Observation of low-lying isomeric states in 136Cs:

A new avenue for dark matter and solar neutrino detection in xenon detectors

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NEWS Colloquium
November 21, 2023

Outline

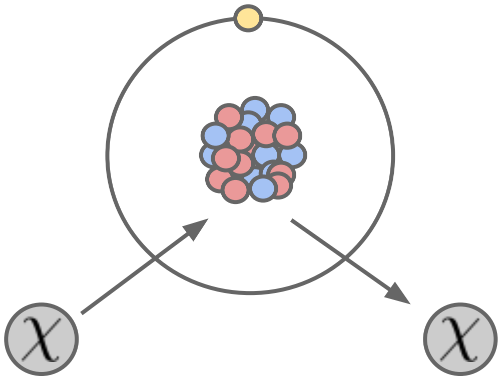
1. Large, low-background xenon detectors in particle physics
2. Solar neutrinos and charged-current interactions on ^{136}Xe
3. New measurements of ^{136}Cs excited state spectrum using ^{138}Ba(d,a)^{136}Cs reactions
4. New measurements of gamma ray emission from ^{136}Cs excited states using ^{136}Xe(p,n)^{136}Cs reactions
5. Implications and summary

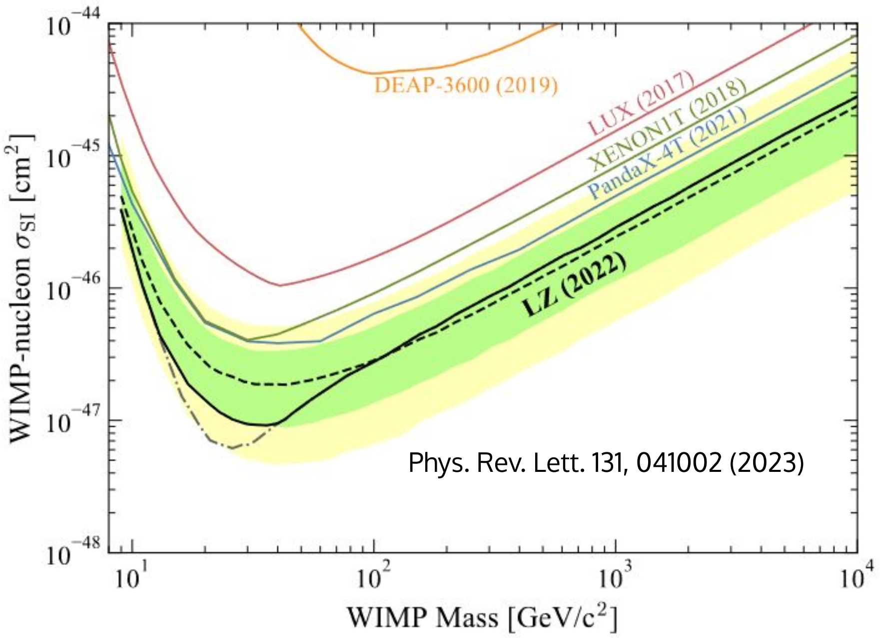
The search for WIMP dark matter

Weakly **I**nteracting **M**assive **P**articles

Generic thermal relic dark matter

→ Searching for **low-energy nuclear recoils in large, low-background detectors**



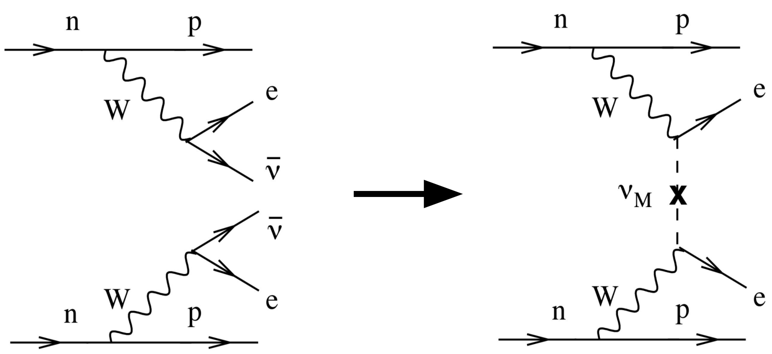


The **most sensitive searches** to date use **liquid-xenon-based detectors**

The state-of-the-art at present

There are *multiple* **multi-tonne-scale experiments** (LZ, XENONnT, Panda-X) using **liquid xenon time projection chambers** to search for WIMP dark matter and other rare processes

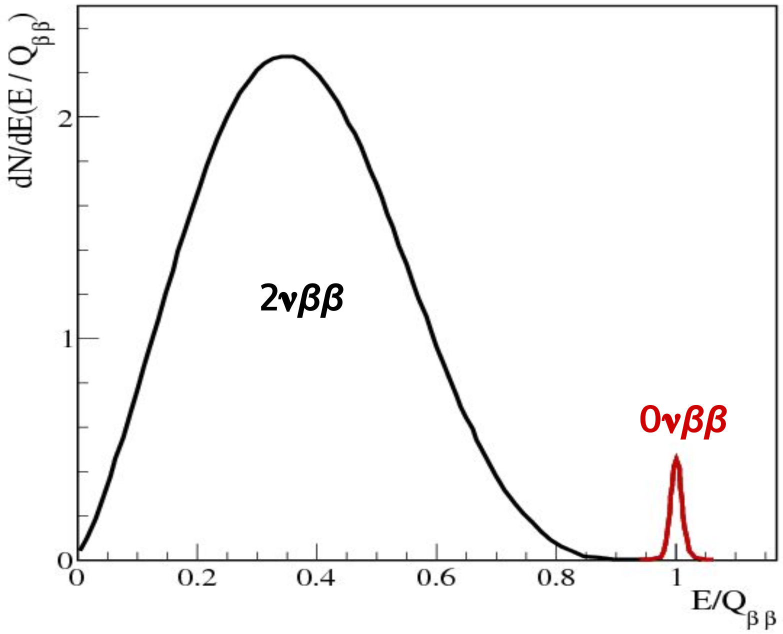
Neutrinoless double beta decay ($0\nu\beta\beta$)



Avignone, Elliott, & Engel *Rev. Mod. Phys.* **80** (2008)

A rare nuclear decay: the single most sensitive probe of lepton number non-conservation and the Majorana neutrino hypothesis

- Could reveal neutrino mass mechanism
- Could provide physics for generating baryon asymmetry

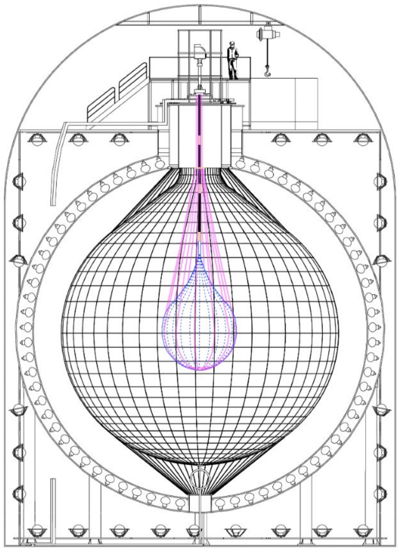


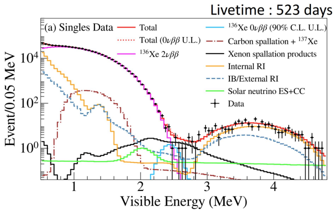
Current and upcoming xenon detectors for 0νββ searches

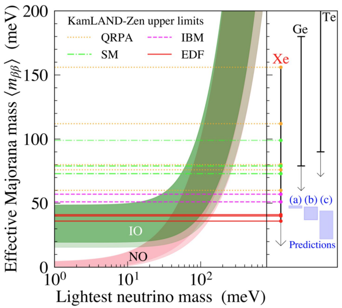
KamLAND-Zen 800

Liquid scintillator loaded with **~800 kg of xenon enriched in ^{136}Xe**

- **World's most sensitive search for 0νββ**
- Currently operating with upgrades planned! (KamLAND2-Zen)



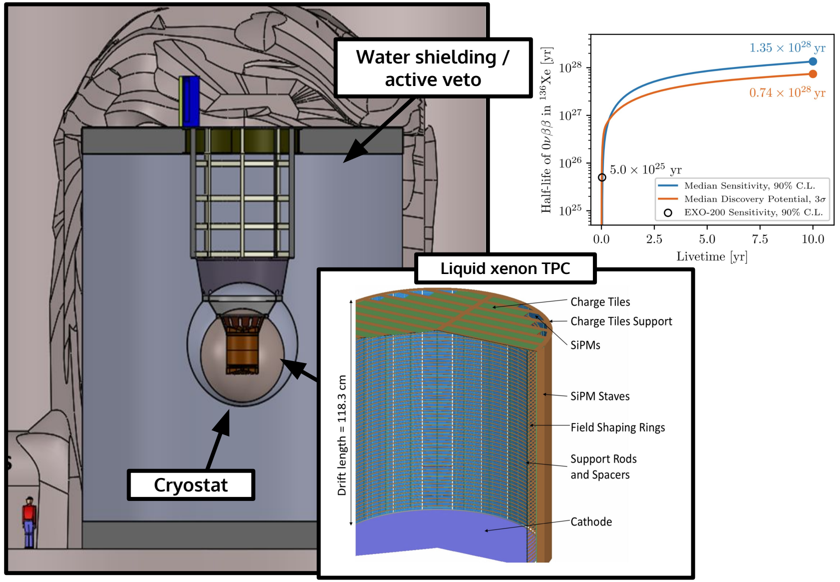




The nEXO experiment

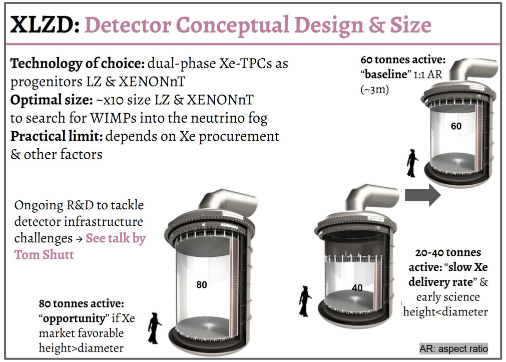
Liquid xenon time projection chamber (TPC) filled with **~5 tonnes of xenon enriched in ^{136}Xe**

- Currently under development
- Projected sensitivity $T_{1/2} > 10^{28}$ years



What the future could look like

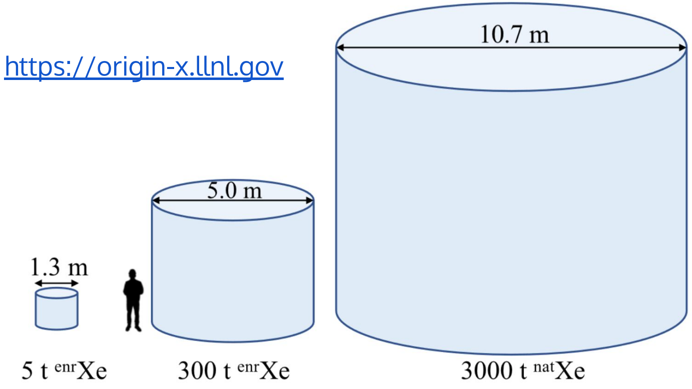
100-tonne-scale dark matter experiments?



[Slide from Alvine Kamaha](#)

Kilotonne-scale xenon TPCs for 0νββ?

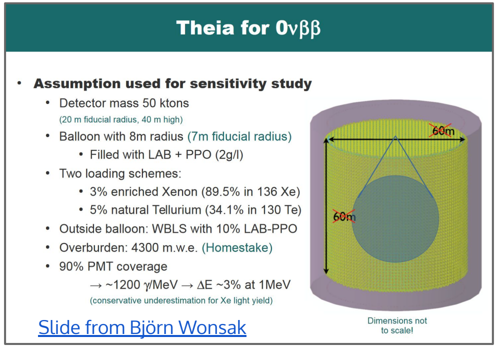
https://origin-x.llnl.gov



A. Avasthi et al., *Phys Rev D* **104,** 112007 (2021)

Enormous ^{136}Xe-loaded liquid scintillator detectors?

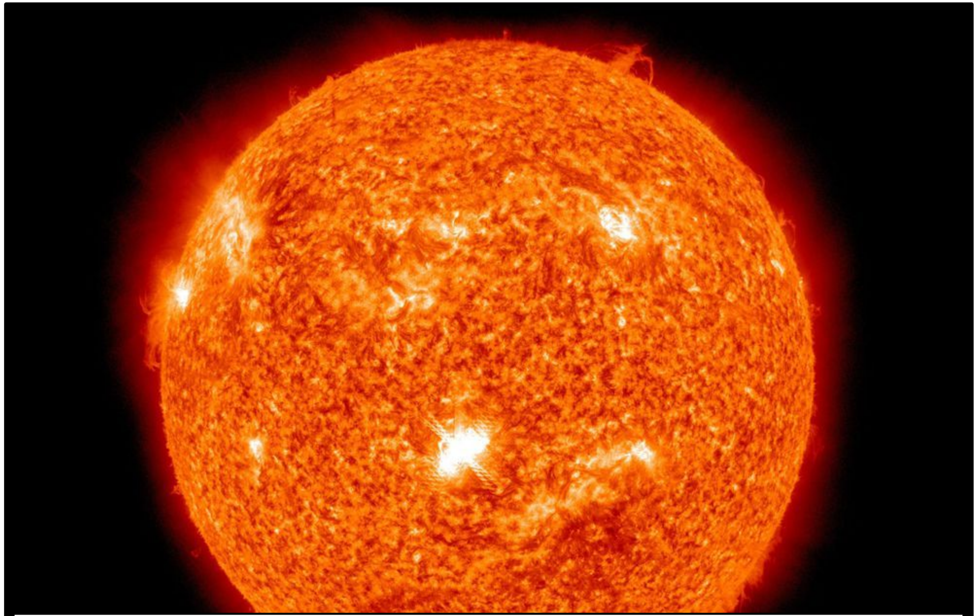
THEIA & JUNO both have sensitivity projections for far-future 0νββ searches with ^{136}Xe



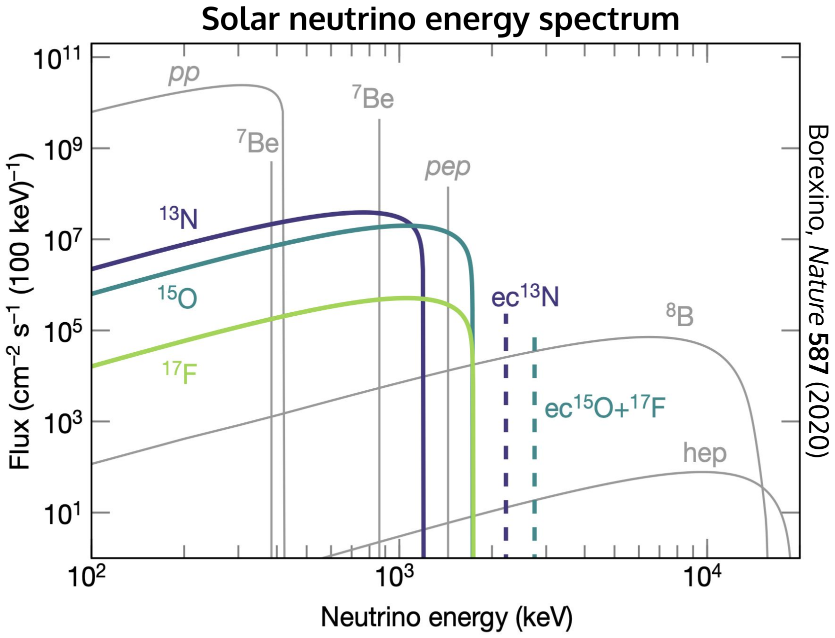
Will require new sources of xenon (see recent workshop @ SLAC!), but exciting possibilities

So, what other physics can we do with these detectors?

