



快时间探测阵列的测试和展望

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快时间阵列：探测激发态能级寿命信息 / 跃迁强度测量



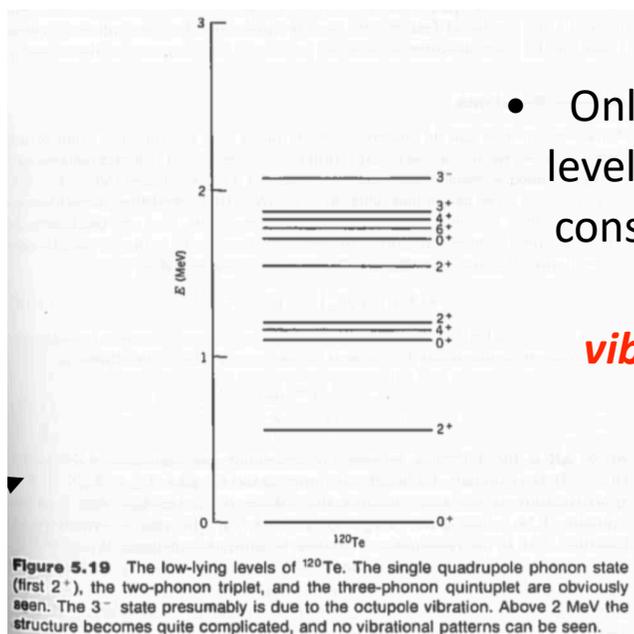
- 利用gamma谱学的方式研究原子核结构信息（激发能高度，寿命，磁矩……），测量关键核数据，贯穿整个核物理实验发展的历史；
- 与能级高度相比，能级寿命，以及推导出的退激射线的约化跃迁概率，可以被视作一个更灵敏的原子核结构探针。

$$T_{if}(\lambda L) = \frac{8\pi(L+1)}{\hbar L((2L+1)!!)^2} \left(\frac{E_\gamma}{\hbar c}\right)^{2L+1} B(\lambda L; J_i \rightarrow J_f)$$

快时间阵列：探测激发态能级寿命信息 / 跃迁强度测量



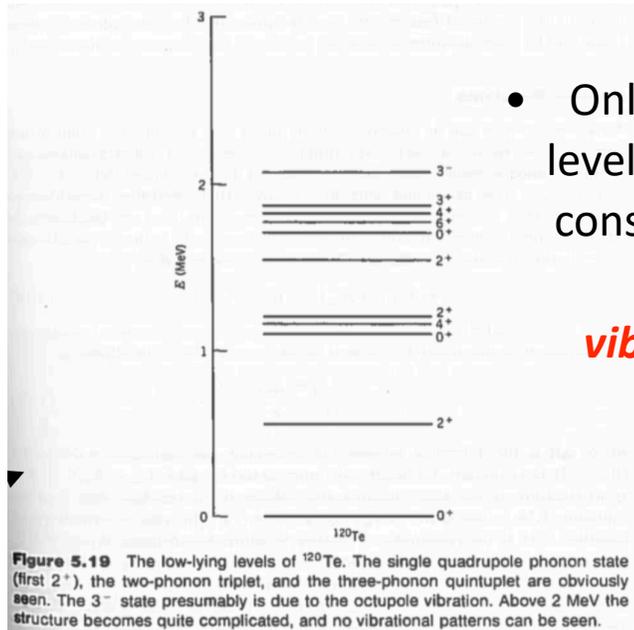
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- 利用gamma谱学的方式研究原子核结构信息（激发能高度，寿命，磁矩……），测量关键核数据，贯穿整个核物理实验发展的历史；
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- Only with the energy level scheme, ^{120}Te was considered **a textbook example of a vibrational nucleus**

TABLE II. Comparison of the measured data for the $^{120,122,124}\text{Te}$ isotopes various available models.

	A	Experiment	Vibrator	Asymmetric rotor
$Q_s(2^+)/Q_0$	120		0	$-0.179 \gamma = 25^\circ$
$Q_s(2^+)/Q_0$	122	-0.182 (12)		$-0.105 \gamma = 27.5^\circ$
$Q_s(2^+)/Q_0$	124	-0.189 (16)		
$\frac{B(E2; 4^+ \rightarrow 2^+)}{B(E2; 2^+ \rightarrow 0^+)}$	120	1.640 (33)	2.0	$1.426 \gamma = 25^\circ$
$\frac{B(E2; 4^+ \rightarrow 2^+)}{B(E2; 2^+ \rightarrow 0^+)}$	122	1.500 (40)		$1.394 \gamma = 27.5^\circ$
$\frac{B(E2; 4^+ \rightarrow 2^+)}{B(E2; 2^+ \rightarrow 0^+)}$	124	1.162 (53)		
$\frac{B(E2; 6^+ \rightarrow 4^+)}{B(E2; 2^+ \rightarrow 0^+)}$	120	2.37 (58)	3.0	$1.781 \gamma = 25^\circ$
$\frac{B(E2; 6^+ \rightarrow 4^+)}{B(E2; 2^+ \rightarrow 0^+)}$	122			$1.748 \gamma = 27.5^\circ$
$\frac{B(E2; 6^+ \rightarrow 4^+)}{B(E2; 2^+ \rightarrow 0^+)}$	124			
$\frac{B(E2; 2^+ \rightarrow 2^+)}{B(E2; 2^+ \rightarrow 0^+)}$	120	1.215 (50)	2.0	$0.906 \gamma = 25^\circ$
$\frac{B(E2; 2^+ \rightarrow 2^+)}{B(E2; 2^+ \rightarrow 0^+)}$	122	0.954 (74)		$1.255 \gamma = 27.5^\circ$
$\frac{B(E2; 2^+ \rightarrow 2^+)}{B(E2; 2^+ \rightarrow 0^+)}$	124	1.115 (175)		
$\frac{B(E2; 2^+ \rightarrow 2^+)}{B(E2; 2^+ \rightarrow 0^+)}$	120	82.9 (47)	∞	$20.42 \gamma = 25^\circ$
$\frac{B(E2; 2^+ \rightarrow 2^+)}{B(E2; 2^+ \rightarrow 0^+)}$	122	102 (11)		$82.60 \gamma = 27.5^\circ$
$\frac{B(E2; 2^+ \rightarrow 2^+)}{B(E2; 2^+ \rightarrow 0^+)}$	124	154 (35)		

- The **transition strength fit a asymmetric rotor** far better than a vibrator;
- Instead of a pure vibration motion, an important **configuration mixing from asymmetric rotor** has to be considered
- **The lesson: level energies are never enough**

快时间阵列：探测激发态能级寿命的不同方法



Lower limit

Upper limit

直接测量：需要高时间分辨的gamma探测器

Electronic timing

10 ps

∞^*

间接测量：HPGe/Clover+多普勒效应

RDDS

1 ps

100 ps

DSAM

10 fs

10 ps

Lineshape

1 fs

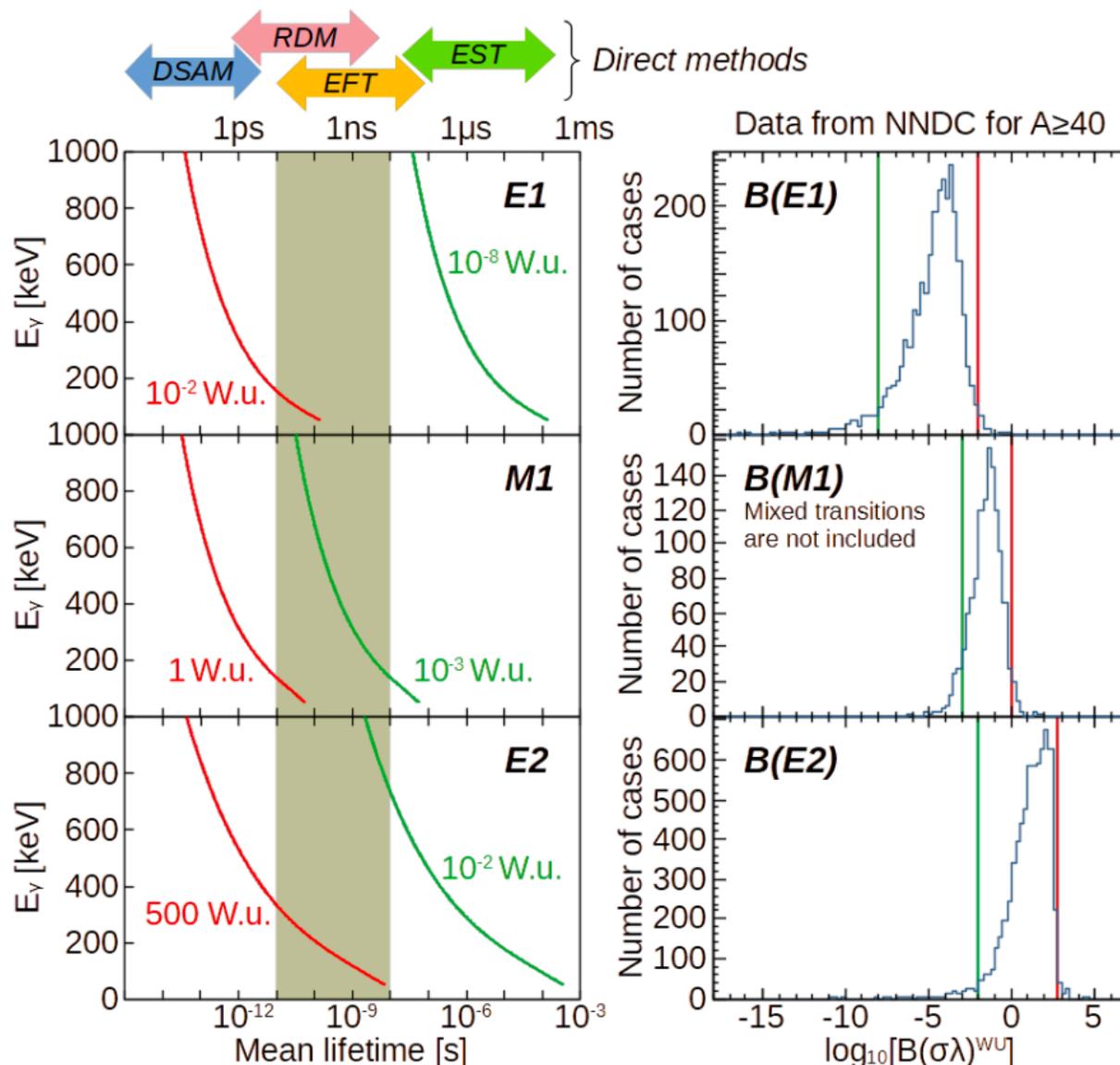
100 fs

间接测量：测量库伦激发截面

CouEx

0^*

∞^*



快时间阵列：溴化镧探测器阵列



- FATIMA from Surrey Univ, start from 2014,
- 36 1.5*2 inch² LaBr₃, used at Argonne, GANIL, RIBF-RIKEN, GSI.....



