
BACK UP SLIDES

Pd Isotopes A/Q



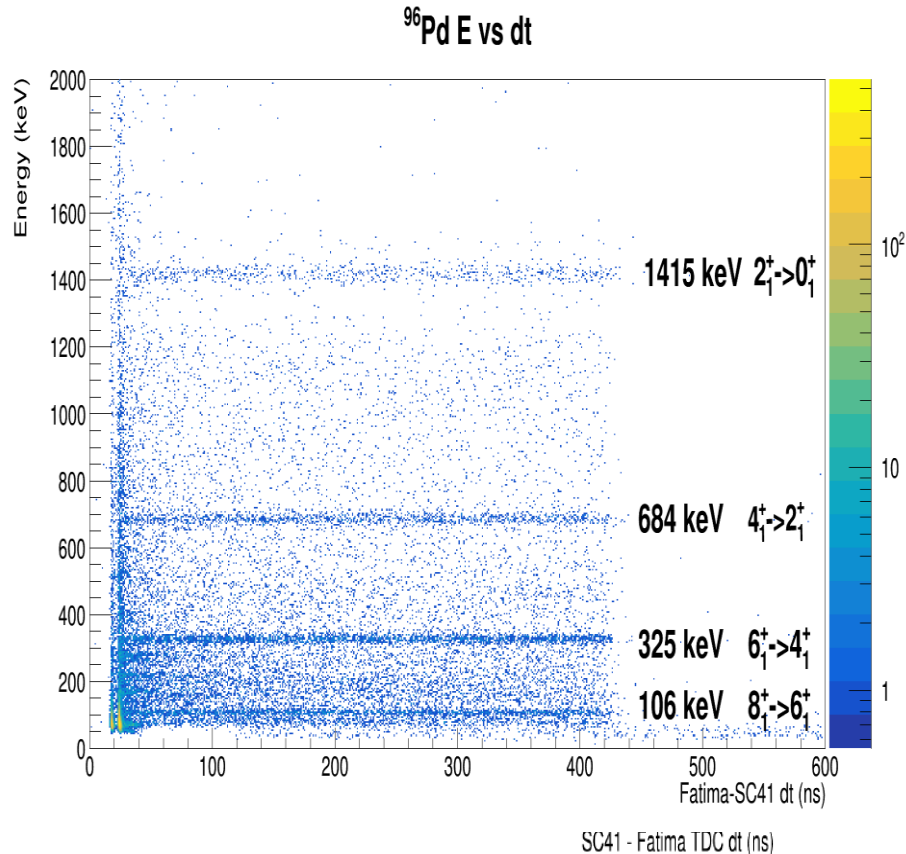
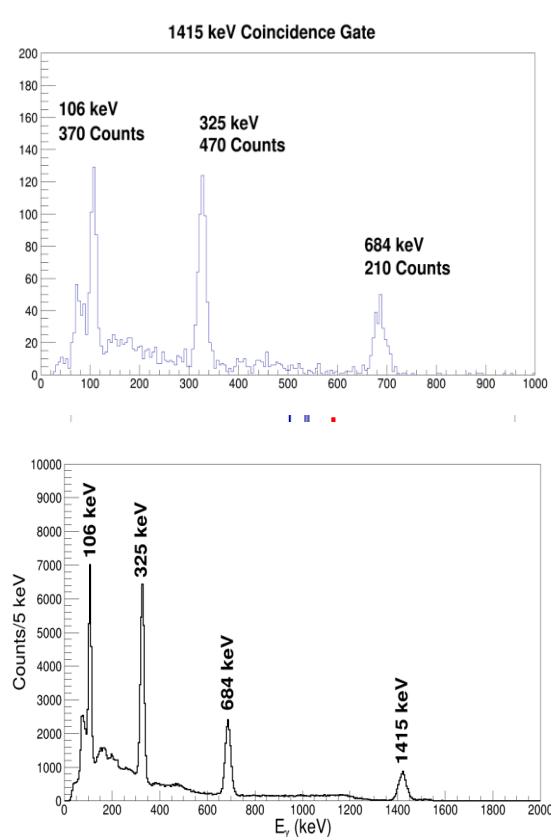
Gate	⁹⁶ Pd Ions	⁹⁴ Pd Ions
Ungated	9.5E6	1.8E6
SC41/42 Energy	8.5E6	1.6E6
SC41/42 Energy + Plastic Energy	3.2E6	4.4E5
SC41/42 Energy + Stopped in AIDA	2.7E6	4.0E5
SC41/42 Energy + Plastic Energy + Stopped in Aida	1.8E6	2.4E5

S480 (March 2020) ^{124}Xe @ 850 MeV/u. PID-isomer gated ΔT - γ - γ using FATIMA.
 Decay of ^{96}Pd $I^\pi=8^+$ $T_{1/2}=2\ \mu\text{s}$ isomer as test example for LaBr3-LaBr3 $\sim\text{ns}$ fast-timing.