Solar neutrinos



Neutrinos provide direct information about nuclear processes in the sun's core, and can shed light on its composition

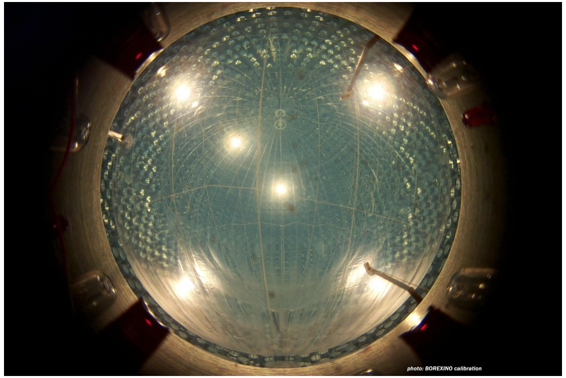


Borexino: a groundbreaking experiment

Neutrino-electron elastic scattering in ultra-low-background liquid scintillator

Myriad "firsts" in solar neutrino physics

- Real-time detection of ^{7}Be neutrinos
- Comprehensive measurement of pp-chain
- First (and only) detection of CNO cycle
    - Direct measure of solar metallicity in core
- Pioneered many experimental techniques and performed comprehensive tests of solar models



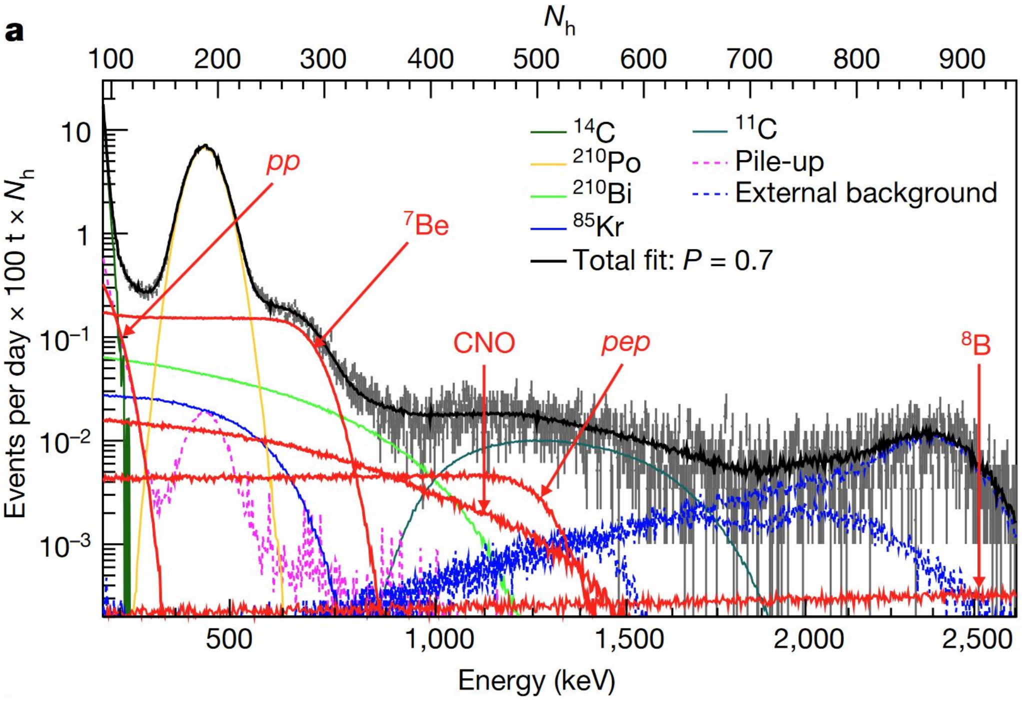
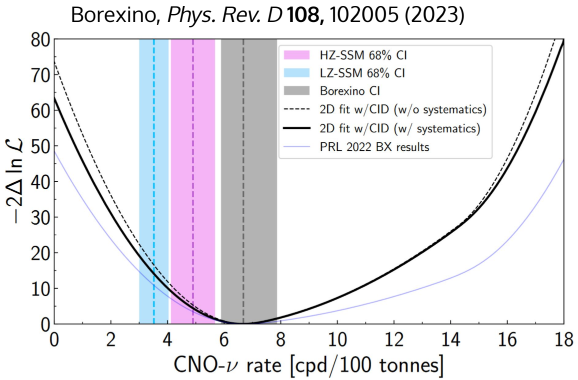


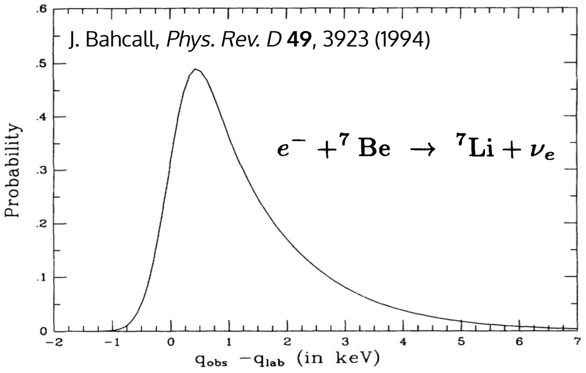
Figure from "*Comprehensive measurement of pp-chain solar neutrinos*", Borexino Collaboration, *Nature* **562** (2018)

What can we still learn about solar neutrinos?

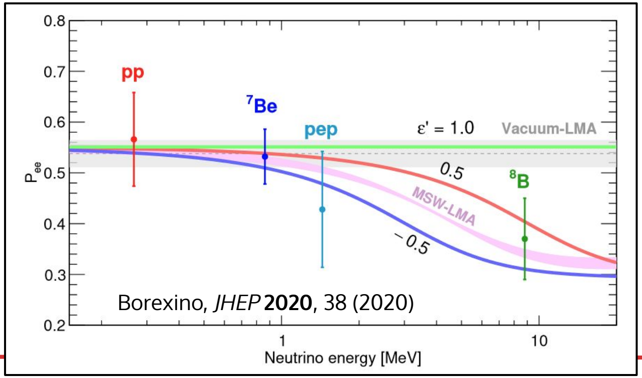
Independent, precise measurements of CNO flux could help address solar metallicity problem



Precision measurements of ^{7}Be line position & width provide independent measurement of solar core temperature



New measurements of *pep* neutrino flux could constrain new physics in the transition region of the LMA-MSW survival probability curve



Neutrino CC interactions with $\beta\beta$ isotopes

A (negligible) background for 0νββ searches…

PHYSICAL REVIEW C **89**, 055501 (2014)

Charged current neutrino cross section for solar neutrinos, and background to $\beta\beta(0\nu)$ experiments

H. Ejiri[1] and S. R. Elliott[2]
[1] *Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan*
[2] *Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

(Received 30 September 2013; revised manuscript received 2 January 2014; published 8 May 2014)

But also a signal!

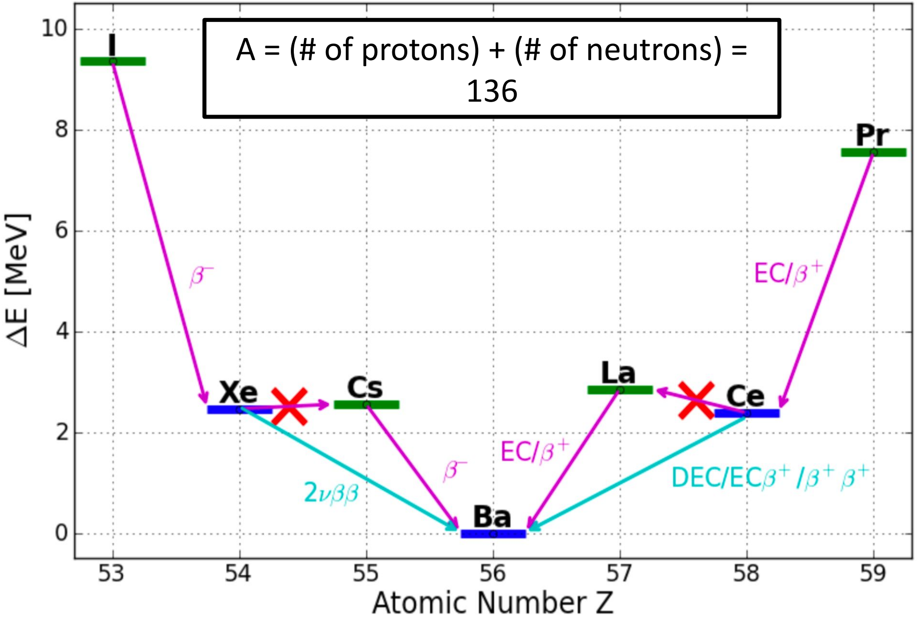
VOLUME 78, NUMBER 19 PHYSICAL REVIEW LETTERS 12 MAY 1997

New Prospects for Real-Time Spectroscopy of Low Energy Electron Neutrinos from the Sun

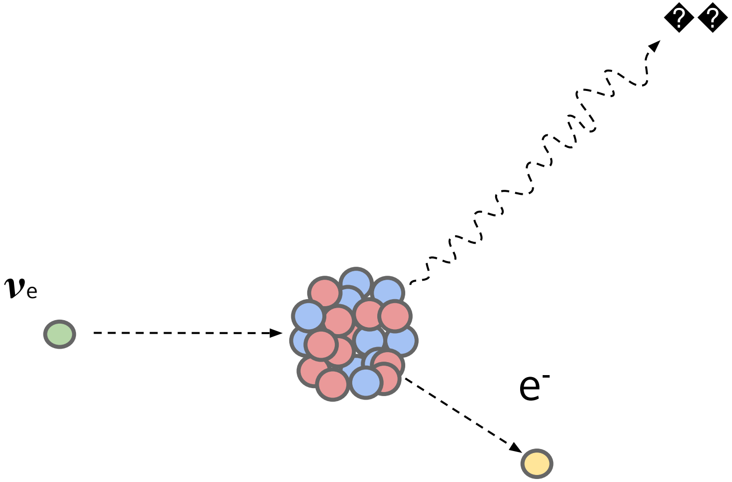
R. S. Raghavan
Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974

(Received 20 December 1996; revised manuscript received 3 March 1997)

No tagged ν_e reactions on *stable* targets have been found up to now. The breakthrough occurred with the realization that *double* β *decay* prescribes the precise framework for discovering new tagged low energy ν_e reactions without the target stability problem. Isobaric triplets $[I(A, Z,$ even A, even Z, spin $0^+)$, $F(A, Z + 1)$, $FF(A, Z + 2)]$ are



Charged-current reactions on ^{136}Xe



$$\boxed{\nu_e + {}^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Cs}^* + e^-}$$

"Stimulated beta decay" provides a new detection channel for neutrinos with xenon detectors

- *Very low threshold* - mass difference between ^{136}Xe and ^{136}Cs nuclei is ~90 keV
- *Relatively high cross section* - larger than elastic **ν + e** scattering by a factor of ~2
- *Opportunities for final-state tagging* - ^{136}Cs could be tagged via emission of characteristic γ-rays

S. Haselschwardt, **BL**, P. Pirinen, J. Suhonen, *Phys. Rev. D* **102** (2020)

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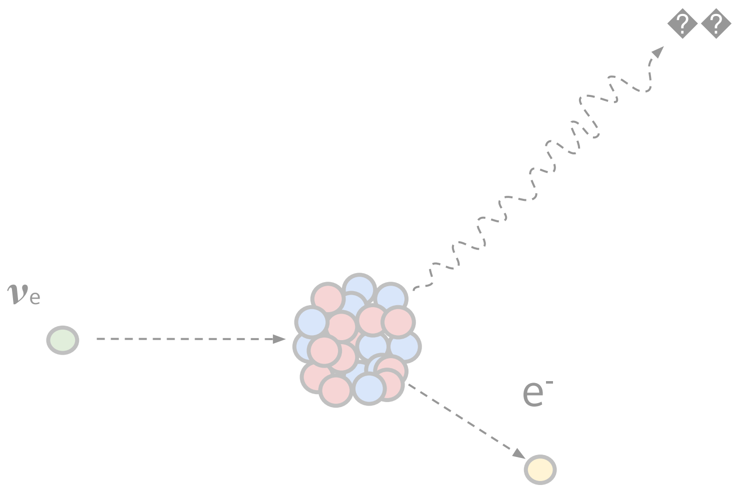

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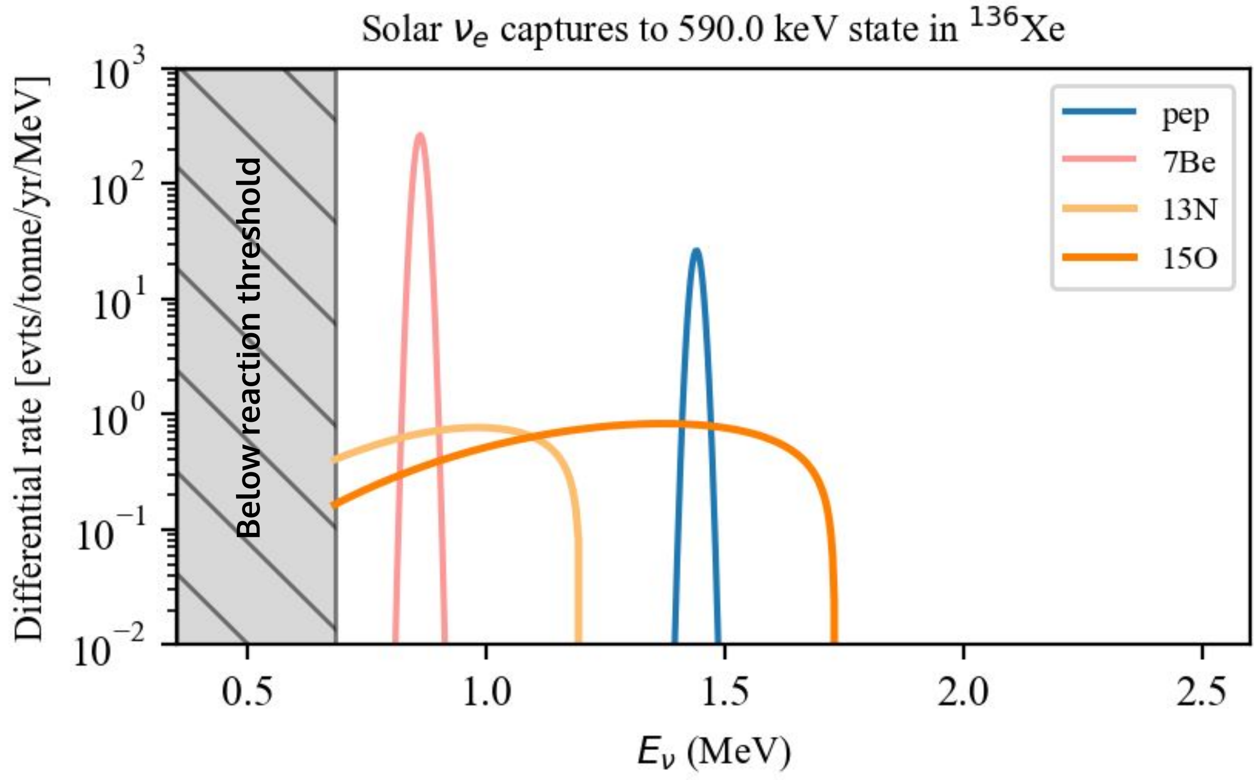
If possible, could allow *background-free measurements* of these interactions

S. Haselschwardt, **BL**, P. Pirinen, J. Suhonen, *Phys. Rev. D* **102** (2020)

Charged-current events in xenon detectors



See: S. Haselschwardt, **BL**, P. Pirinen, J. Suhonen, *Phys. Rev. D* **102** (2020)