文本

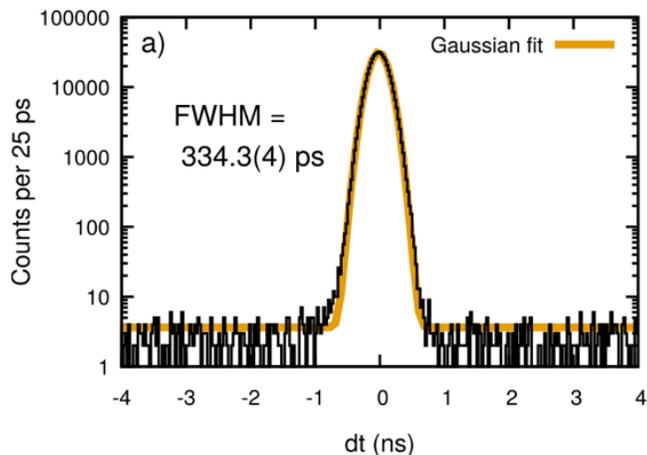
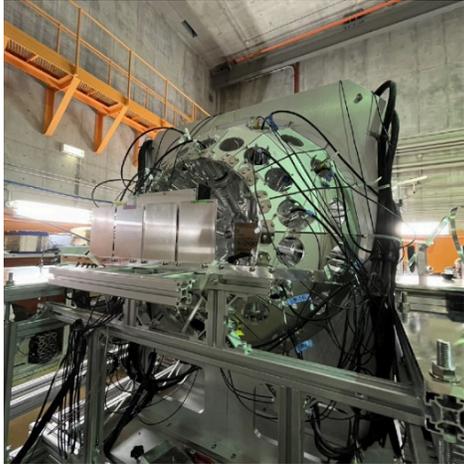


Fig. 14. (Colour online) Different setups in which the FATIMA detectors described in this paper have been mounted and used in experiments or tests. (a) At Argonne National Laboratory with half of the Gammasphere array. 25 detectors mounted in a hemisphere. (b) At the University of Surrey, some detectors are mounted on the DESPEC FATIMA frame in its core configuration with space for 36 detectors on three rings. (c) At GANIL at the LISE station together with HPGe Clover detectors. (d) At IPN Orsay during the ν -Ball campaign 2017/2018. (e) At IPN Orsay for the Stella experiment. 36 detectors in a semi-cylindrical configuration. A manual lift system with counter-weights is used to allow access to the target chamber. (f) At RIKEN during the EURICA campaign. The detectors have been placed in free spaces in the array in clusters of six. (g) and (h) At GSI in the S4 cave in the configuration designed for use in the DESPEC station for FAIR (AIDA snout and rack to the left, beam from left to right).

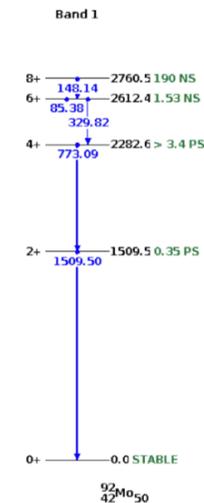
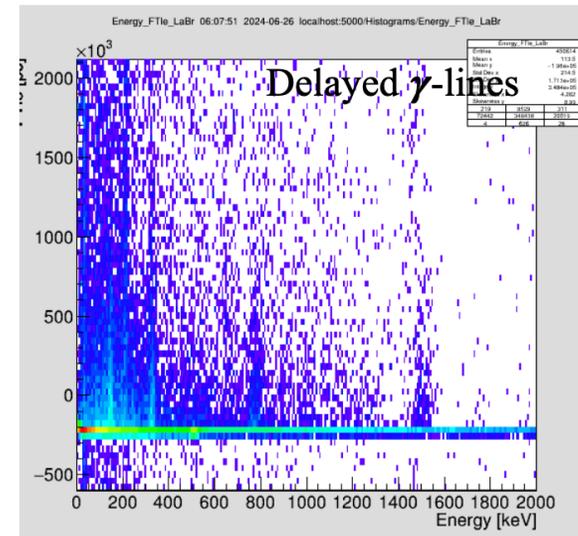
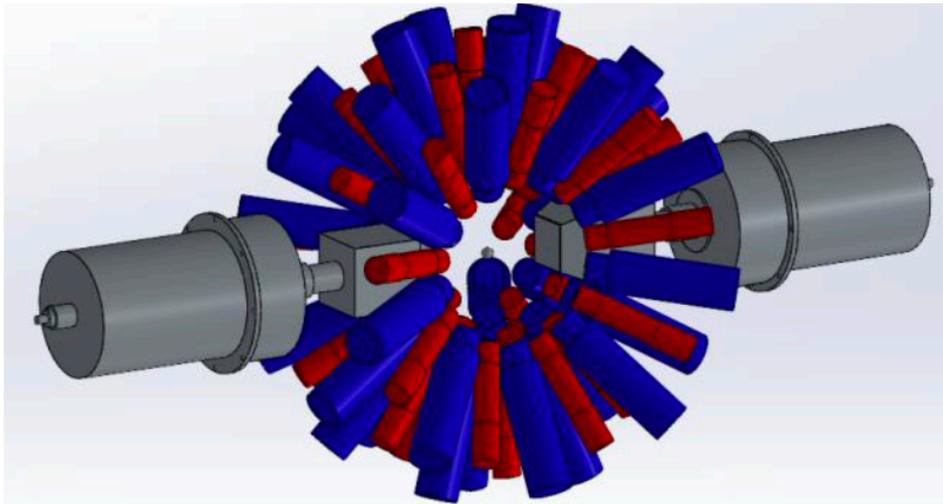
快时间阵列：溴化镧探测器阵列



- IDATEN @ RIBF, start from June 2024



	FATIMA	KHALA
Number of detectors	36	36
LaBr ₃ (Ce) crystal size	Φ1.5" × 2"-length	Φ1.5" × 1.5"-length
PMT	R9779	R13408
Energy resolution	3.4 % @779 keV	3.3 % @662 keV
Time resolution in FWHM (γ-γ coincidence)	334.3(4) ps @1332-1173 keV (32 detectors w/ ⁶⁰ Co)	335(1) ps @511-511 keV (12 detectors w/ ²² Na)
Passive Pb shield	Optional	No
Owners	U. of Surrey, U. of Brighton	Korea U.



快时间阵列：溴化镧探测器阵列

• 中山大学中法核核数据学科与应用团队：

✓ 18台溴化镧（圣戈班制造）：探头尺寸 $\Phi 2$ 英寸(50.8 mm), 长3英寸(76.2 mm),

✓ 数字化获取,

✓ 已开展一系列实验工作。

• ^{252}Cf 裂变碎片激发态寿命测量

● ~4500小时

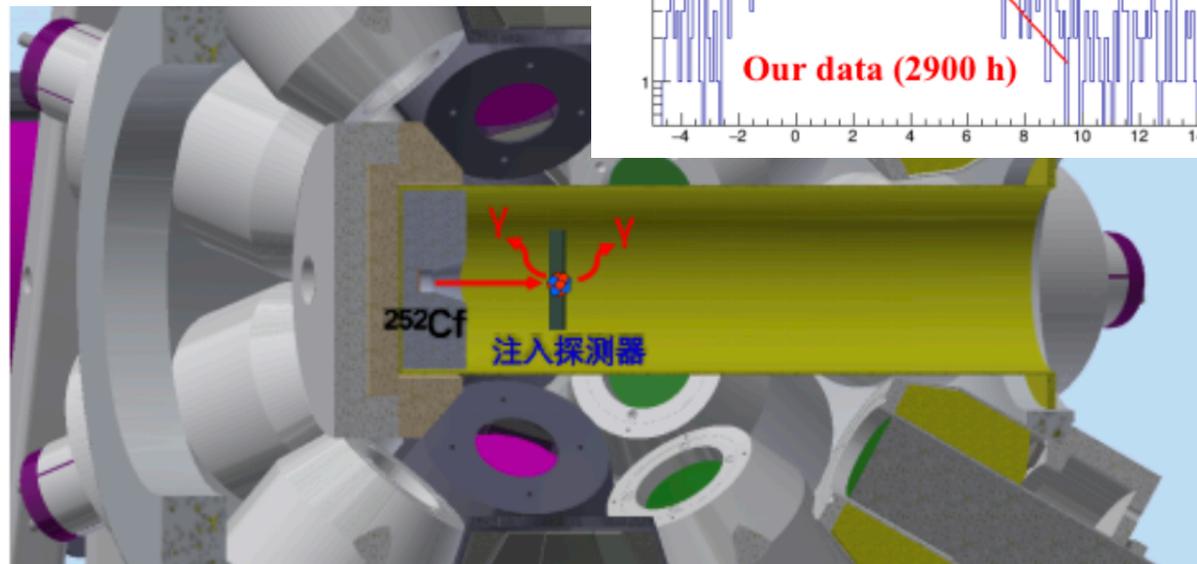
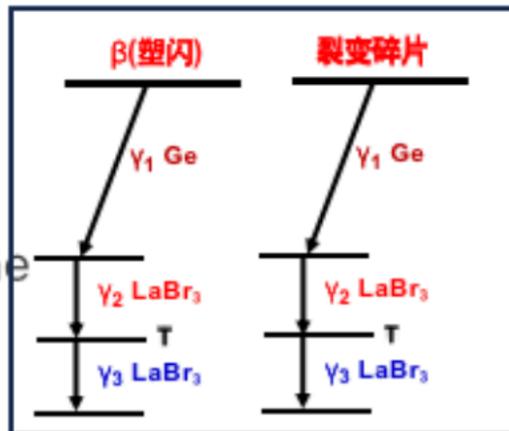
● 1.3×10^{11} 裂变碎片