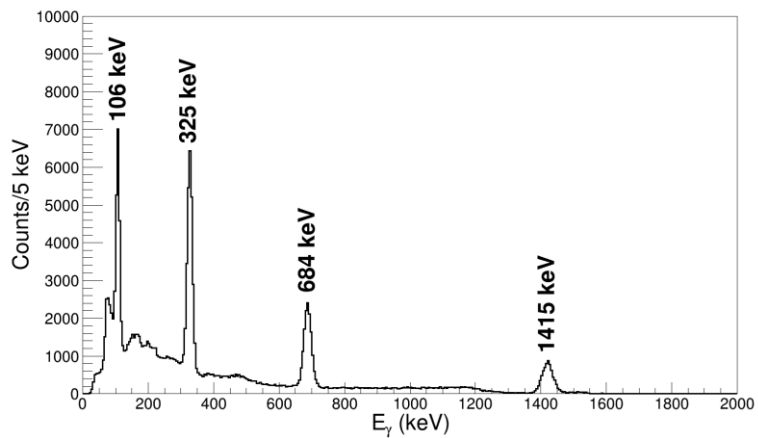


S480, M.Gorska, P.H.Regan, J. Jolie, B. Cederwall et al., Figure courtesy of S. Jazrawi et al.,

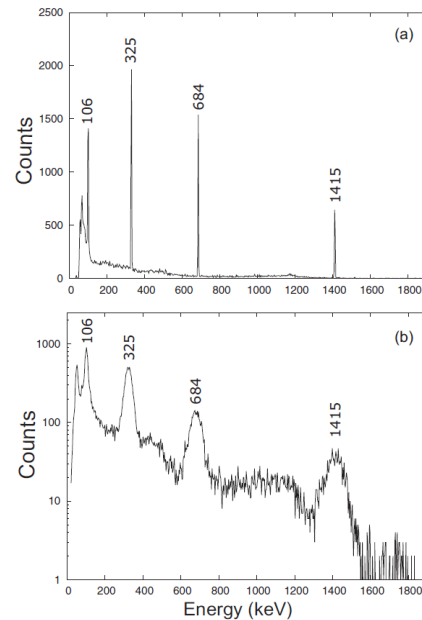
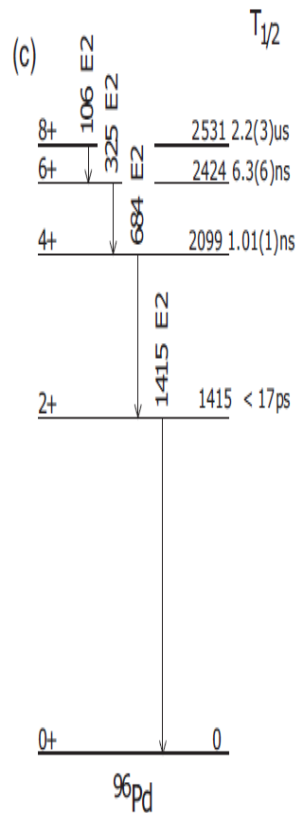
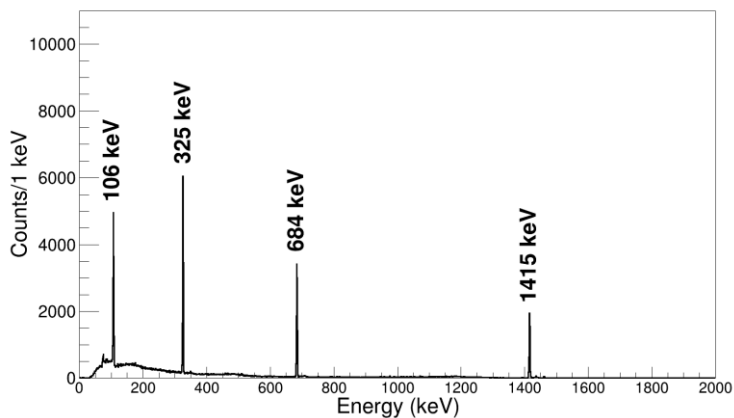
S480 (March 2020) ^{124}Xe @ 850 MeV/u. PID-isomer gated ΔT - γ - γ using FATIMA.
 Decay of ^{96}Pd $I^\pi=8^+$ $T_{1/2}=2\text{ }\mu\text{s}$ isomer as test example for LaBr_3 - LaBr_3 - $\Delta T \sim \text{ns}$ fast-timing.