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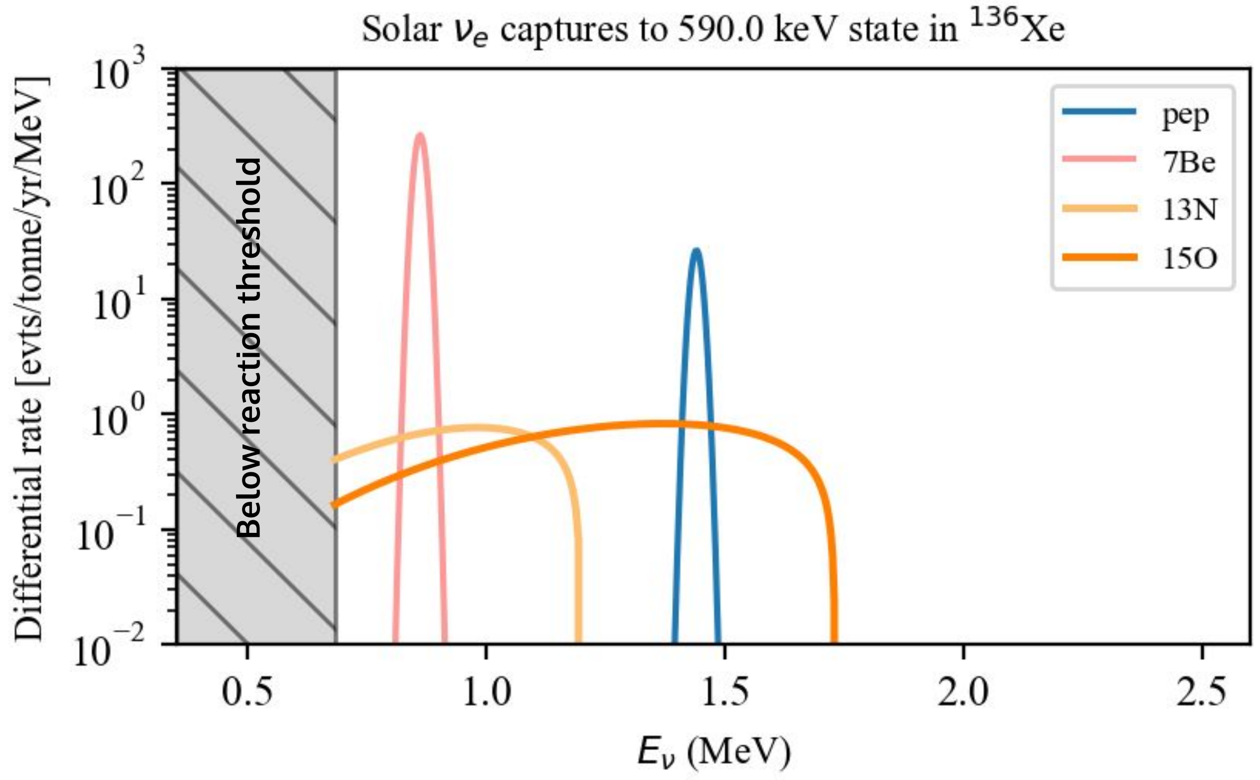


See: S. Haselschwardt, **BL**, P. Pirinen, J. Suhonen, *Phys. Rev. D* **102** (2020)

In addition to low-energy neutrinos: fermionic dark matter

Fermionic dark matter absorption on nuclei via a new charged-current interaction:

$$\chi + {}^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Cs}^{*} + e^{-}$$

PHYSICAL REVIEW LETTERS **124,** 181301 (2020)

Directly Detecting Signals from Absorption of Fermionic Dark Matter

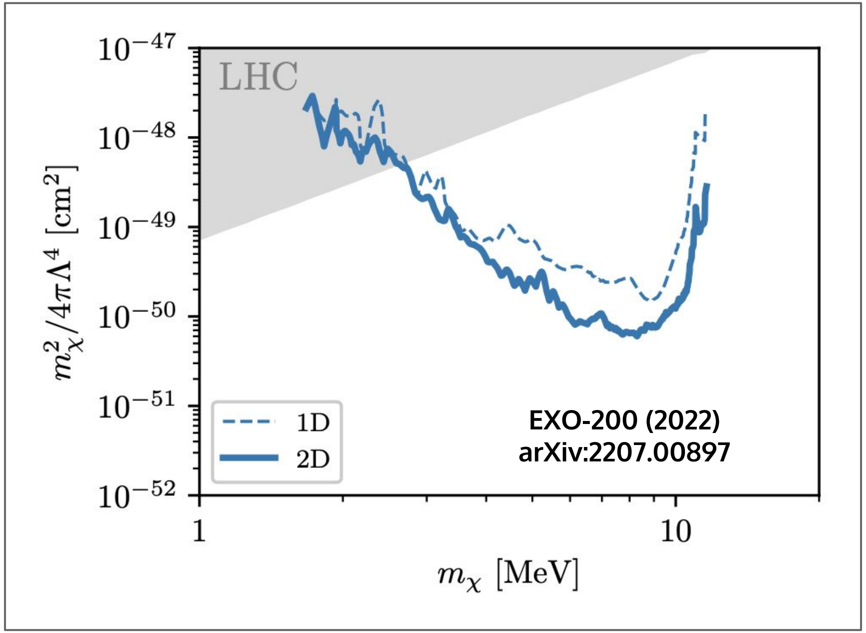
Jeff A. Dror,[1,2] Gilly Elor,[3] and Robert McGehee[2,1]
[1]*Theory Group, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2]*Berkeley Center for Theoretical Physics, University of California, Berkeley, California 94720, USA*
[3]*Department of Physics, Box 1560, University of Washington, Seattle, Washington 98195, USA*

(Received 5 June 2019; revised manuscript received 2 March 2020; accepted 16 April 2020; published 4 May 2020)

https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.124.181301

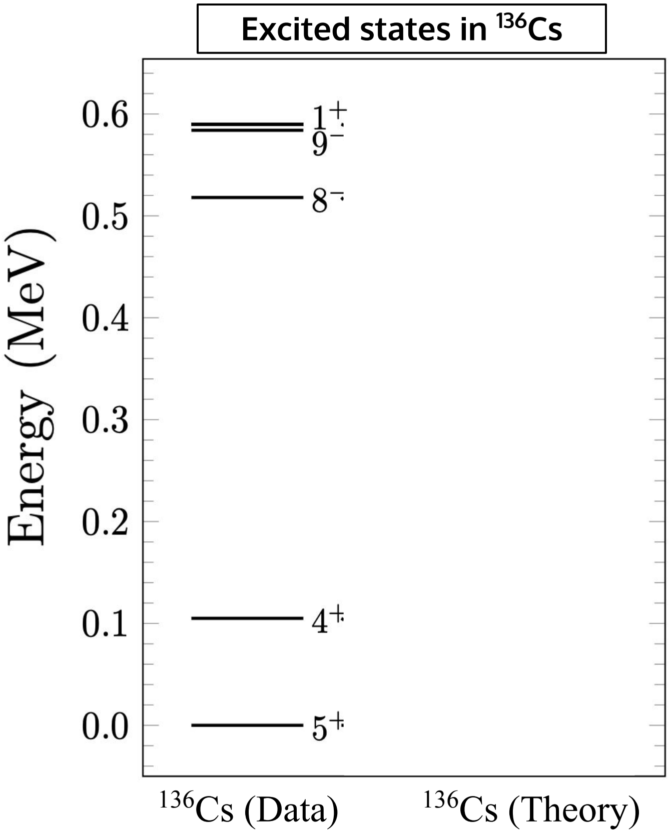
Larger exposure and *background reduction via* ^{136}*Cs tagging* would allow **dramatically increased sensitivity**

World-leading DM limits from EXO-200



What would I look for in a large xenon detector?

Modeling the process



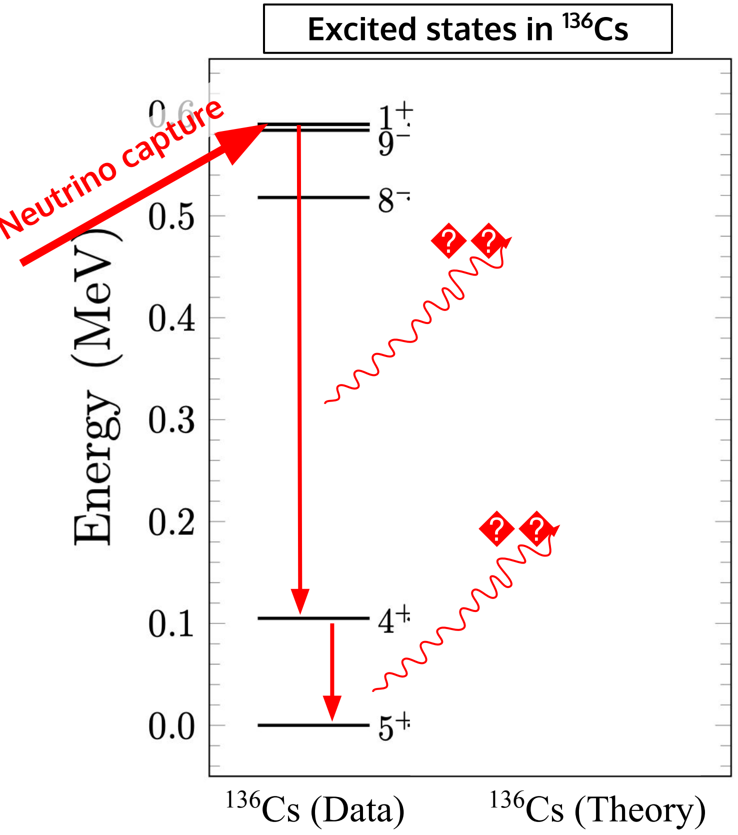
^{136}Xe ground state has $J^\pi = 0^+$

Charged-current reactions preferentially populates the lowest-lying $J^\pi = 1^+$ state in ^{136}Cs

However, nuclear data in ^{136}Cs is sparse

S. Haselschwardt, **BL**, P. Pirinen, J. Suhonen, *Phys. Rev. D* **102** (2020)

Modeling the process



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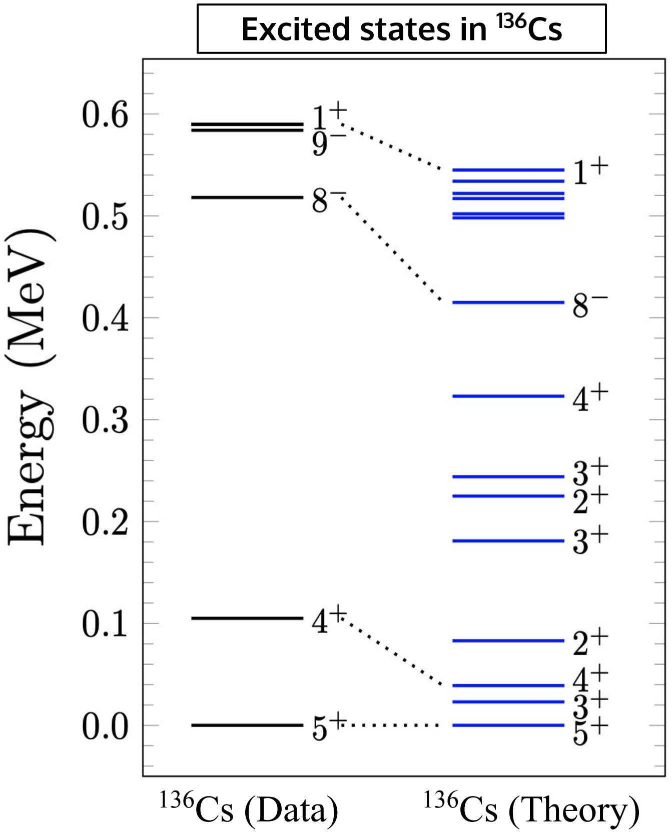

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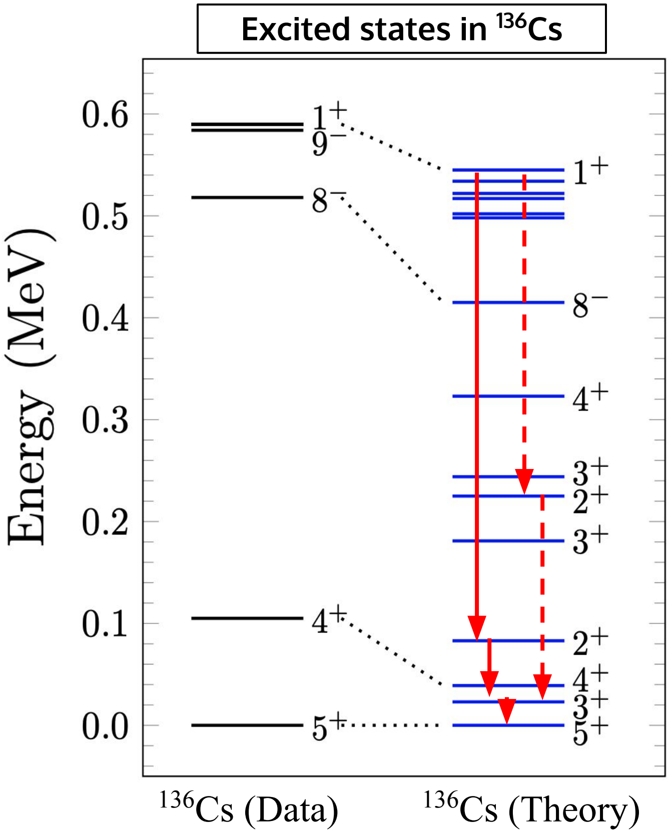
Nuclear shell model calculations predict a much more complex level scheme

S. Haselschwardt, **BL**, P. Pirinen, J. Suhonen, *Phys. Rev. D* **102** (2020)

Modeling the process



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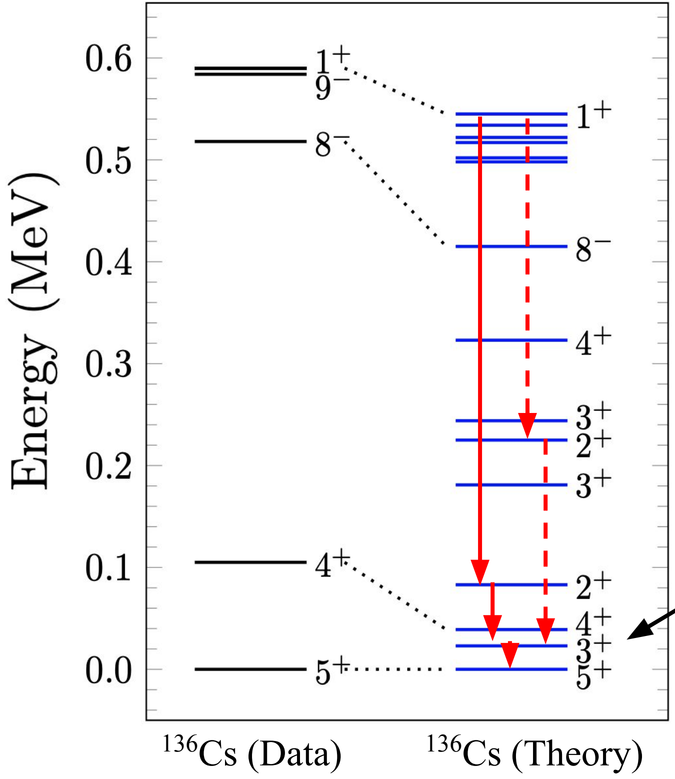
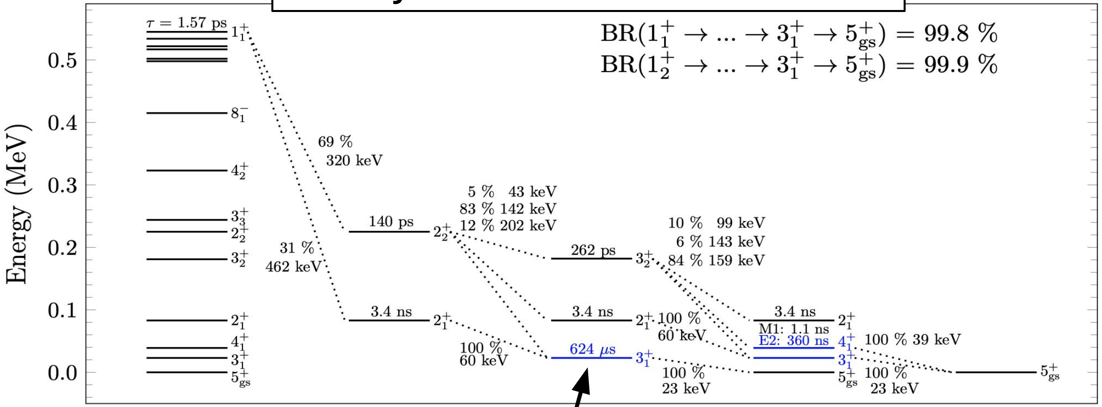
S. Haselschwardt, **BL**, P. Pirinen, J. Suhonen, *Phys. Rev. D* **102** (2020)

Tagging ^{136}Cs via gamma cascade

Excited states in ^{136}Cs



Decay scheme of 1⁺ state at 590 keV



Low-lying 3⁺ state is predicted to be very long-lived: O(100) microseconds (easily resolved in modern expts)