● 5.0×10^9 γ - γ T(± 200 ns)

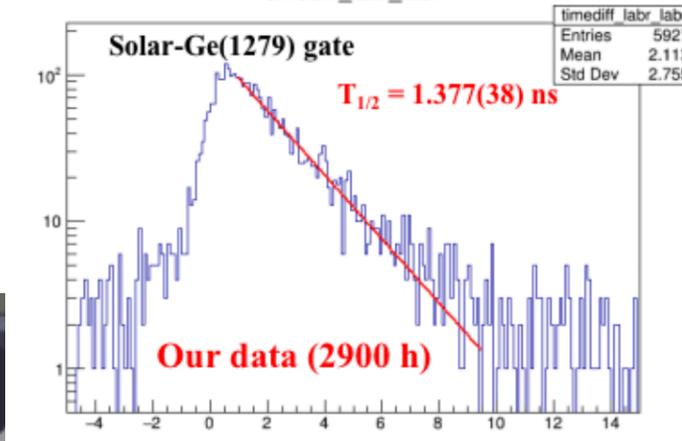
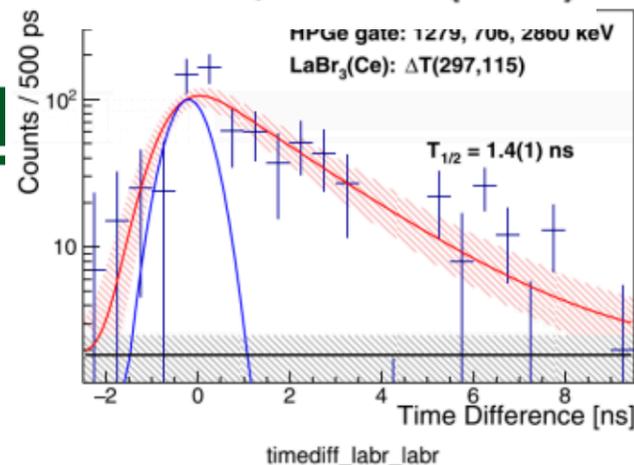
● 2×10^8 γ - γ T(5us) Solar-Ge-Ge

● 8×10^8 γ - γ T(5us) EJ-Ge-Ge

● LaBr3-LaBr3未统计



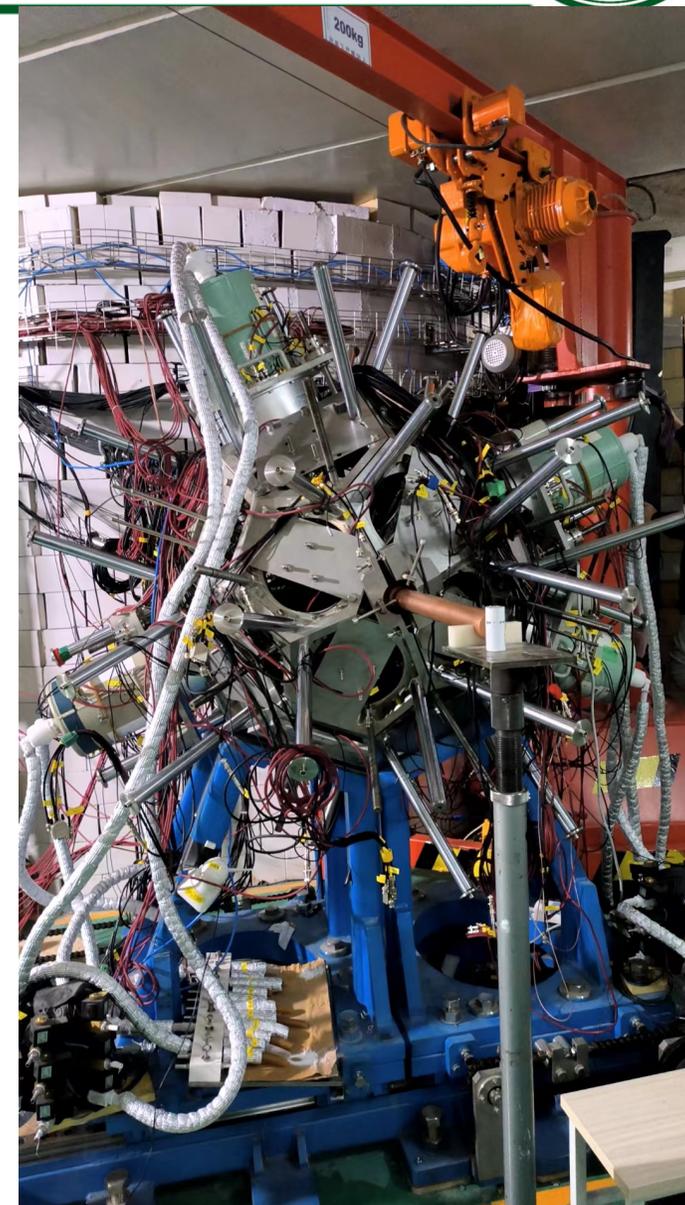
PRC 103, 034317 (2021)



快时间阵列：溴化镧探测器阵列



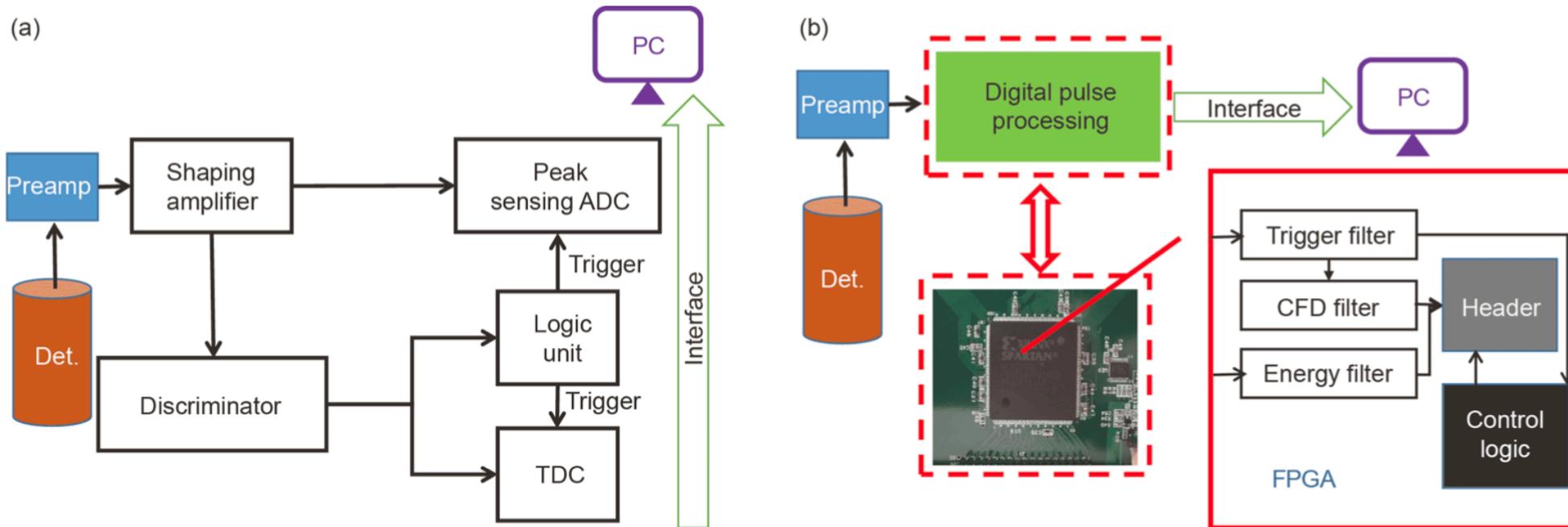
- 中山大学中法核核数据学科与应用团队：
 - ✓ 18台溴化镧（圣戈班制造）：探头尺寸 $\Phi 2$ 英寸
 - ✓ 数字化获取，
 - ✓ 已开展一系列实验工作。
- 质子 $g_{9/2}$ 轨道辛弱数对称性破缺研究： ^{94}Ru 的 $4+$ 态寿命测量
- May 12 - 18 at IMP, $^{36}\text{Ar} + ^{64}\text{Zn}$, beam energy@160 MeV, cross section for ^{94}Ru :160 mb;
- 4 Clover and 26 LaBr_3