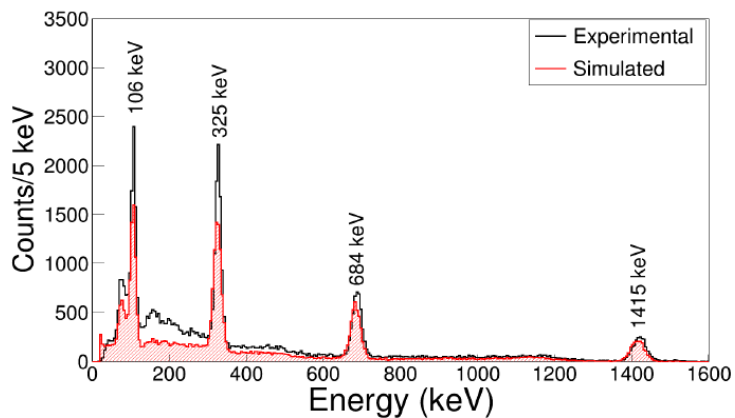
S480, M.Gorska, P.H.Regan, J. Jolie, B. Cederwall et al., Figure courtesy of S. Jazrawi et al.,



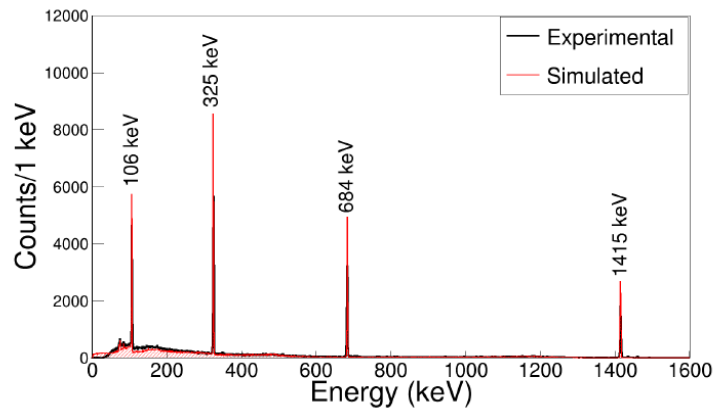
^{96}Pd $I^\pi = 8^+$ Isomer



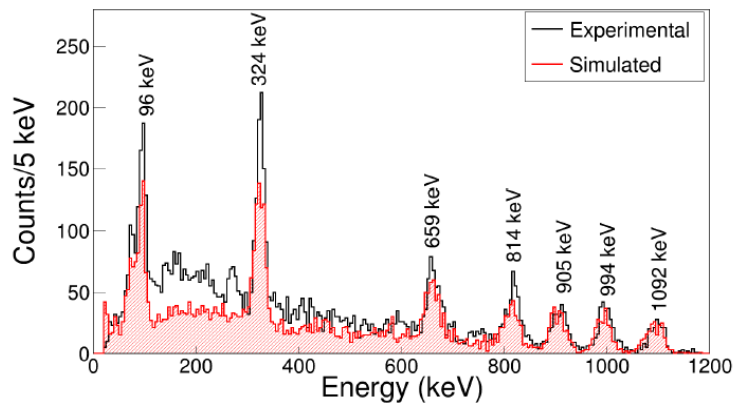
$^{96}\text{Pd}_{50}$ ($T_z=+2$), $I^\pi=8^+$ isomer, $T_{1/2}=2.2(3) \mu\text{s}$. Mach et al., Phys. Rev. C95, 014313 (2017), using BaF_2 .



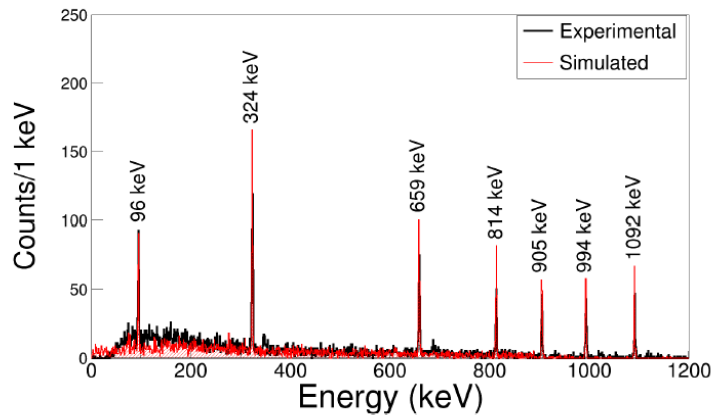
(a)



(a)



(b)



(b)