S. Haselschwardt, **BL**, P. Pirinen, J. Suhonen, *Phys. Rev. D* **102** (2020)

Tagging ^{136}Cs via gamma cascade

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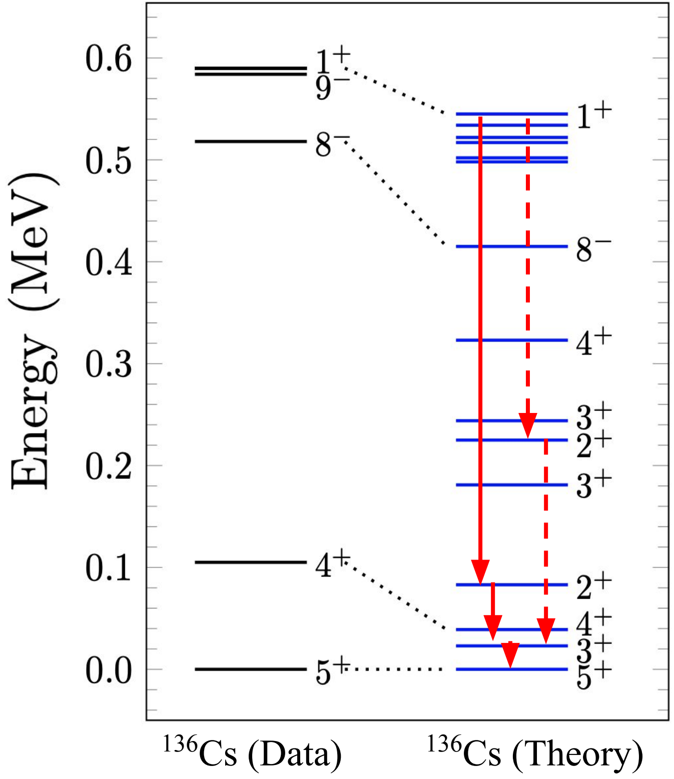
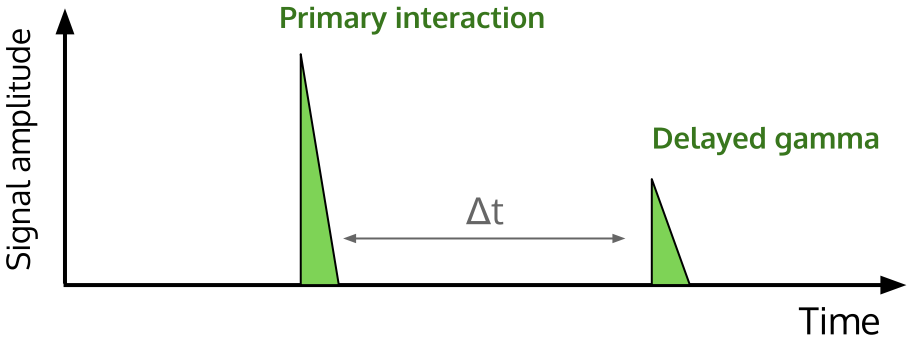


Time coincidence signal in detector



Delayed signal from predicted 3^+ state could be easily resolved in time and position

Estimated background suppression up to ~ 10^{-10}

Background-free solar ν_e measurements and searches for dark matter?

S. Haselschwardt, **BL**, P. Pirinen, J. Suhonen, *Phys. Rev. D* **102** (2020)

Other reasons to be interested in the nuclear structure of ^{136}Cs

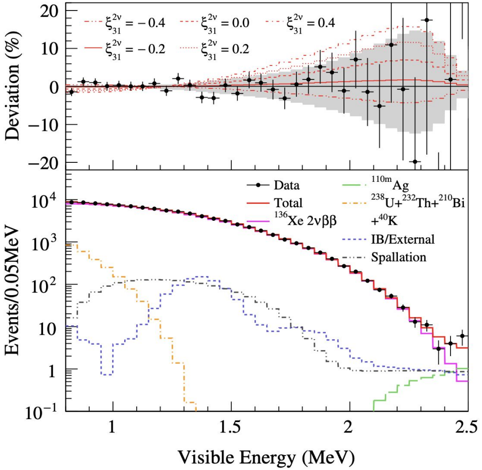
Low-energy ^{136}Cs states relevant for calculations of the half-life and spectral shape of ^{136}Xe 2νββ

PHYSICAL REVIEW LETTERS **122,** 192501 (2019)

Precision Analysis of the ^{136}Xe Two-Neutrino $\beta\beta$ Spectrum in KamLAND-Zen and Its Impact on the Quenching of Nuclear Matrix Elements

A. Gando,[1] Y. Gando,[1] T. Hachiya,[1] M. Ha Minh,[1] S. Hayashida,[1] Y. Honda,[1] K. Hosokawa,[1] H. Ikeda,[1] K. Inoue,[1,2] K. Ishidoshiro,[1] Y. Kamei,[1] K. Kamizawa,[1] T. Kinoshita,[1] M. Koga,[1,2] S. Matsuda,[1] T. Mitsui,[1] K. Nakamura,[1,2] A. Ono,[1] N. Ota,[1] S. Otsuka,[1] H. Ozaki,[1] Y. Shibukawa,[1] I. Shimizu,[1] Y. Shirahata,[1] J. Shirai,[1] T. Sato,[1] K. Soma,[1] A. Suzuki,[1] A. Takeuchi,[1] K. Tamae,[1] K. Ueshima,[1] H. Watanabe,[1] D. Chernyak,[2] A. Kozlov,[2] S. Obara,[3] S. Yoshida,[4] Y. Takemoto,[5] S. Umehara,[5] K. Fushimi,[6] S. Hirata,[7] B. E. Berger,[2,8] B. K. Fujikawa,[2,8] J. G. Learned,[9] J. Maricic,[9] L. A. Winslow,[10] Y. Efremenko,[2,11] H. J. Karwowski,[12] D. M. Markoff,[12] W. Tornow,[2,12] T. O'Donnell,[13] J. A. Detwiler,[2,14] S. Enomoto,[2,14] M. P. Decowski,[2,15] J. Menéndez,[16] R. Dvornický,[17,18] and F. Šimkovic[17,19,20]

(KamLAND-Zen Collaboration)



$$(T_{1/2}^{2\nu})^{-1} \simeq (g_A^{\rm eff})^4 |M_{GT}^{2\nu}|^2 G_0^{2\nu},$$

$$\downarrow$$

$$(T_{1/2}^{2\nu})^{-1} \simeq (g_A^{\rm eff})^4 \left|(M_{GT}^{2\nu})^2 G_0^{2\nu} + M_{GT}^{2\nu} M_{GT-3}^{2\nu} G_2^{2\nu}\right| = (g_A^{\rm eff})^4 |M_{GT-3}^{2\nu}|^2 \frac{1}{|\xi_{31}^{2\nu}|^2} \left|G_0^{2\nu} + \xi_{31}^{2\nu} G_2^{2\nu}\right|, \quad (2)$$

Ordinary muon capture

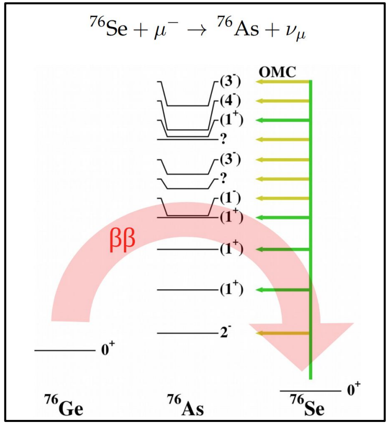
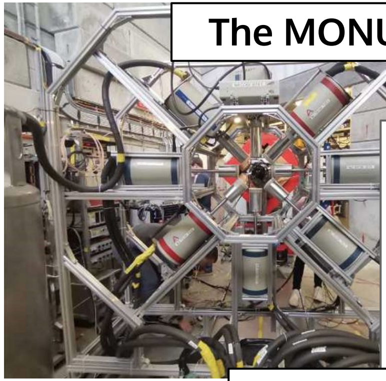


Figure borrowed from J. Suhonen

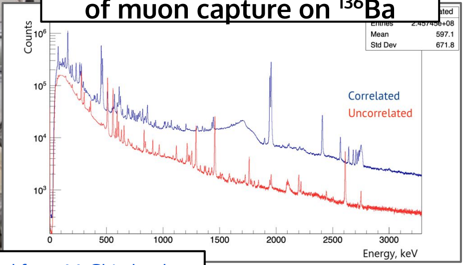
Muon capture to excited states in intermediate nuclei

Probes nuclear physics at momentum transfers relevant for 0νββ

The MONUMENT experiment



Preliminary measurements of muon capture on ^{136}Ba



Figures borrowed from M. Shirchenko

A dearth of data for ^{136}Cs

The relevant energy levels have never been measured!

Experiments to date have been highly selective

- Charge exchange targeting 1^{+} states
- Heavy ion interactions targeting high-spin states
- Studies of 8^{-} isomer at 518 keV

To explore the physics we've discussed, we need new data!

Screenshot of NNDC nuclear data table for ^{136}Cs

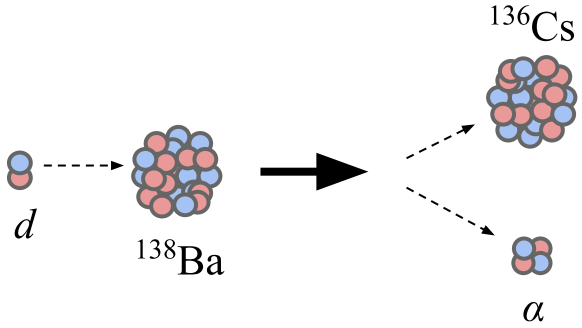
References:

A ^{136}Cs IT decay (17.5 S) B ^{136}Xe(^{3}He,t)
C ^{138}Ba(μ^{-},2nγ) D ^{238}U(^{12}C,Fγ),^{208}Pb(^{18}O,Fγ)

E(level) (keV)	XREF	Jπ(level)	$T_{1/2}$(level)	E(γ) (keV)	I(γ)	M(γ)	Final level	
0.0	A	5+	13.01 d 5 % β⁻ = 100					
104.8 3	A	4+		104.8	100	(E2)	0.0	5+
517.9 1	A D	8-	17.5 s 2 % IT > 0 % β⁻ = ?	413.1 3 517.9 1	0.072 100	M4 E3	104.8 0.0	4+ 5+
583.9 5	D	9-		66.0 5	100	M1	517.9	8-
590 5	B	1+						
850 5	B	1+						
1000 5	B	(2-)						
1910 5	B	1+						
1982.3 6	D	(11-)		1398.4 3	100		583.9	9-
2010 5	B	1+						
2243.9 6	D	(12-)		261.6 2	100		1982.3	(11-)
2290 5	B	1+						
2360 5	B	1+						
2450 5	B	1+						
2500 5	B	1+						
2550 5	B	1+						
2600 5	B	1+						
2710 5	B	1+						
2810 5	B	1+						
2910 5	B	1+						
2927.6 7	D	(12-)		945.3 4	100		1982.3	(11-)
2973.7 7	D	(13-)		729.8 3	100		2243.9	(12-)
3257.8 7	D	(13-)		330.2 3 1013.7 5	100 25 100 40		2927.6 2243.9	(12-) (12-)
3380.1 7	D	(14-)		406.4 3	100		2973.7	(13-)
3420 5	B	1+						
3486.8 7	D	(14-)		229.0 4 513.2 4	100 25 100 30		3257.8 2973.7	(13-) (13-)

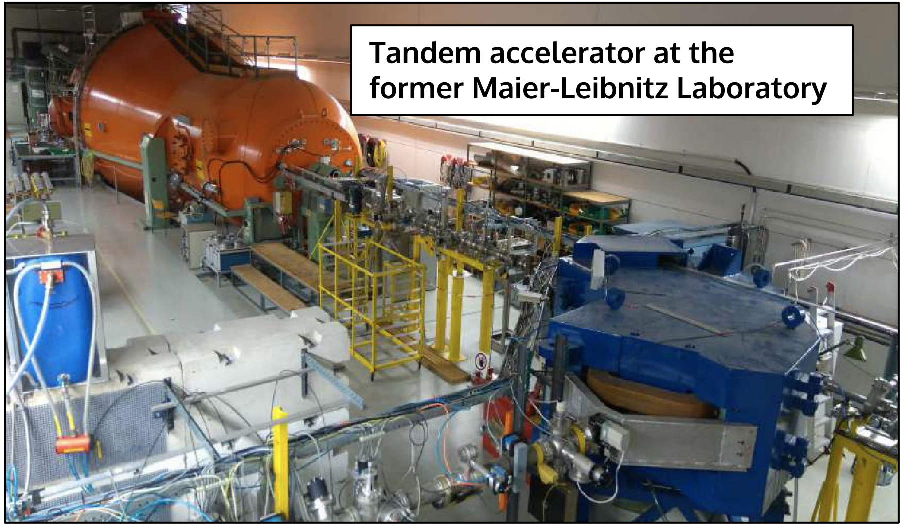
New measurements of ^{136}Cs nuclear structure

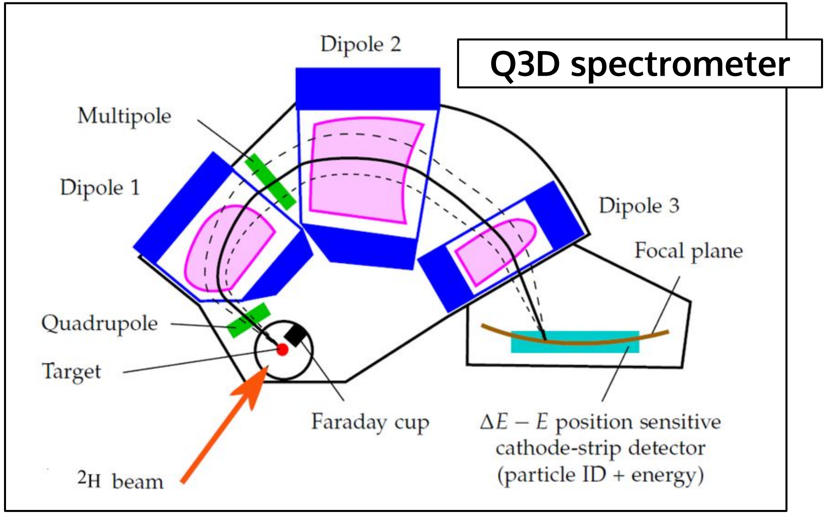
(d,a) reactions on a ^{138}Ba target, led by UWC