快时间阵列关键技术：数字化获取中的定时精度？

快时间探测阵列存的问题：

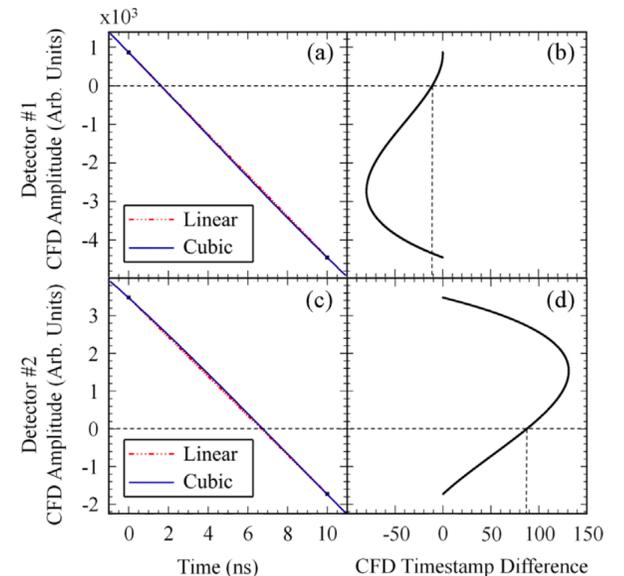
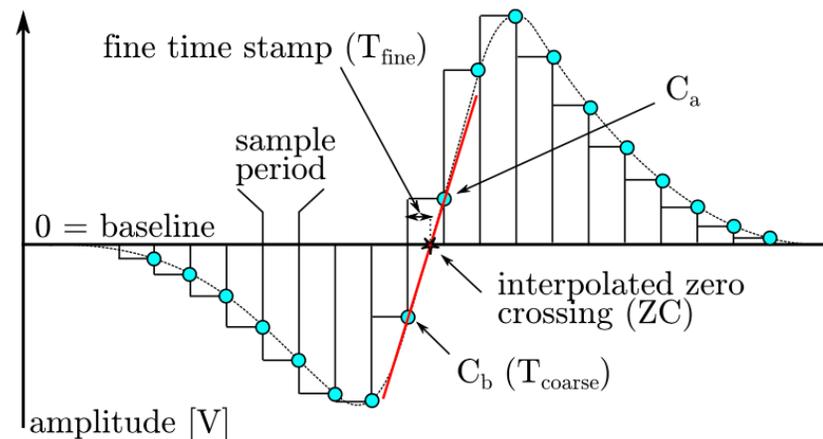
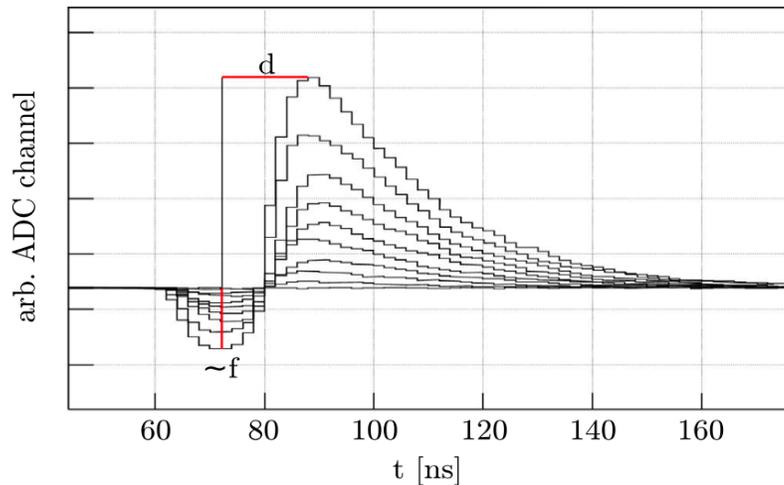
- 传统的**模拟电路**定时方法：CFD（恒比定时）+TAC（时间-幅度转换器）+ADC，时间分辨性能好；
- 但是线路复杂，需要插件多，死时间大，不适合高计数率和大规模阵列；
- **数字化获取**，滤波参数/trigger均可灵活调节，死时间小，在能谱测量上已经被证明性能由于模拟电路方法；**但定时精度仍然受到采样周期的限制！**



快时间阵列关键技术：数字化获取中的定时精度？

快时间探测阵列存的问题：

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- **数字化获取**，滤波参数/trigger均可灵活调节，死时间小，在能谱测量上已经被证明性能由于模拟电路方法；**但是**
 - ➔ 恒比定时中，**delay**无法根据实际需要灵活调整，一般只能选择采样周期整数倍，
 - ➔ 过零定时精度受到采样周期和相位的影响！
- 500 MHz = 采样周期 2 ns，1 GHz = 1ns，FPGA一般通过线性内差找过零点。





快时间阵列关键技术：数字化获取中的定时精度？

数字化获取新的定时方式：在已有采样点的基础上，内插更多的点来尽可能恢复原波形！

- 保持纵向精度的基础上，增加横向定时精度！

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 64, NO. 12, DECEMBER 2017

$$g(x) = sinc(x) * g_s(x) = \int_{-\infty}^{+\infty} sinc(\lambda)g_s(x - \lambda) d\lambda$$

$$sinc(\lambda) = \sin\lambda/\lambda.$$

$$tsinc[i] = sinc\left(\frac{i\pi}{N}\right) \exp\left(-\left(\frac{i}{T}\right)^2\right)$$

$$g(j, k) = \sum_{i=0}^{L-1} (data[j - i]tsinc[iN + k] + data[j + 1 + i]tsinc[(i + 1)N - k])$$

- Original Sampling rate: 100 MHz
- Change to 2 GHz

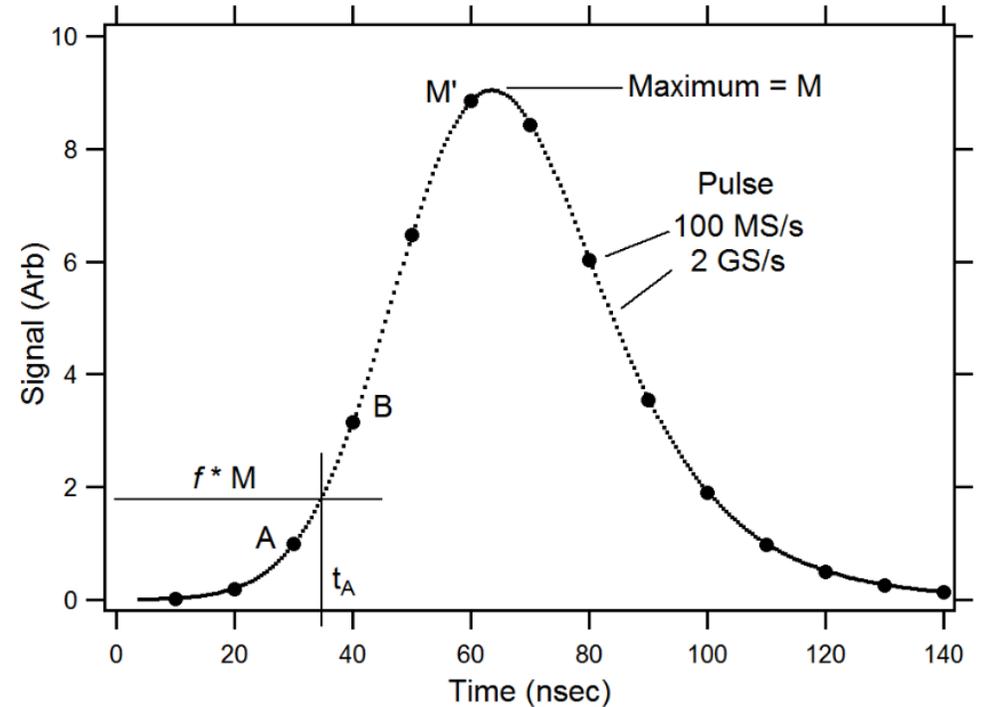
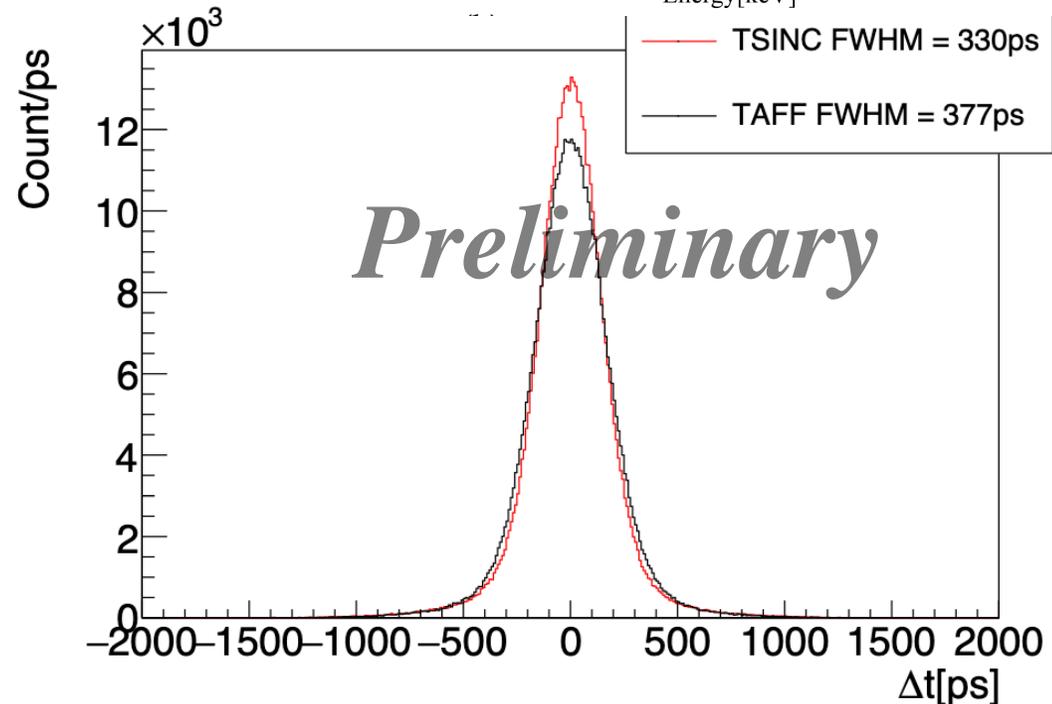
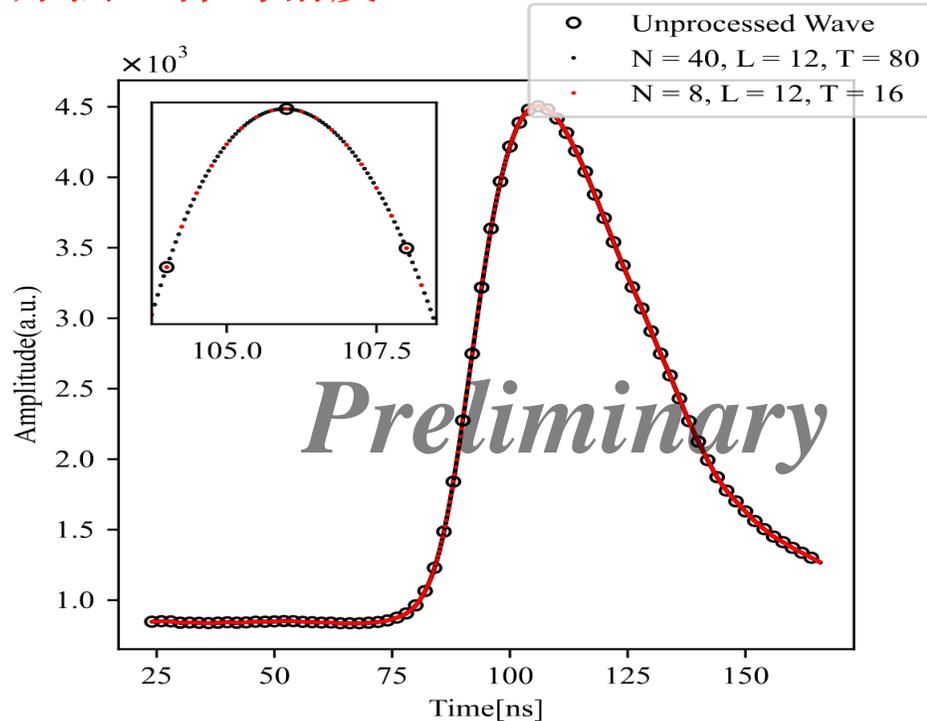
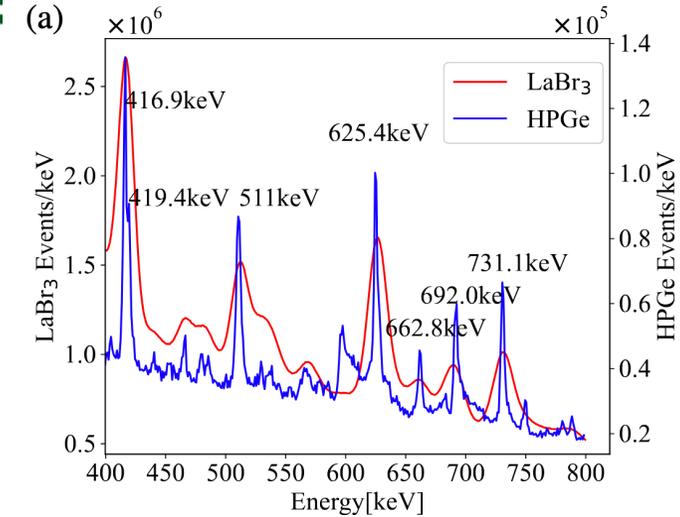