B. Rebeiro
(now at GANIL)

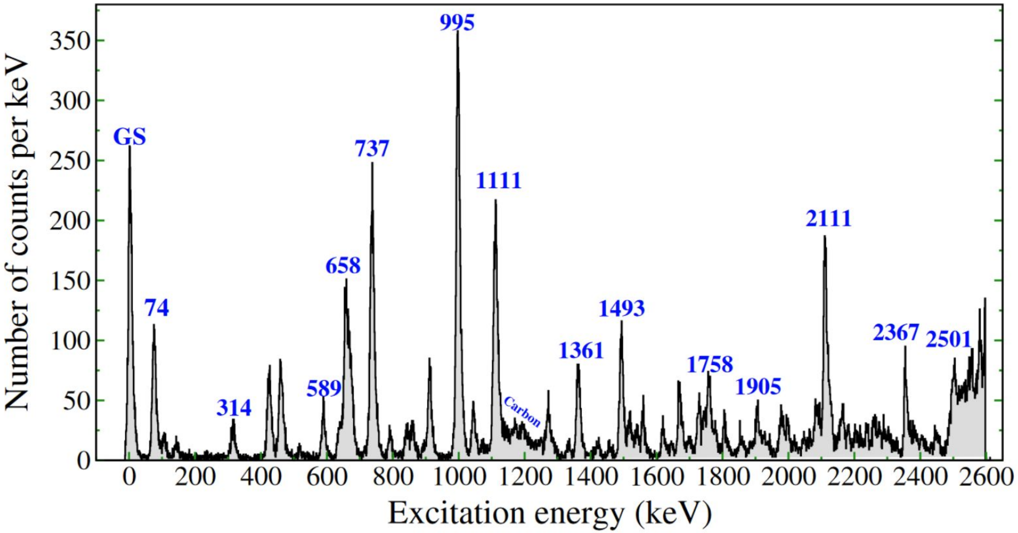
S. Triambak
University of Western Cape

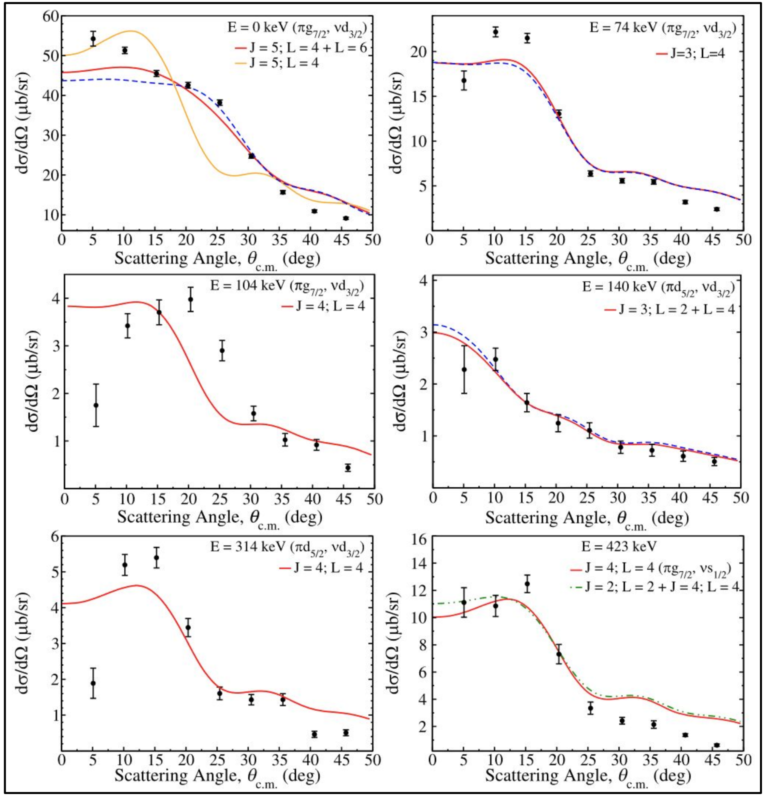




Spectra and J^{π} assignments

B. Rebeiro et al., *Phys. Rev. Lett.* **131** 052501 (2023)





A key result: comparison with nuclear models

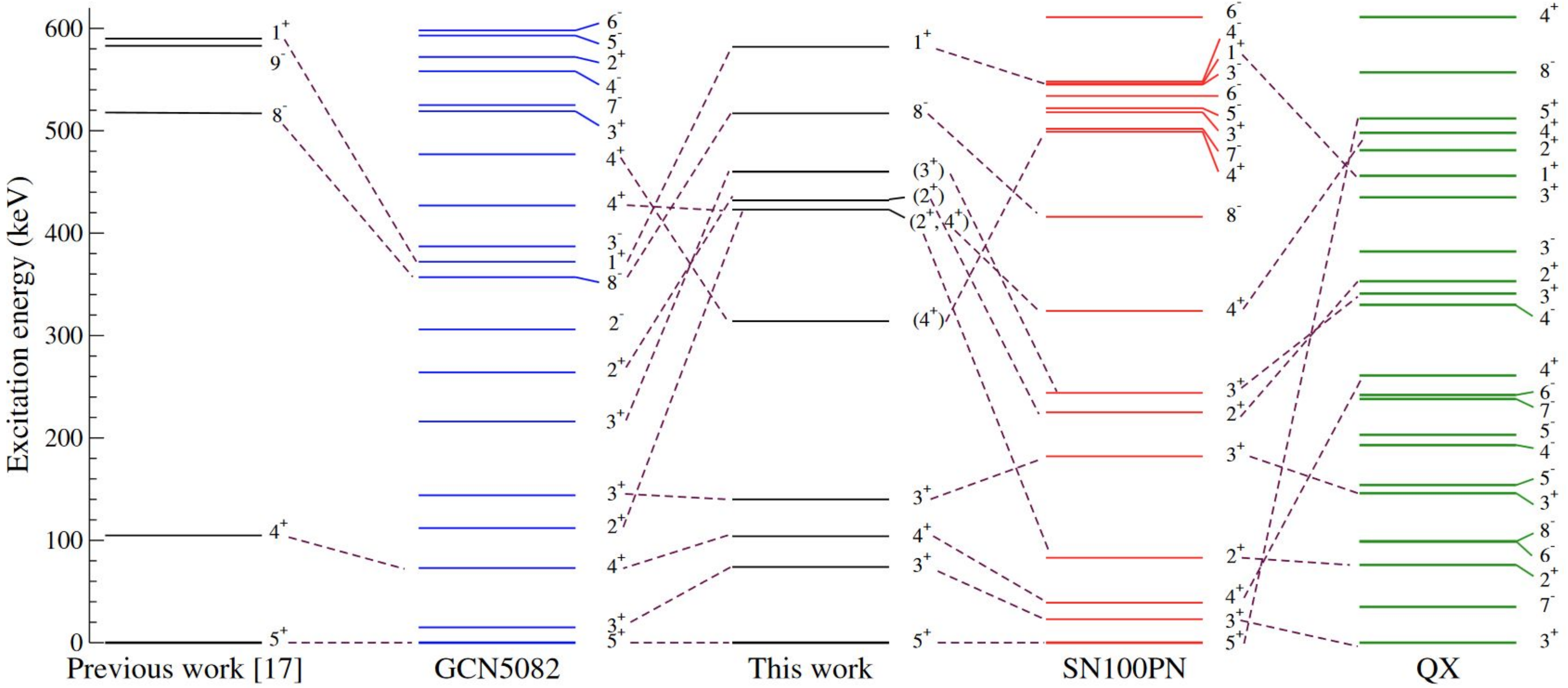
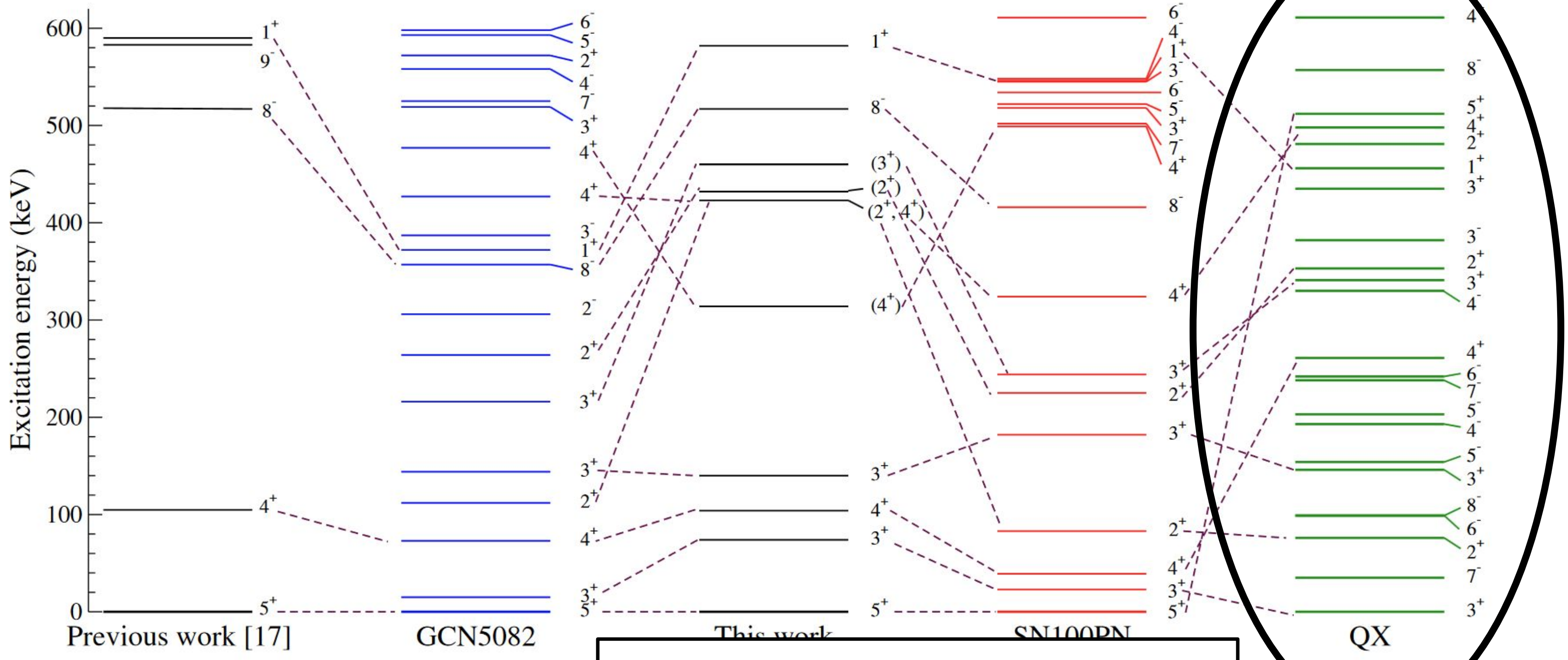


FIG. 2. Comparison between theory and experiment for the low-lying energy spectrum of ^{136}Cs. The shell-model results were obtained with the GCN5082, SN100PN, and QX effective interactions.

B. Rebeiro et al., *Phys. Rev. Lett.* **131** 052501 (2023)

A key result: comparison with nuclear models



QX Hamiltonian gives particularly poor agreement with data

FIG. 2. Comparison between theory and experiment … el results were obtained with the GCN5082, SN100PN, and QX effective int…

B. Rebeiro et al., *Phys. Rev. Lett.* **131** 052501 (2023)

The low-lying level structure

Low-lying level structure now much more clear!

- Many new states discovered, and matched to theory
- Spin/parity assignments proposed based on angular info
- Used to benchmark nuclear Hamiltonians relevant for shell model calculations

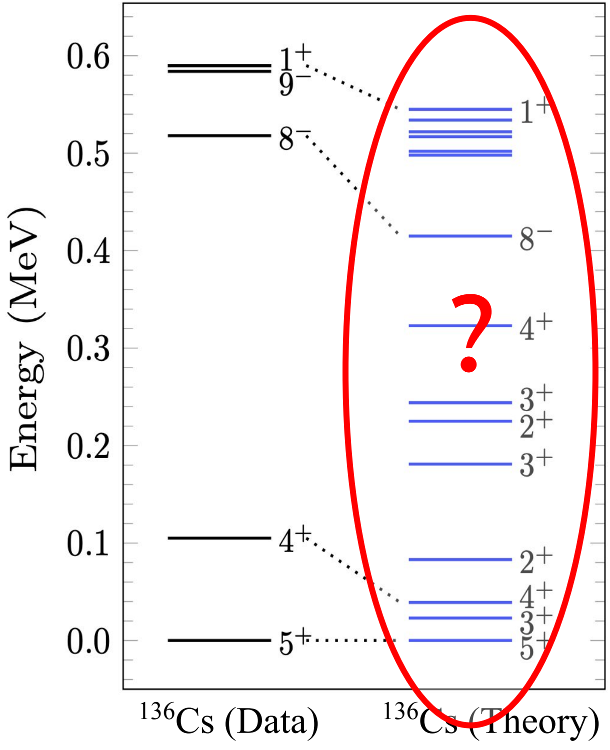
But, what about gamma emission?

Are any of these states long-lived?

TABLE II. Observed ^{136}Cs levels up to the 1_1^+ state.

Refs. [10,17]		This Letter			
E_x (keV)	J^π	E_x (keV)	L	L'	Assigned J^π
0.0	5^+	0.0	4	6	5^+
		74(2)	4	...	3^+
104.8(3)	4^+	104(2)[a]	4	...	4^+
		140(3)	2	4	3^+
		314(2)	4	...	(4^+)
		423(3)[b]	4	...	(4^+)
431(2)	(3^+)	432(3)	2	...	(2^+)
		460(3)	4	...	(3^+)
517.9(1)	8^-	517(3)	7	9	8^-
583.9(5)	9^-	...	...	...	...
591(2)	1^+	589(3)	0	2	1^+

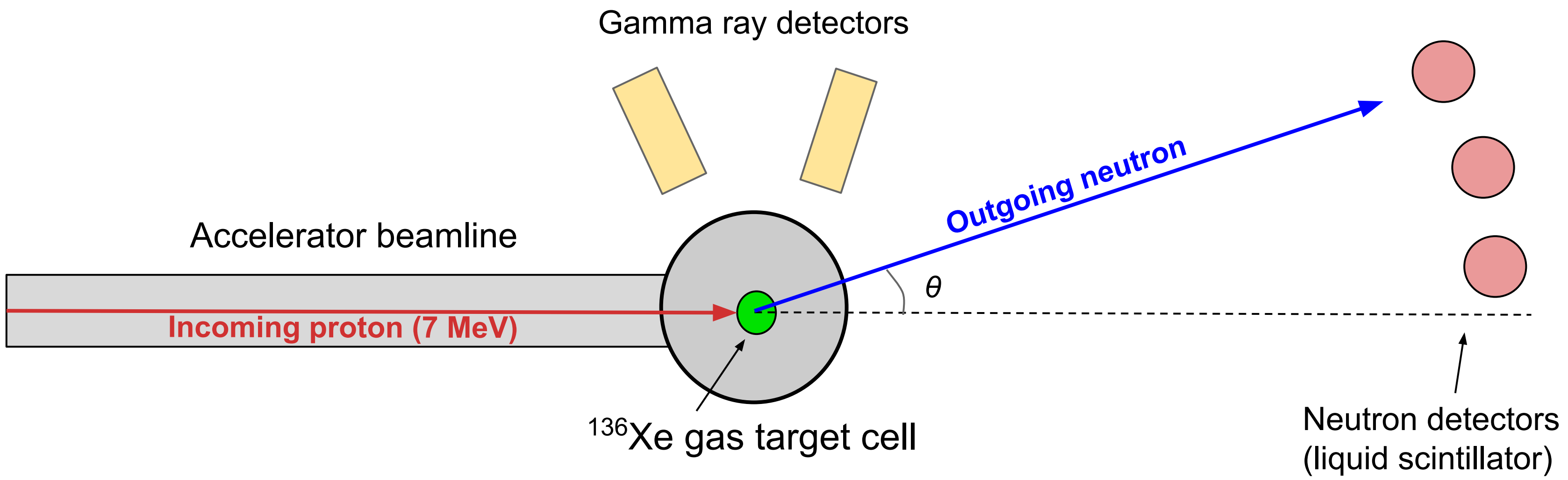
The TUNL measurements: targeting gamma emission



We want an experiment which:

1. Populates the low-lying 1^+ excited states in ^{136}Cs
2. Detects low-energy (<100 keV) gamma rays emitted by the ^{136}Cs nucleus
3. Has timing sensitivity to identify and measure long-lived excited states

$^{136}Xe(p,n)^{136}Cs$ charge-exchange reactions



Charge-exchange can mimic neutrino interactions using a low-energy accelerator

- Kinematics can be used to determine excitation energy
- Selection rules prefer 1^+ states at forward neutron angles

Our Collaboration

BERKELEY LAB

Scott Haselschwardt

LELAND STANFORD JUNIOR UNIVERSITY

Brian Lenardo

UNCW

Tim Daniels

TUNL Triangle Universities Nuclear Laboratory / Duke University

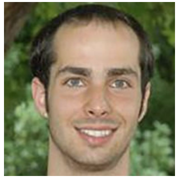
Calvin Howell

Forrest Friesen

Werner Tornow

Collin Malone

Phil Barbeau



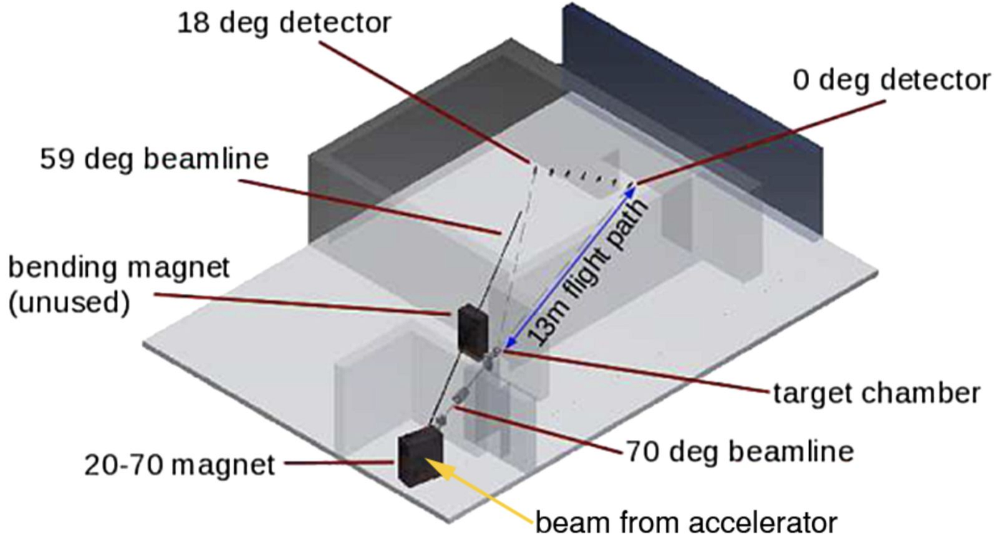
Sean Finch

Ethan Mancil

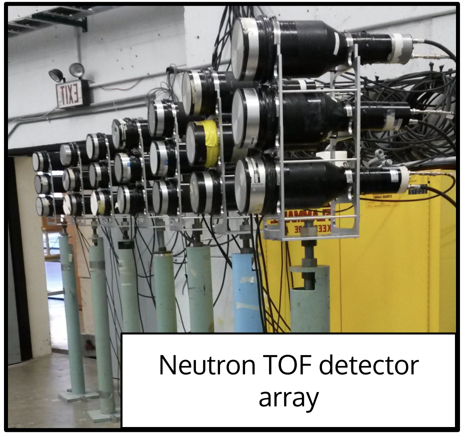
Jay Runge

Pilot experiment at TUNL, August 2021

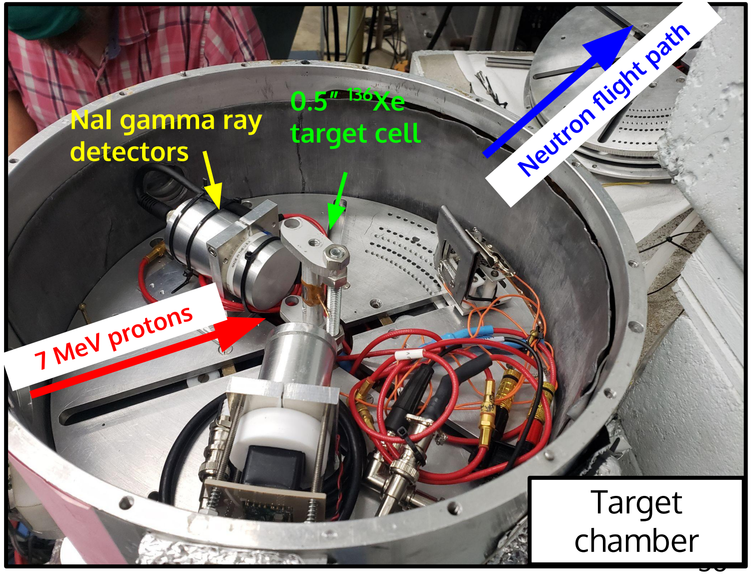
Triangle Universities Nuclear Laboratory, Durham, NC, USA



- 10 MV tandem accelerator produces pulsed proton beam @ 7 MeV
- Existing array of neutron detectors used to measure excitation energy via time-of-flight information

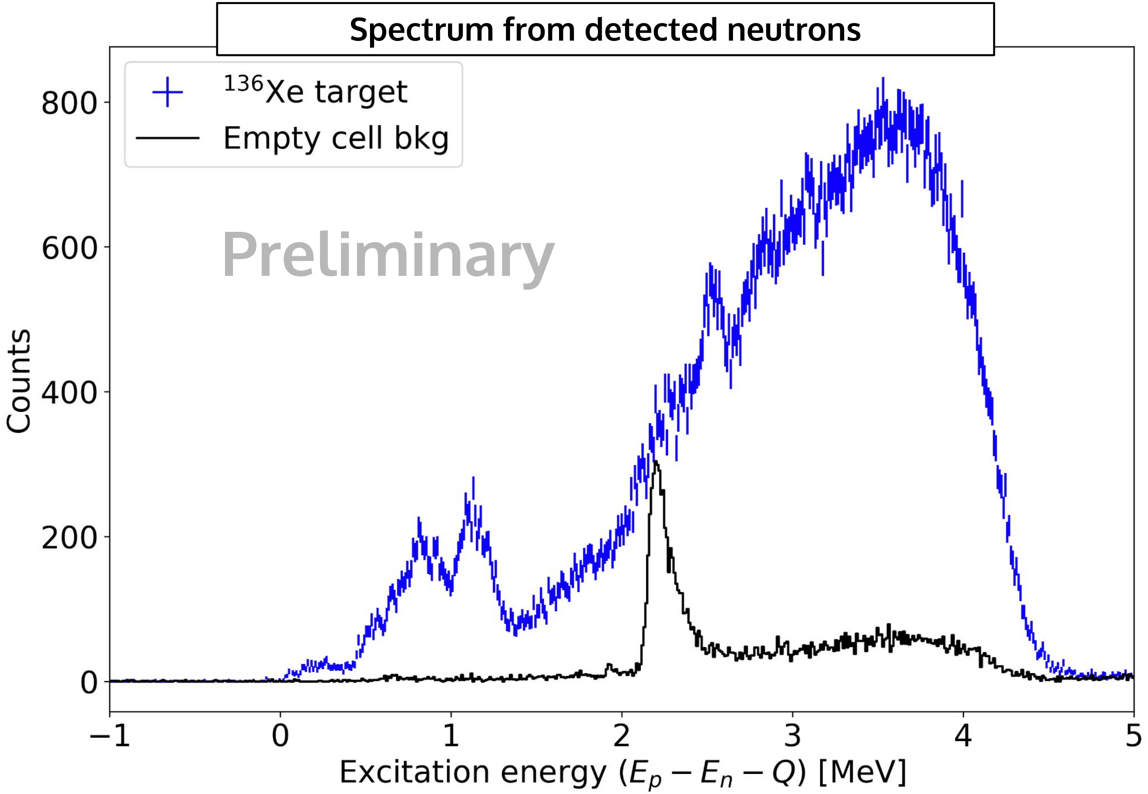


Neutron TOF detector array

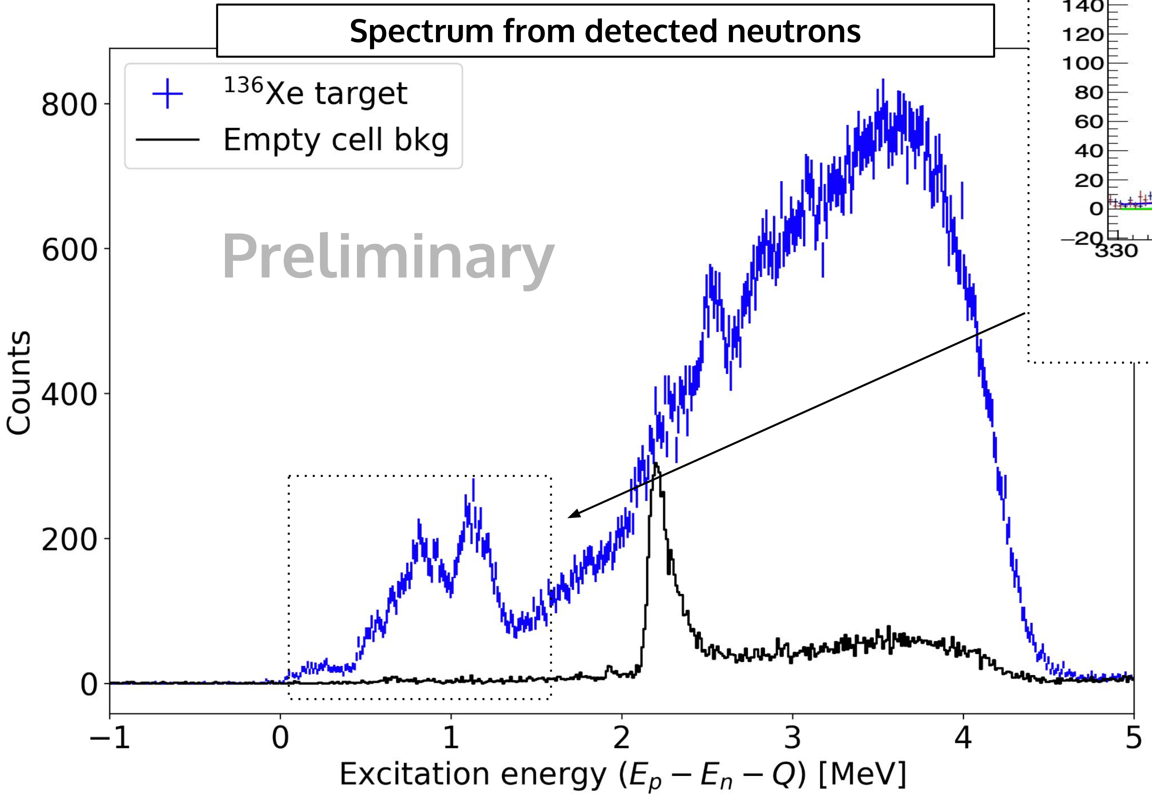


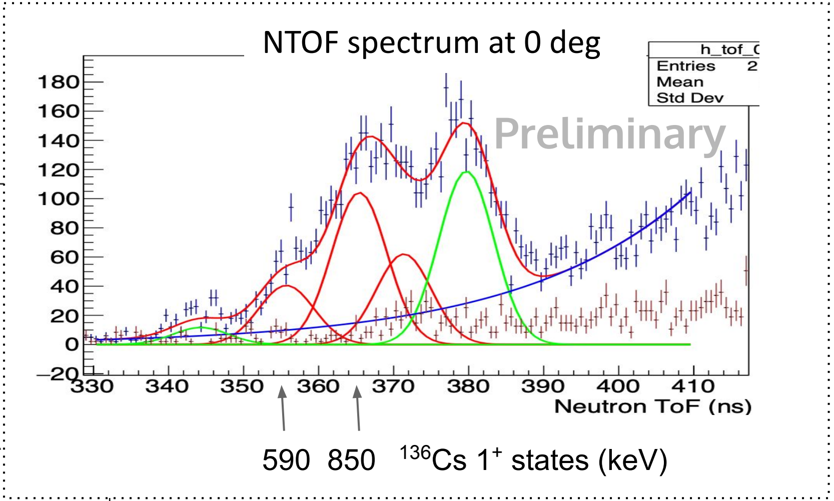
Target chamber

Pilot experiment results



Pilot experiment results

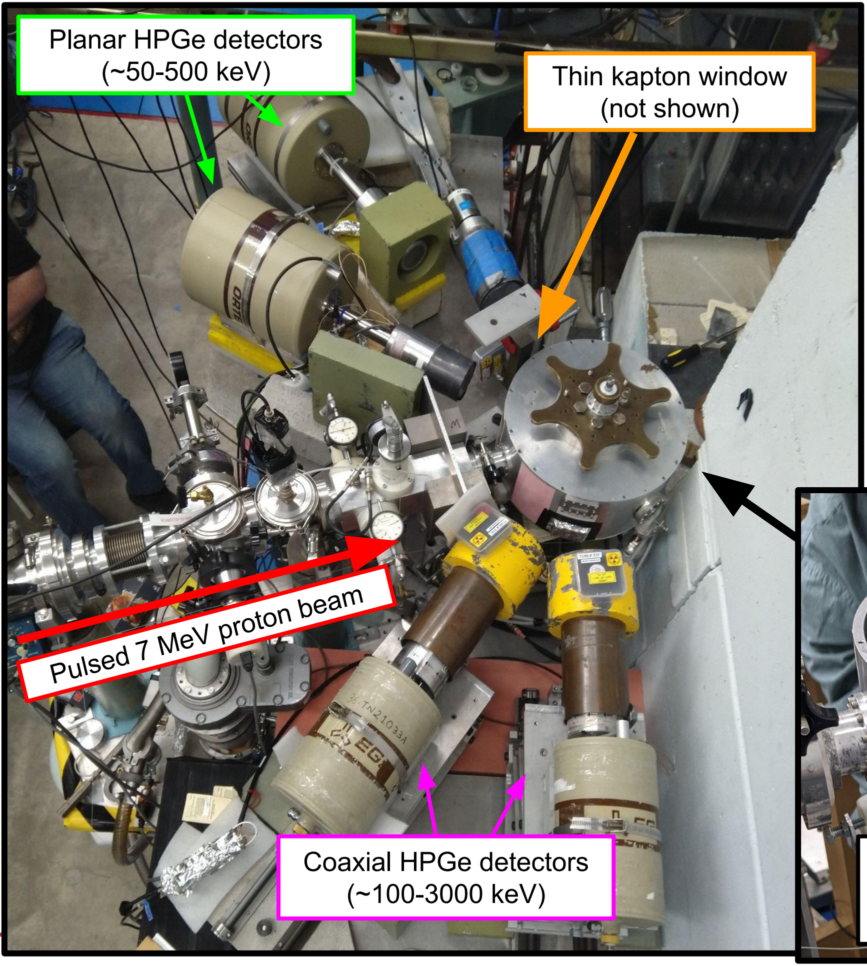


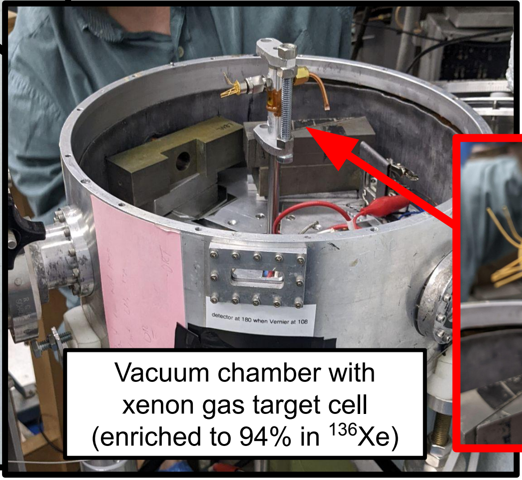


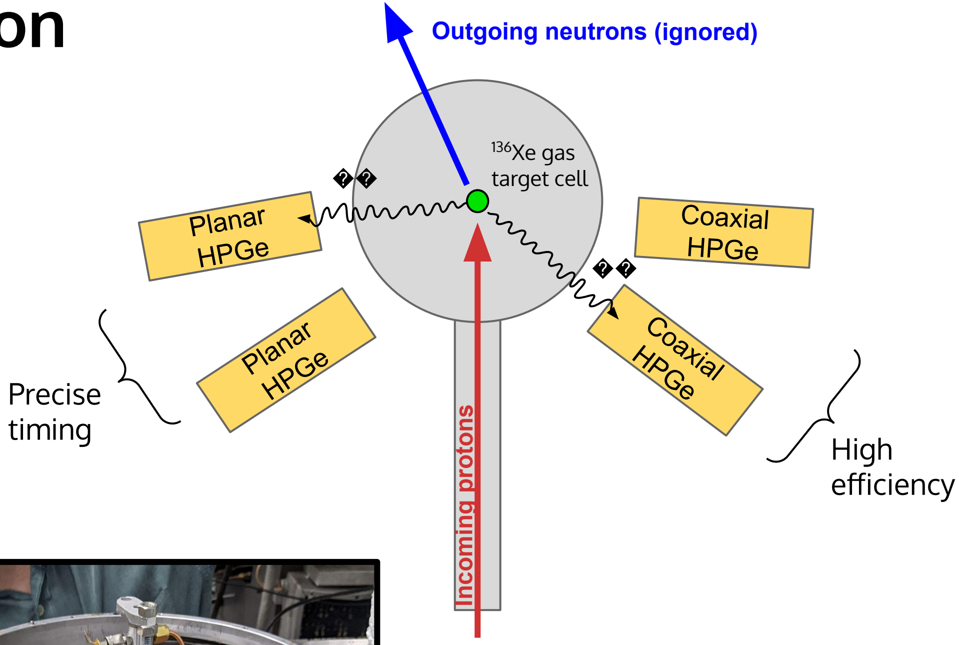
Successfully produced excitation of low-lying states in ^{136}Cs, likely 1^+ states of interest for us