Fig. 2. Fast pulse digitized at two sampling frequencies, showing how the application of DCFD produces errors at lower sampling rates.



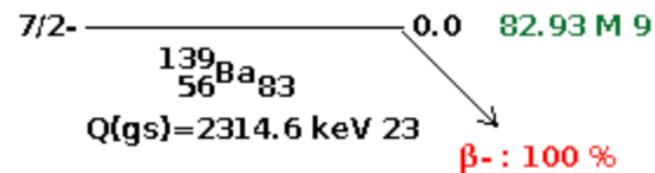
快时间阵列关键技术：数字化获取中的定时精度？

- 2023年7月@IMP，利用 $^{14}\text{N} + ^{181}\text{Ta}$ 反应研究 ^{190}Hg 激发态寿命；
- 16 HPGe + 16 $2 * 2 \text{ inch}^2$ LaBr₃, 14-bit-500MHz digitizer;
- 新定时方法得到了与FATIMA阵列类似的时间分辨（FATIMA使用的传统模拟电路定时方法，且探测器更小）
- **结论：14-bit-500MHz 数字化获取可以达到与传统模拟信号定时方法一样的精度！**

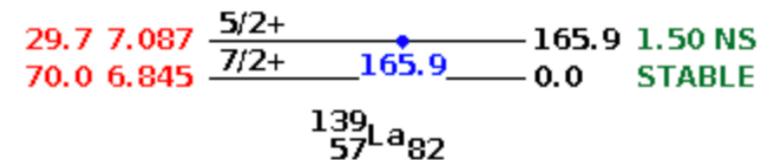


快时间阵列在白光终端的应用

- 2023-11, a test experiment is performed at Back-n beam line at Spallation target at CSNS,
- Back-n neutron beam with an intense flux up to $10^7 \text{ cm}^2/\text{s}$, and the energy can span from 0.3 eV to several hundreds of MeV.
- Natural Ba targets (72% enriched ^{138}Ba) and ^{89}Y targets (the thickness for one target is around 3~mm)
- 2个2*3 inch² 的LaBr₃, 塑闪+PMT, XIA数字化获取, 离线测量阵列,
- ^{138}Ba 和 ^{89}Y 靶放在中子束流线上辐照活化, 然后进行离线测量,
 - ➔ ^{138}Ba 中子俘获后产生 ^{139}Ba , beta-衰变到 ^{139}La , 主要布局基态和第一激发态,
 - ➔ ^{139}La N=82, Z=57, 第一激发态到基态之间的跃迁: L-forbidden M1 transition (g7/2, d5/2), Check the importance of core-excitation!



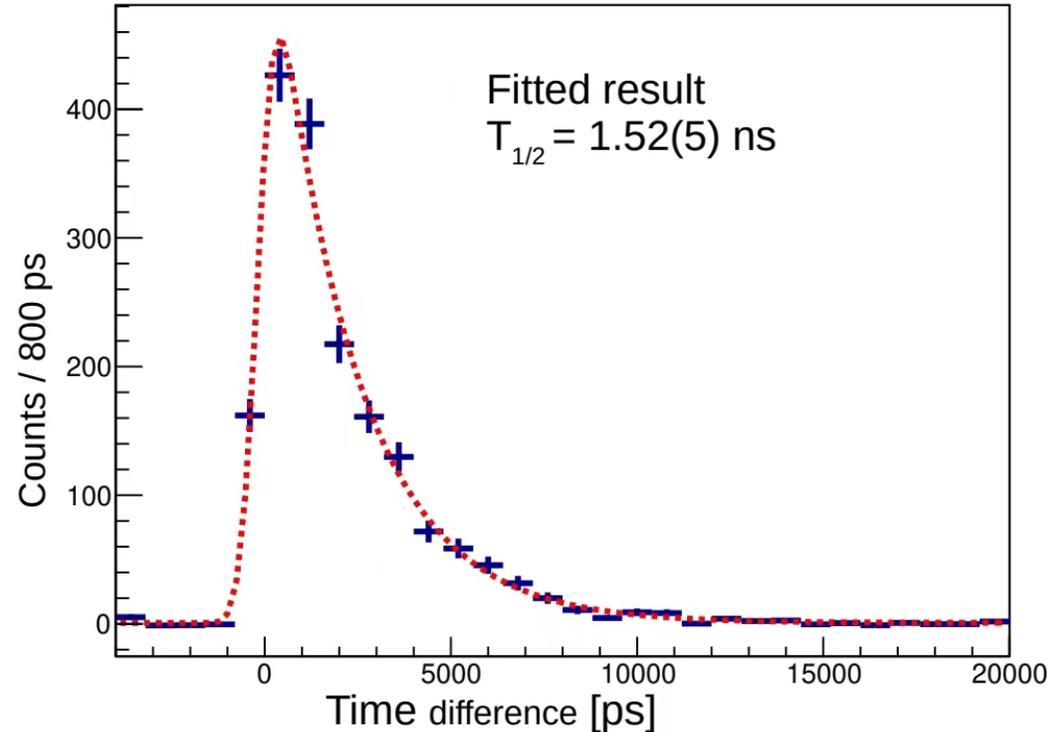
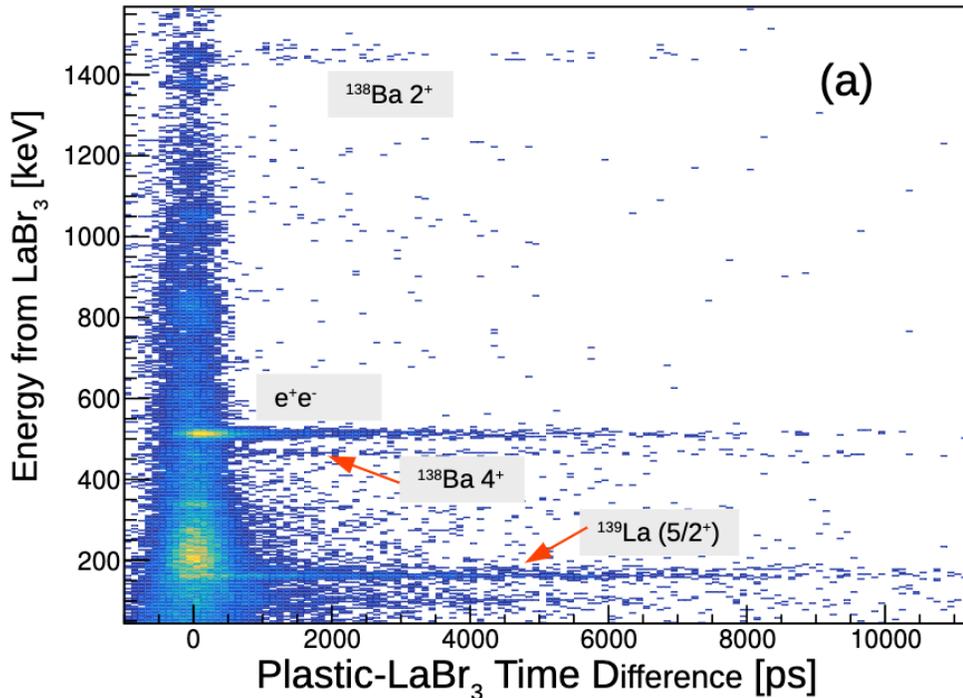
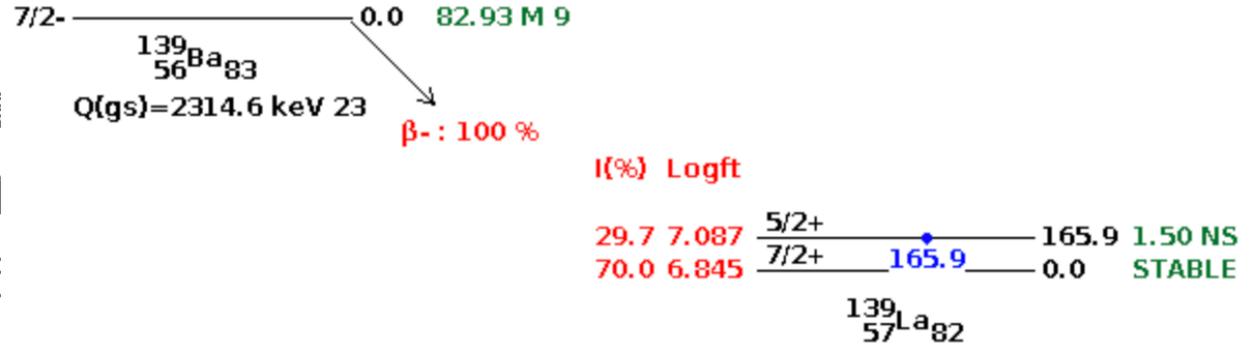
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快时间阵列在白光终端的应用

- 2个2*3 inch² 的LaBr₃, 塑闪+PMT, XIA数字化获取,
- ¹³⁸Ba和⁸⁹Y靶放在中子束流线上辐照活化, 然后进行测量
 - ➔ ¹³⁸Ba中子俘获后产生¹³⁹Ba, beta-衰变到¹³⁹La, 主要
 - ➔ ¹³⁹La N=82, Z=57, 第一激发态到基态之间的跃迁 importance of core-excitation!



快时间阵列在白光终端的应用

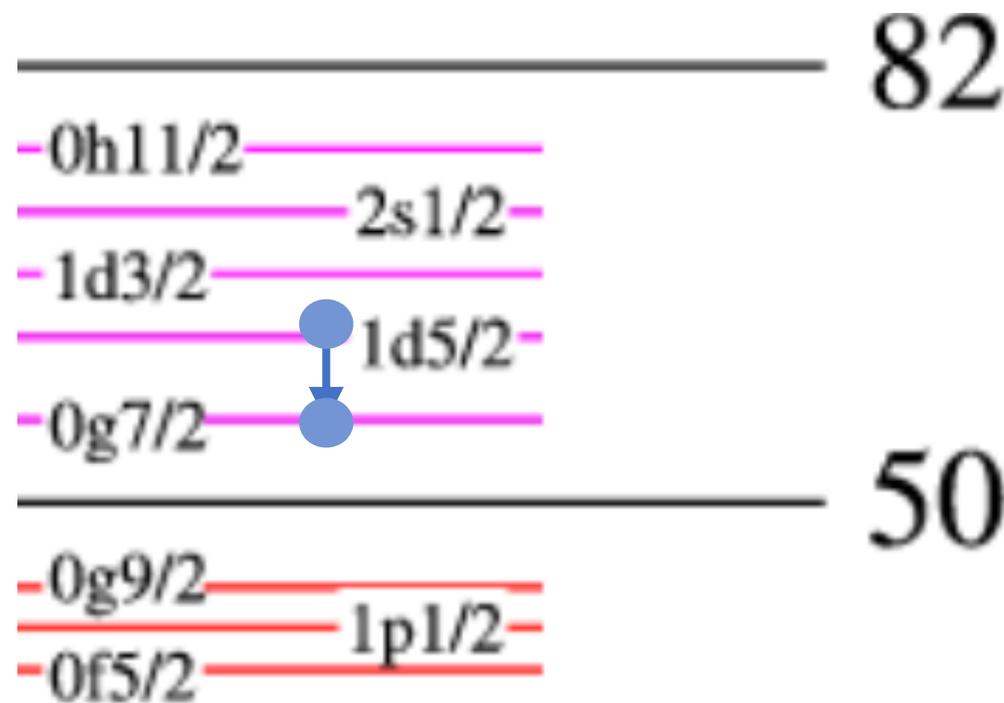
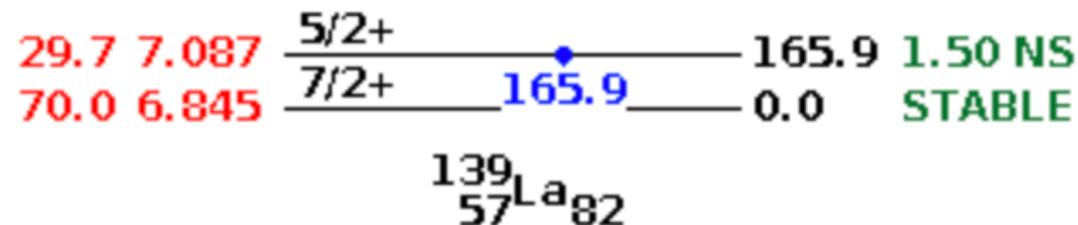


• ^{139}La 第一激发态寿命的物理分析

Core-excitation	$B(M1) [\mu_N^2]$	$T_{1/2}^{total} [\text{ns}]$	$B(M1)^* [\mu_N^2]$	$T_{1/2}^{total*} [\text{ns}]$
None	2.2×10^{-5}	97.5	1.5×10^{-3}	4.5
p1	6.9×10^{-4}	9.5	3.5×10^{-3}	1.9
n1	2.8×10^{-4}	21.5	2.5×10^{-3}	2.7
p1n1	1.3×10^{-3}	5.3	4.6×10^{-3}	1.5
	No tensor part in the g-factor		With $g_{eff}^t = 0.15$	

- M1 transition between $g_{7/2}$ and $d_{5/2}$ orbits are forbidden,
- Both neutron and proton core-excitation can largely reduced the predicted lifetime, but still different from measured value ($1.52 \pm 0.05 \text{ ns}$),
- Inclusion of a small tensor part $g_{eff}^t [Y^2, s]$ for effective g-factor is necessary to perfectly reveal the lifetime.