However, gamma detectors were swamped by x-rays at low energies

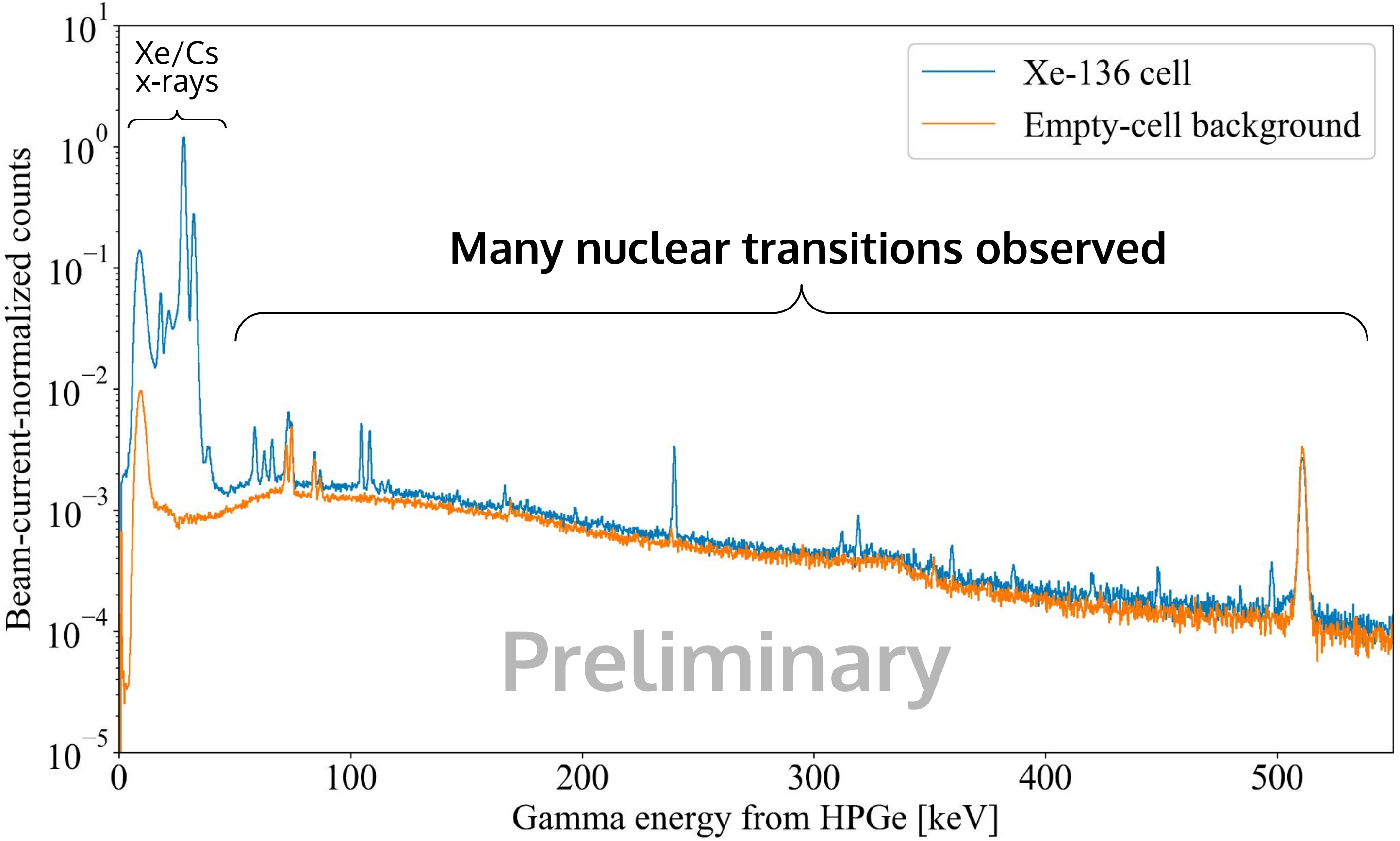
Final experimental configuration



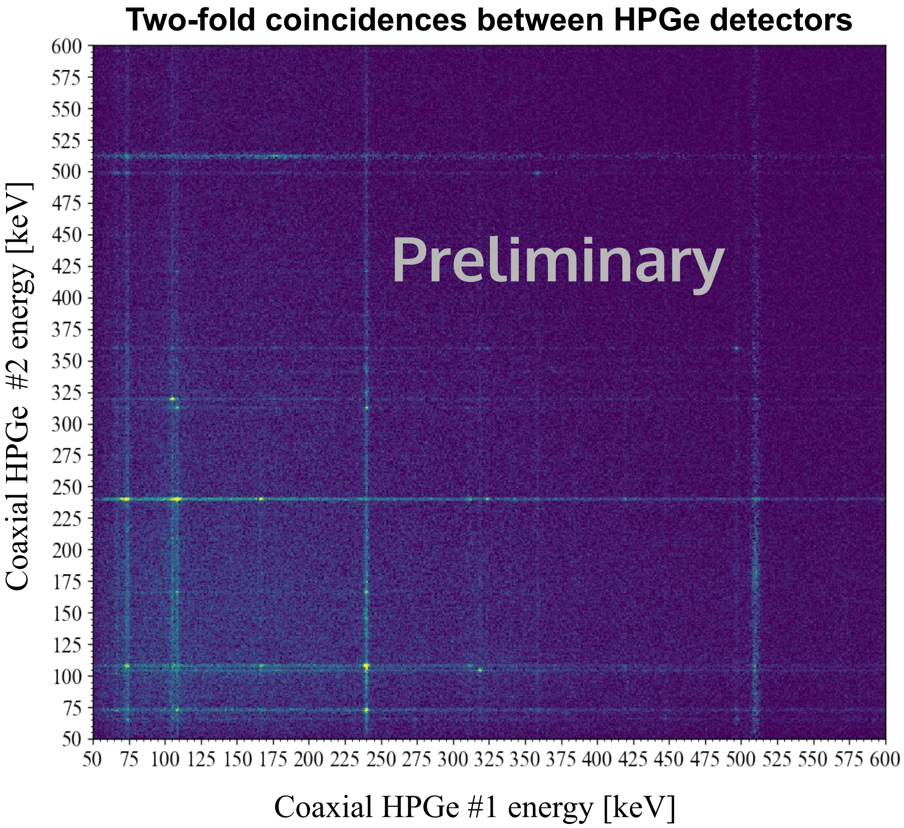


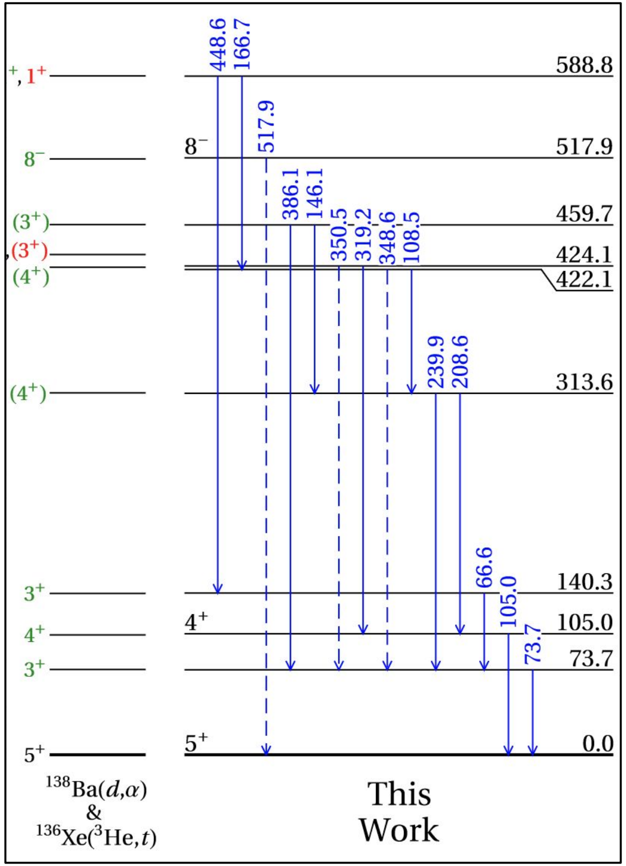


Raw gamma ray spectra



Coincidence analysis to build level scheme



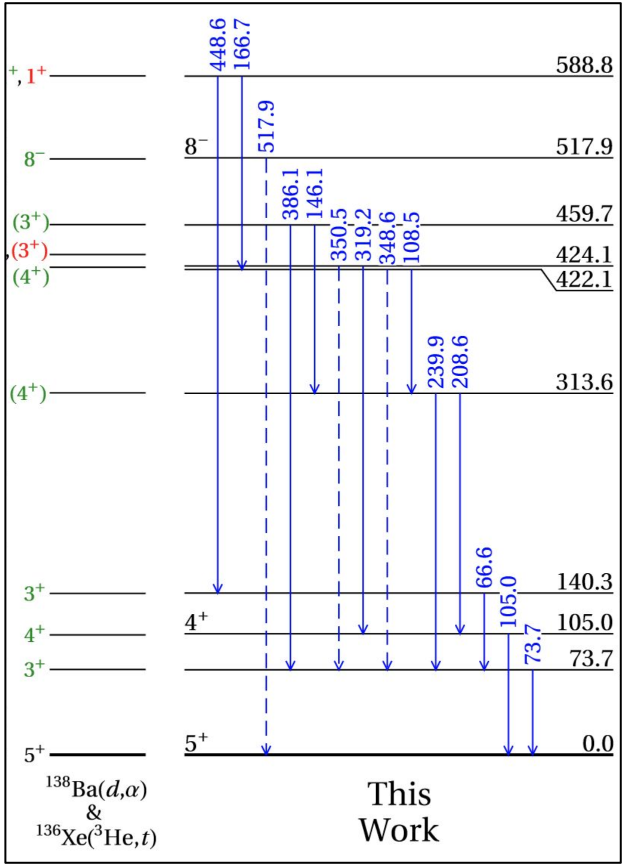


S.J. Haselschwardt et al., *Phys. Rev. Lett.* **131** 052502 (2023)

Coincidence analysis to build level scheme

No direct spin/parity assignments from the gammas, but:

- Confirms energies of excited states and gamma ray emission properties
  - Transition strengths can be compared to spin/parity assignments in other measurements
- Provides ~10x better energy resolution
  - Resolves two states near 420 keV that are unresolved in charged-particle experiments



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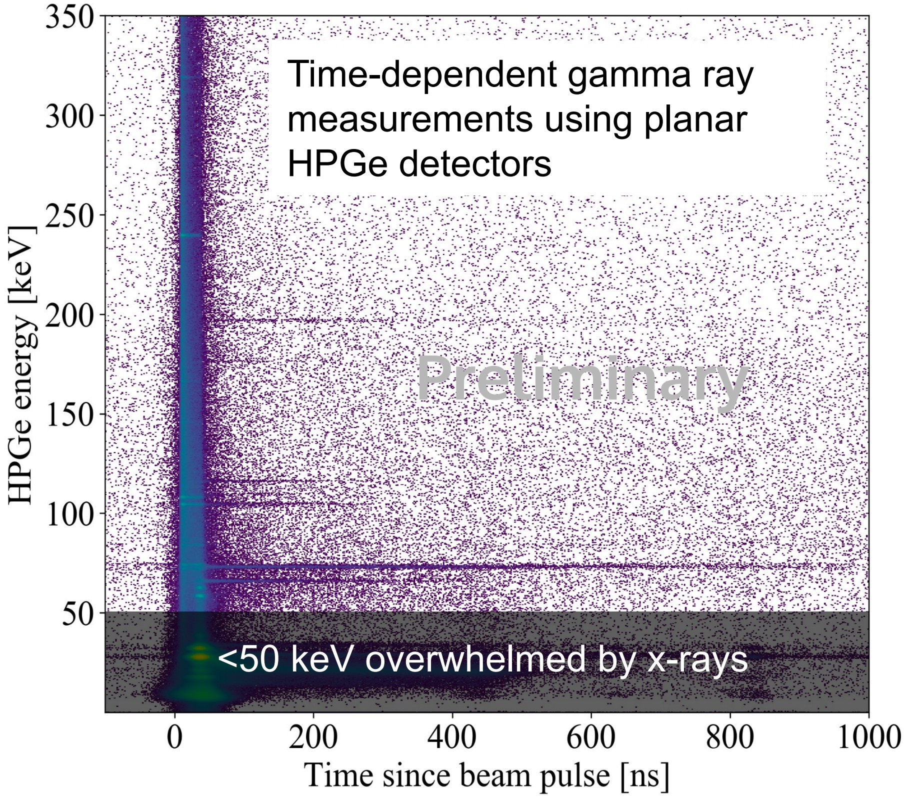
Timing analysis

Gamma ray energy vs. time

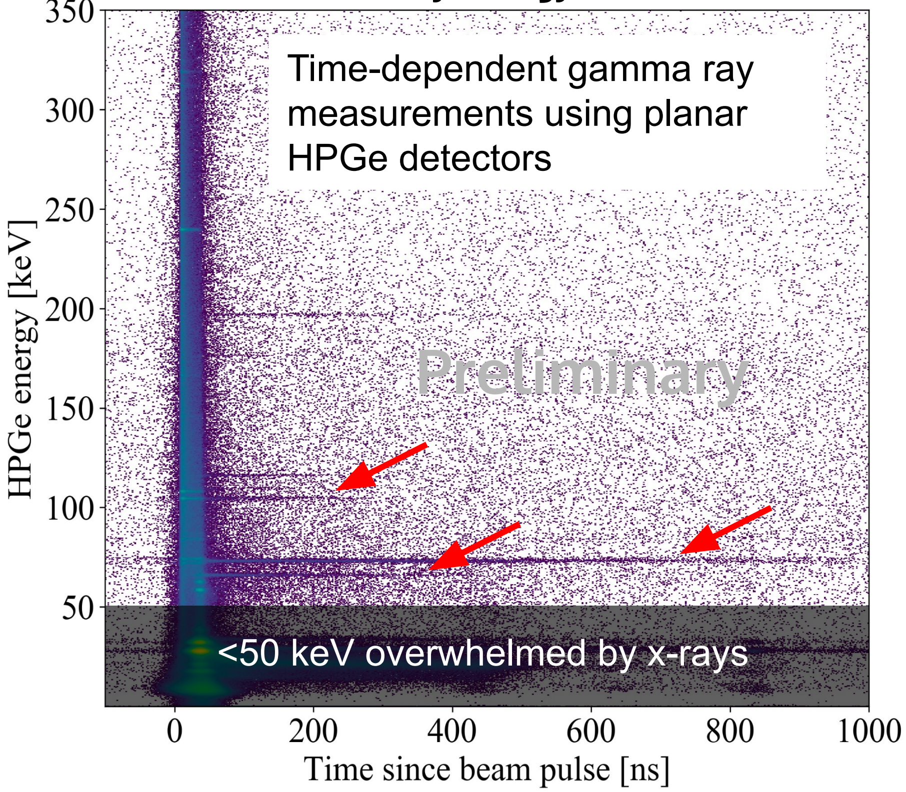


Several transitions observed with extended time distributions

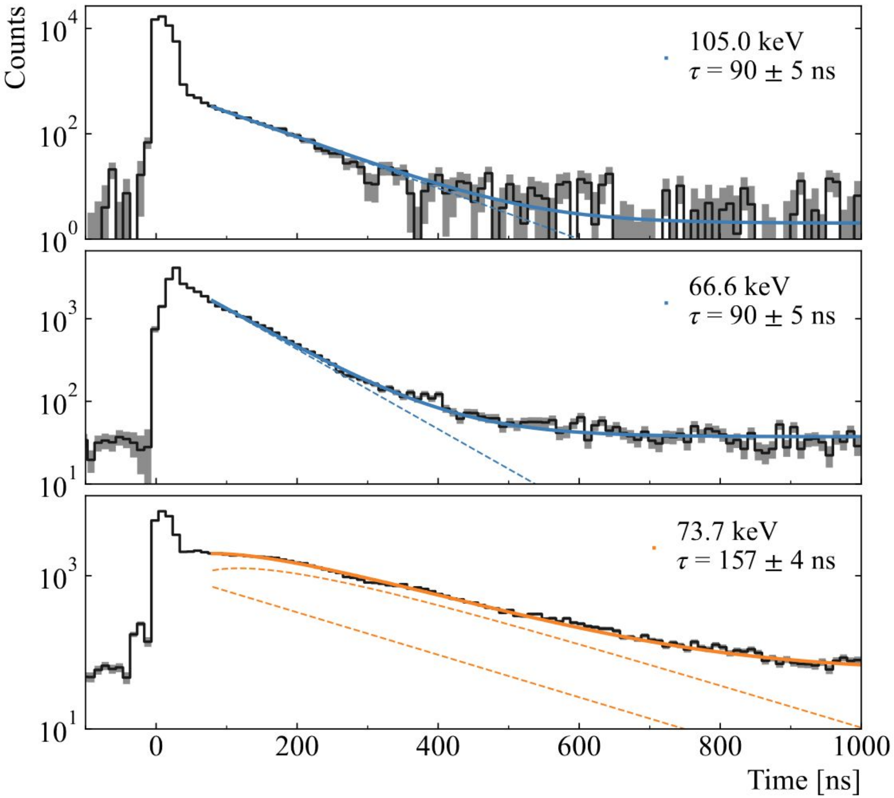
Three of these can be placed in the level scheme reconstructed from coincidences