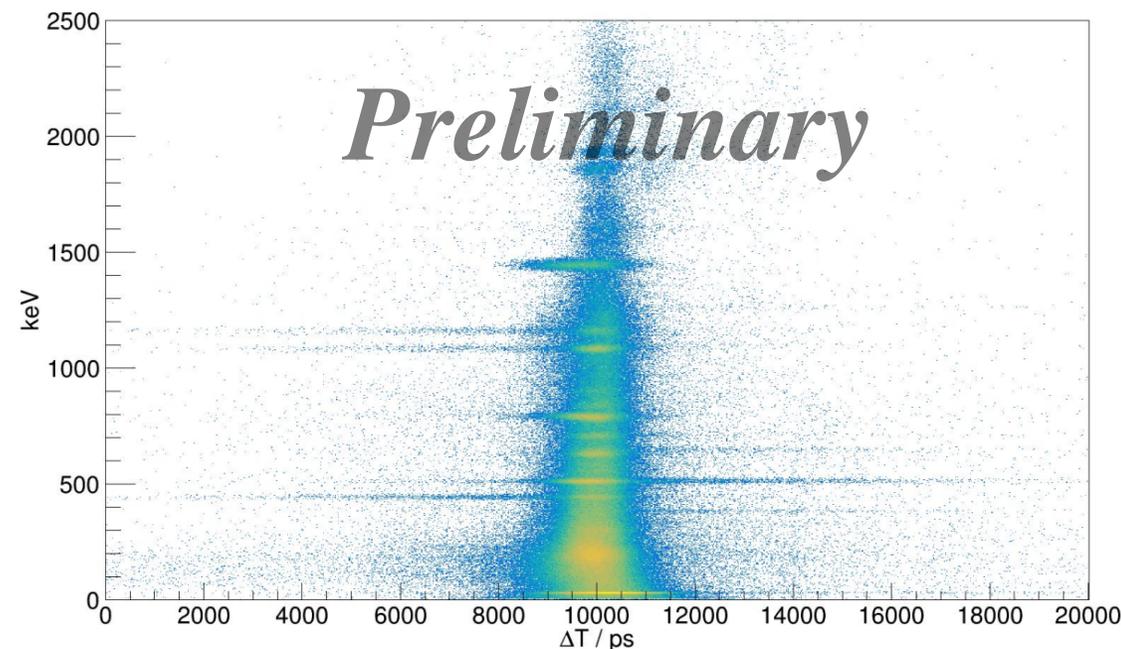
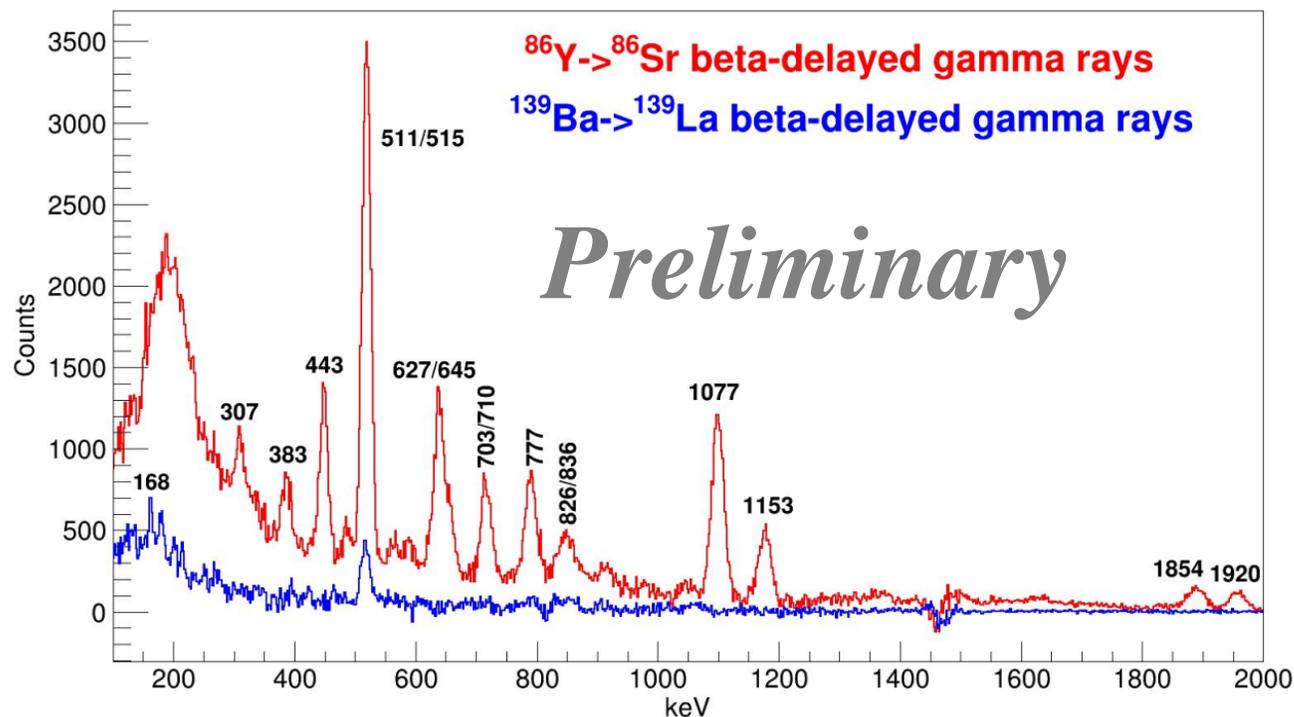
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快时间阵列在白光终端的应用



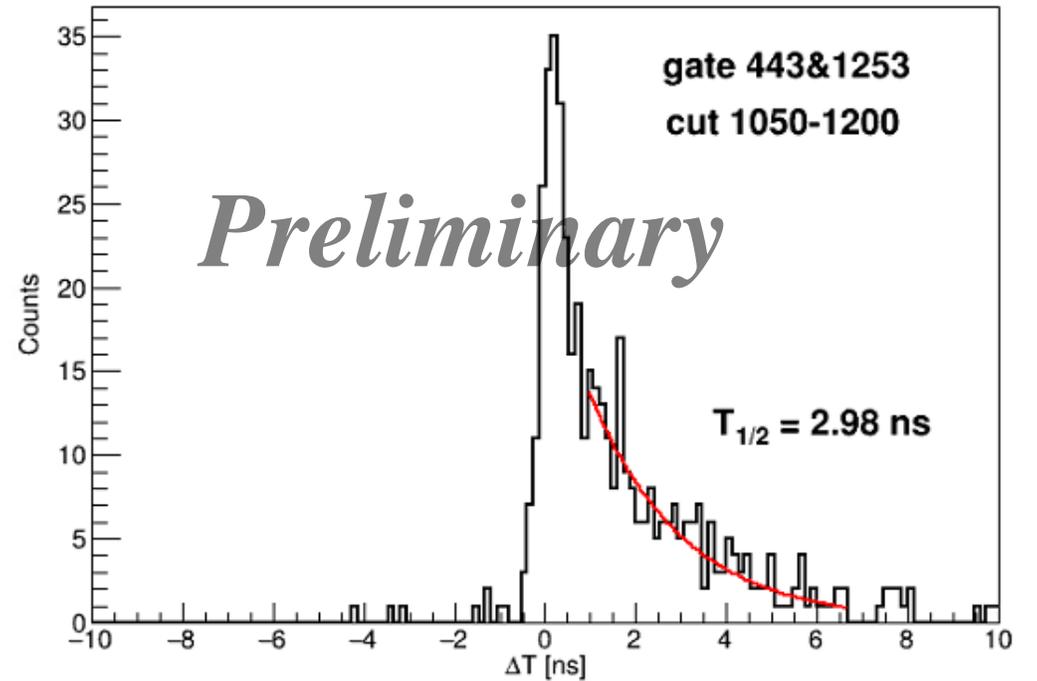
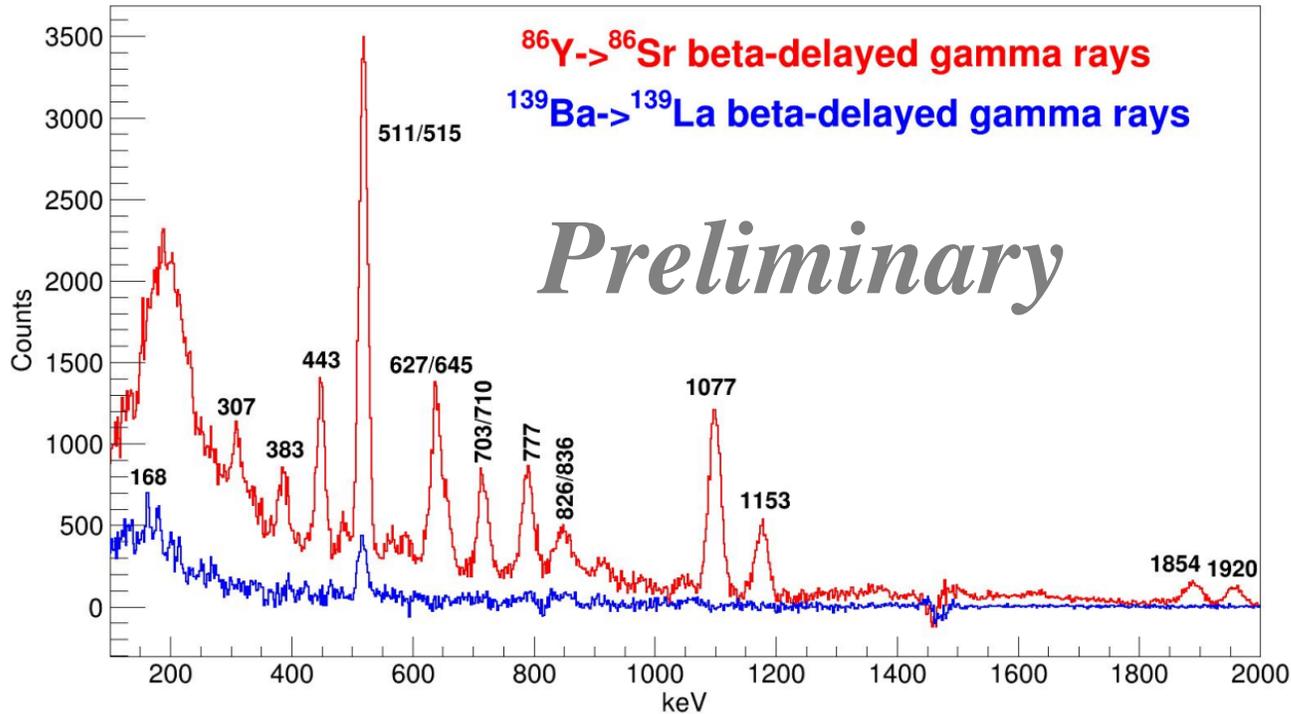
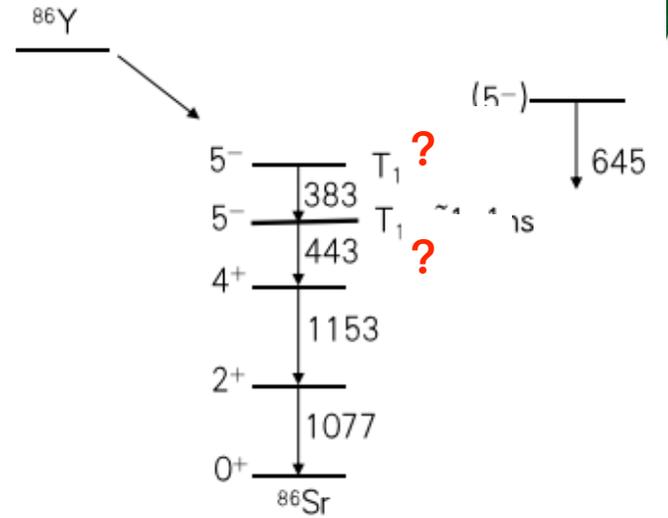
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 - ➔ ¹³⁸Ba中子俘获后产生¹³⁹Ba, beta-衰变到¹³⁹La, 主要布局基态和第一激发态,
 - ➔ ⁸⁹Y (n, 4n) 反应产生⁸⁶Y, beta-衰变到⁸⁶Sr, 首次测量多个激发态寿命。