Timing analysis

Gamma ray energy vs. time



Lifetime fits for the three transitions shown



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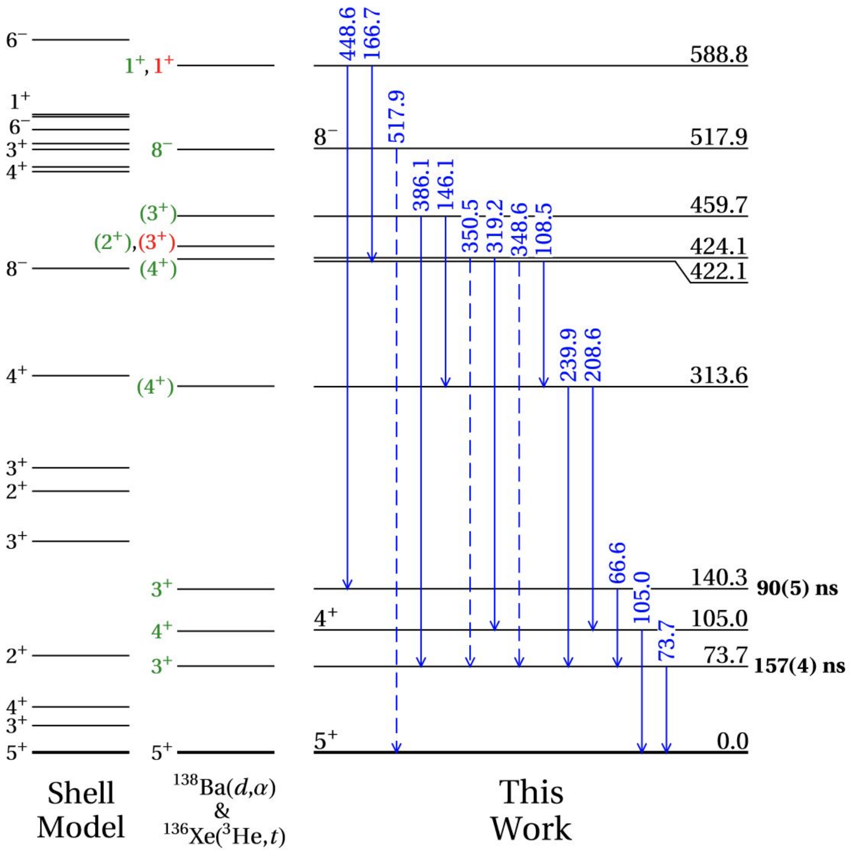
Results



Two isomeric transitions placed in the level scheme

- Lowest-lying state is indeed the longest-lived, with tau = 157ns
- A second state (140 keV) is also isomeric, with tau = 90 ns

Relative intensities indicate that the first 1+ state decays through an isomeric state 99% of the time

- Nearly always a delayed coincidence signal for CC interactions in Xe detectors!

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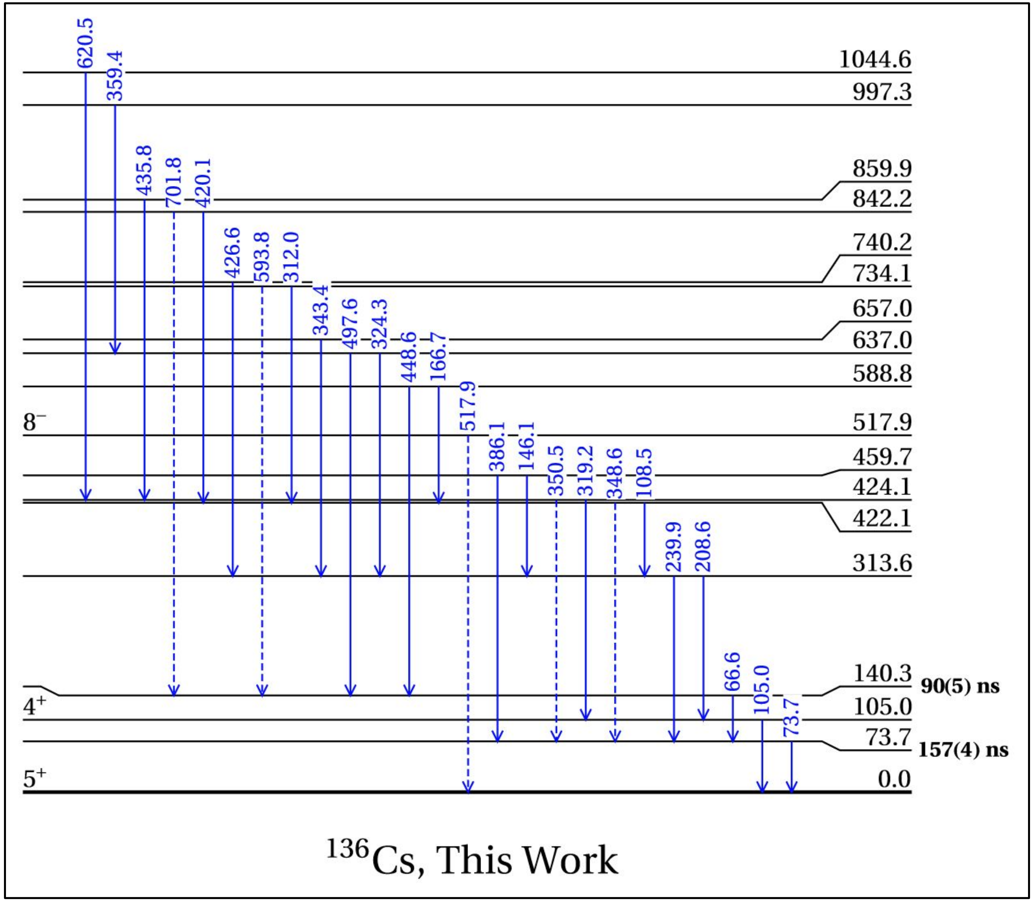
Extended level structure

Data up to ~1.1 MeV available in the Supplemental Material

Data up to ~3 MeV available in principle, but not yet analyzed



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Implications for xenon-based detectors

Solar neutrino interaction rates

Experiment	Mass (t)	Rate (evt/yr) ^{7}Be	CNO
LZ*	0.62	3.7	0.54
KamLAND-Zen*	0.68	4.0	0.59
nEXO	3.2	19.0	2.8
80t ^{nat}Xe TPC	7.1	42.1	6.2

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Operating

In development

Proposed

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} Operating
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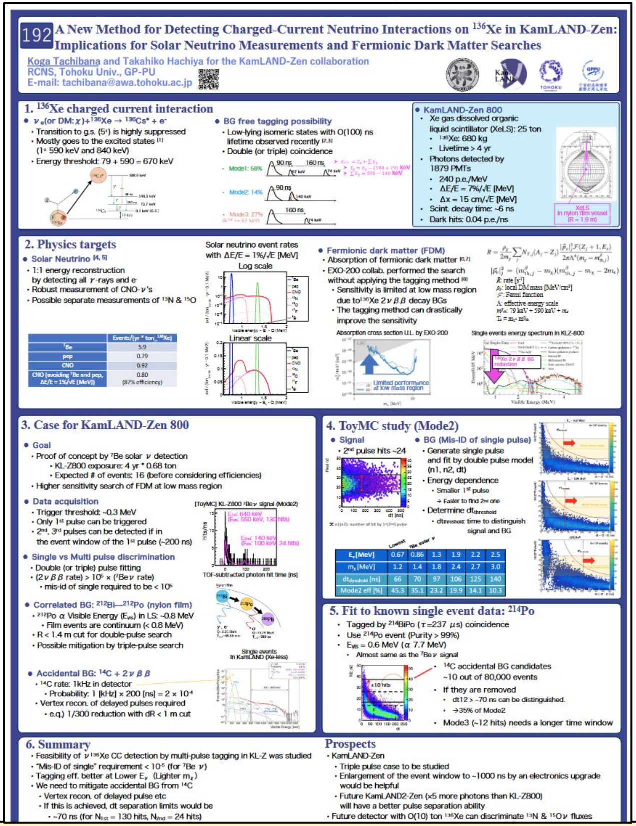
KamLAND-Zen already investigating this!

- Largest exposure in any existing experiment
- Exploring sensitivity and mitigation of ^{14}C background using position reconstruction
- Possible world-leading sensitivity to charged-current dark matter interactions

K. Tachibana @ TAUP



Poster by K. Tachibana and T. Hachiya (KamLAND-Zen), TAUP 2023: https://indico.cern.ch/event/1199289/contributions/5447348/

Some outstanding questions

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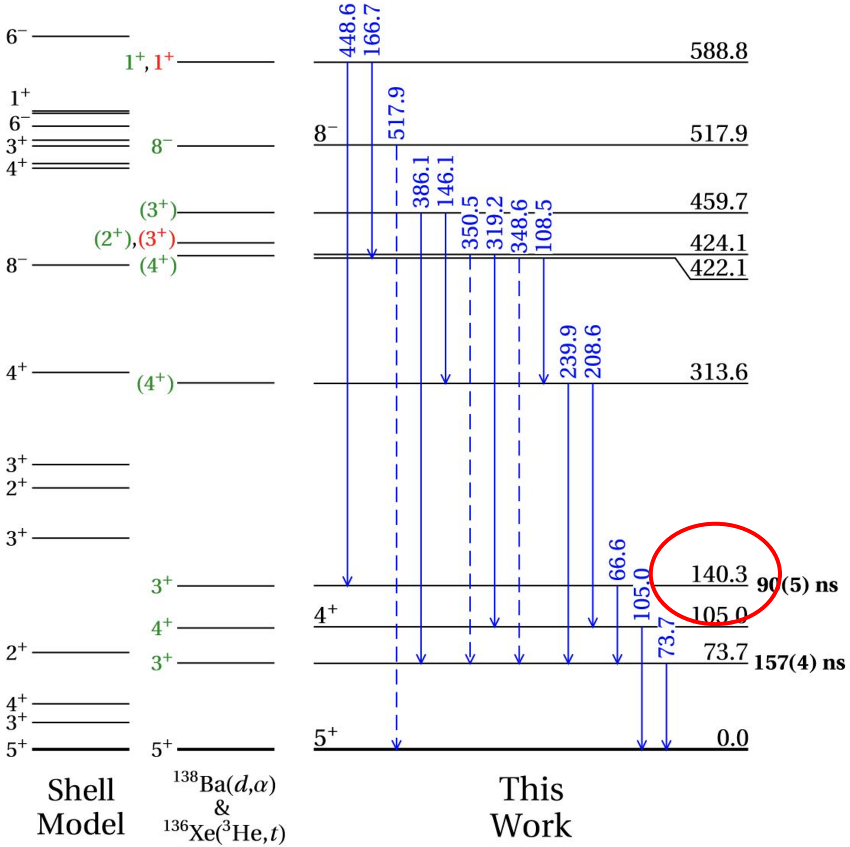
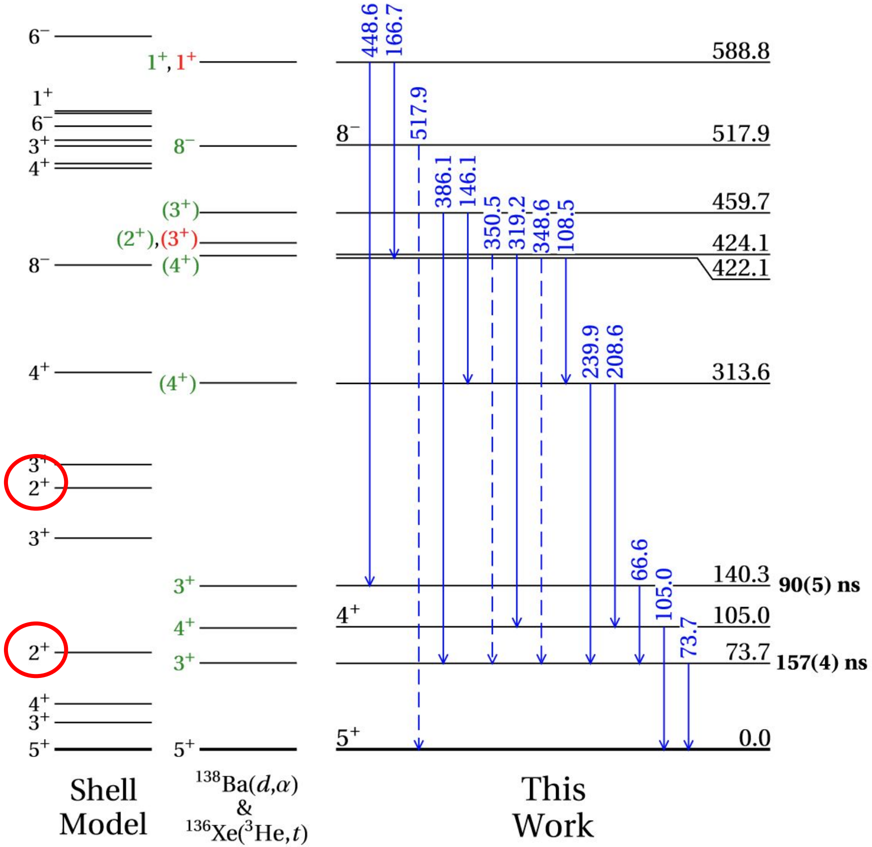


1. **Branching fractions for lowest-lying states**
   a. Internal conversion coefficients still unknown

Some outstanding questions



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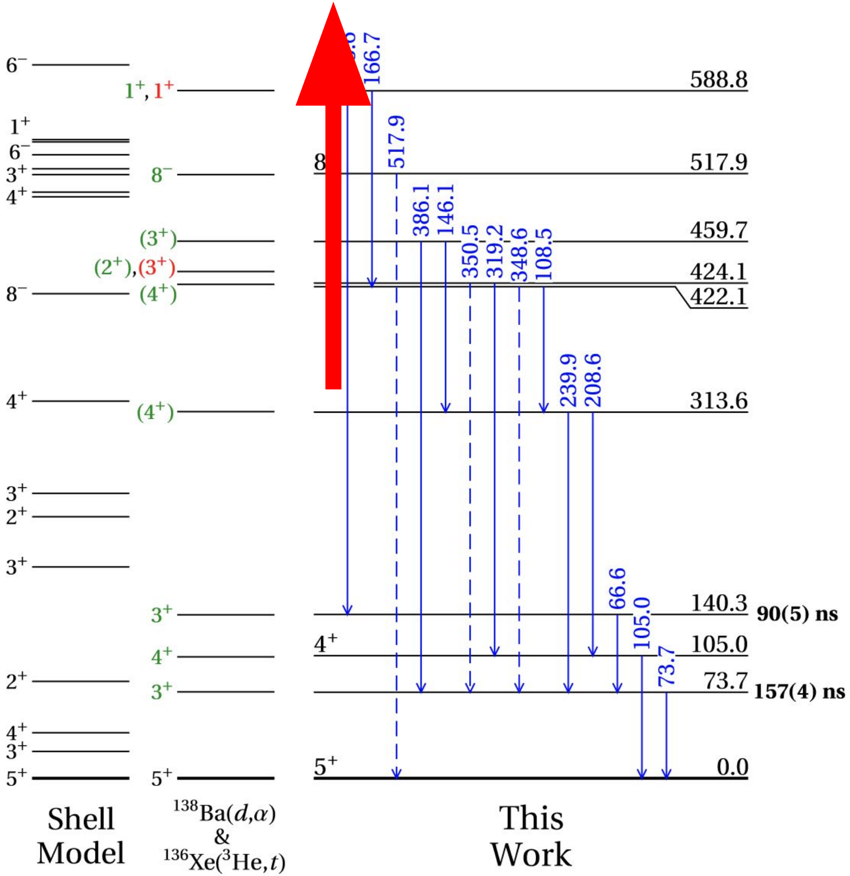

1. **Branching fractions for lowest-lying states**
   a. Internal conversion coefficients still unknown
2. **Where are the 2+ states?**
   a. Some tension between gamma measurements and (d,a) measurements
3. **Higher energies (i.e. few-MeV)?**
   a. Useful for modeling supernova neutrino interactions and interpreting muon capture experiments

To summarize

Summary

- Xenon-based detectors are powerful tools for particle physics, and will be widely used for the foreseeable future
- Charged-current interactions on ^{136}Xe nuclei can be used to perform spectroscopic measurements of solar neutrinos and searches for certain models of dark matter
- Isomeric transitions in the daughter ^{136}Cs will permit delayed-coincidence tagging of these interactions, dramatically reducing backgrounds
- New measurements have identified these isomers and provide crucial data needed for current and future experiments

Thank you!