快时间阵列在白光源终端的应用

- 2个2*3 inch² 的LaBr₃, 塑闪+PMT, XIA数字化获取, 离线测量阵列,
- ¹³⁸Ba和⁸⁹Y靶放在中子束流线上辐照活化, 然后进行离线测量,
 - ➔ ¹³⁸Ba中子俘获后产生¹³⁹Ba, beta-衰变到¹³⁹La, 主要布局基态和第一激发态,
 - ➔ ⁸⁹Y (n, 4n) 反应产生⁸⁶Y, beta-衰变到⁸⁶Sr, 首次测量多个激发态寿命, 极大丰富了可以测量的原子核种类。



- 利用溴化镧阵列+数字化获取，直接测量原子核激发态寿命的实验方法已经十分成熟；
- 在白光终端辐照Bi, Nb, Ni样品，利用 (n, xn) 反应产生放射性核素，再移至离线测量终端（降低本底计数，避免gamma flash的影响），测量子核激发态寿命（伴随实验的可能性）。
- 脉冲束的可能性？

中大：袁岑溪、苏军、祝龙、梅波、滑伟、方晓、魏月环、张振、张玉美、郭琛琛、张一怒、张广鑫

原子能院：吴晓光，吴鸿毅

近代物理研究所：方永得，李广顺，郭松，刘忠，张文强

北航：孙保华，张高龙

深圳大学：胡世鹏

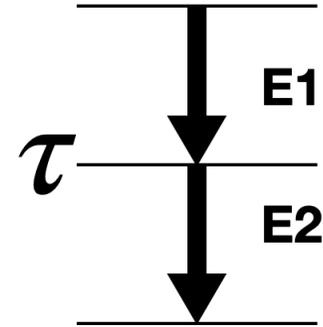
深圳技术大学：钟健





利用LaBr₃探测皮秒量级激发态寿命的实验方法

- 目前矩心差法测量到的最低能级寿命：
 - ➔ 4(3) ps in ²²⁸Th (nature physics 16, 853–856 (2020))
 - ➔ 3(2) ps ¹³¹Sb PRC 107, 014322 (2023)



Direct measurement of the intrinsic electric dipole moment in pear-shaped thorium-228

M. M. R. Chishti^{1,3}, D. O'Donnell¹, G. Battaglia², M. Bowry¹, D. A. Jaroszynski², B. S. Nara Singh¹, M. Scheck¹, P. Spagnoletti¹ and J. F. Smith¹

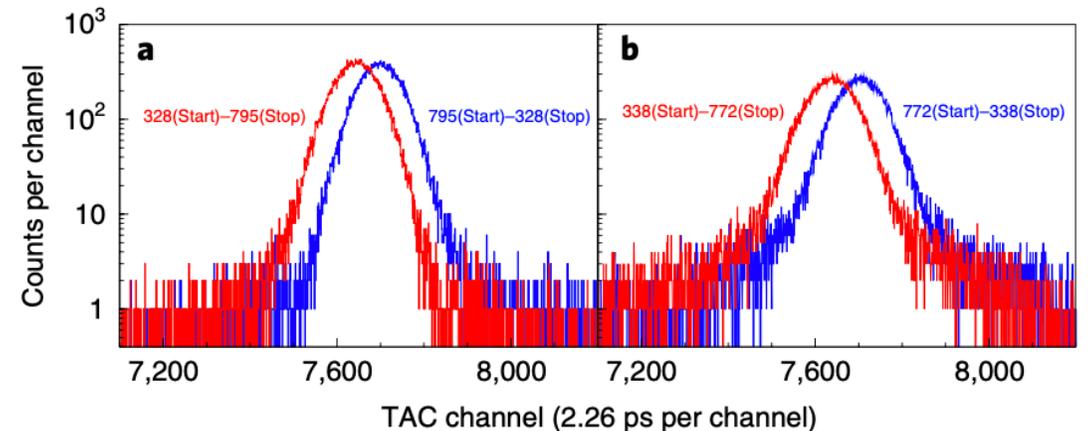
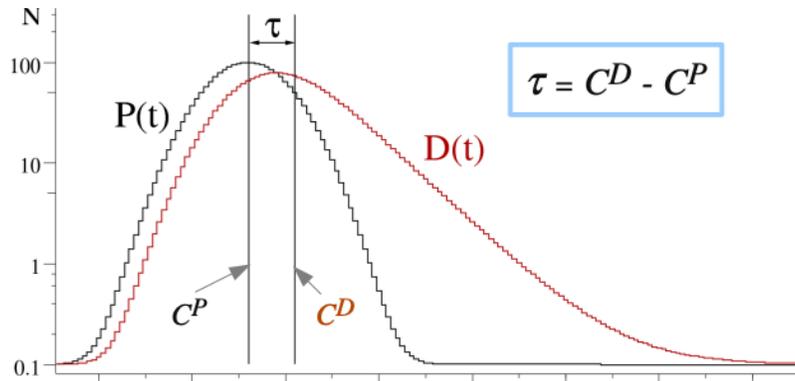
矩心位移法

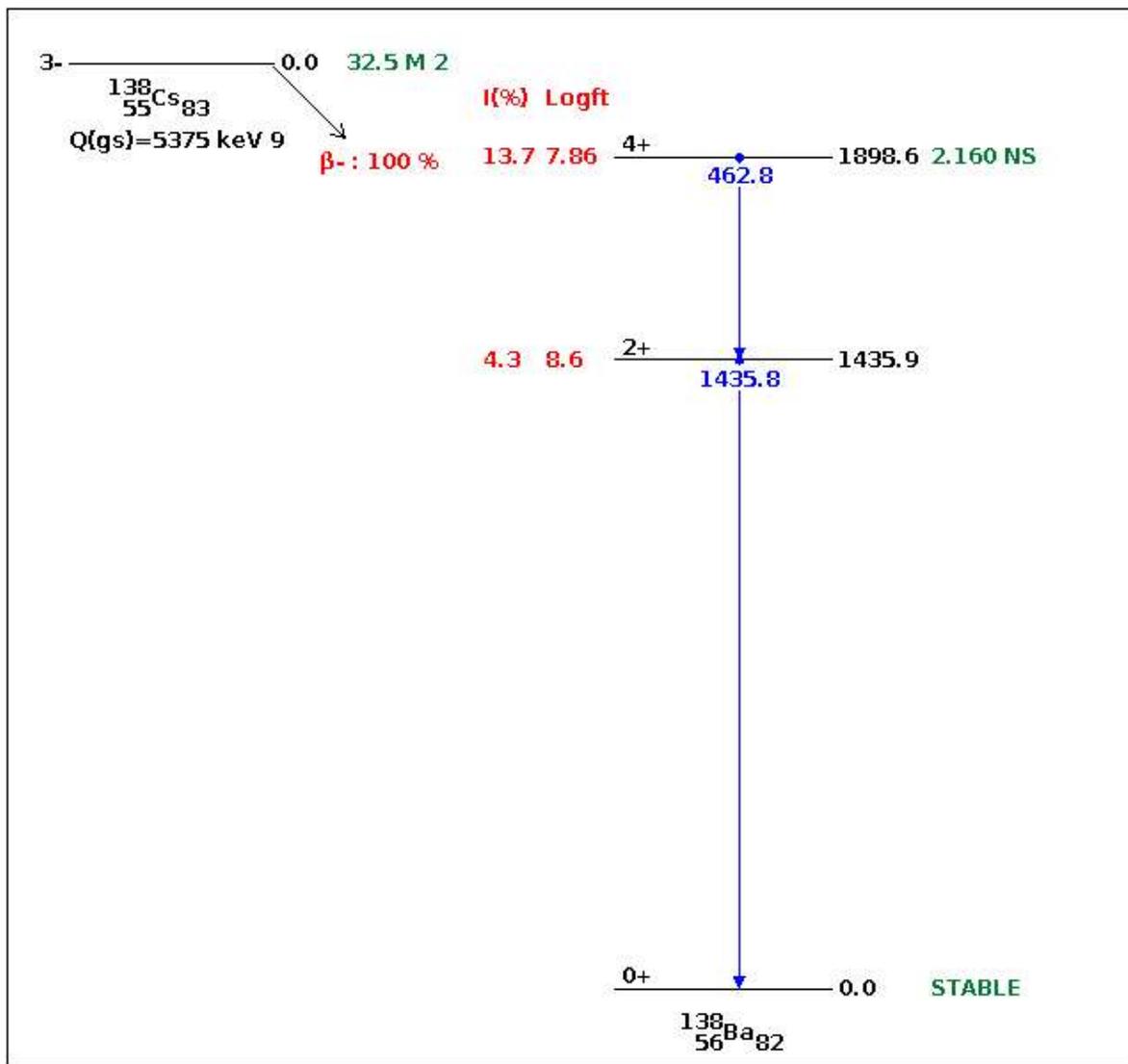
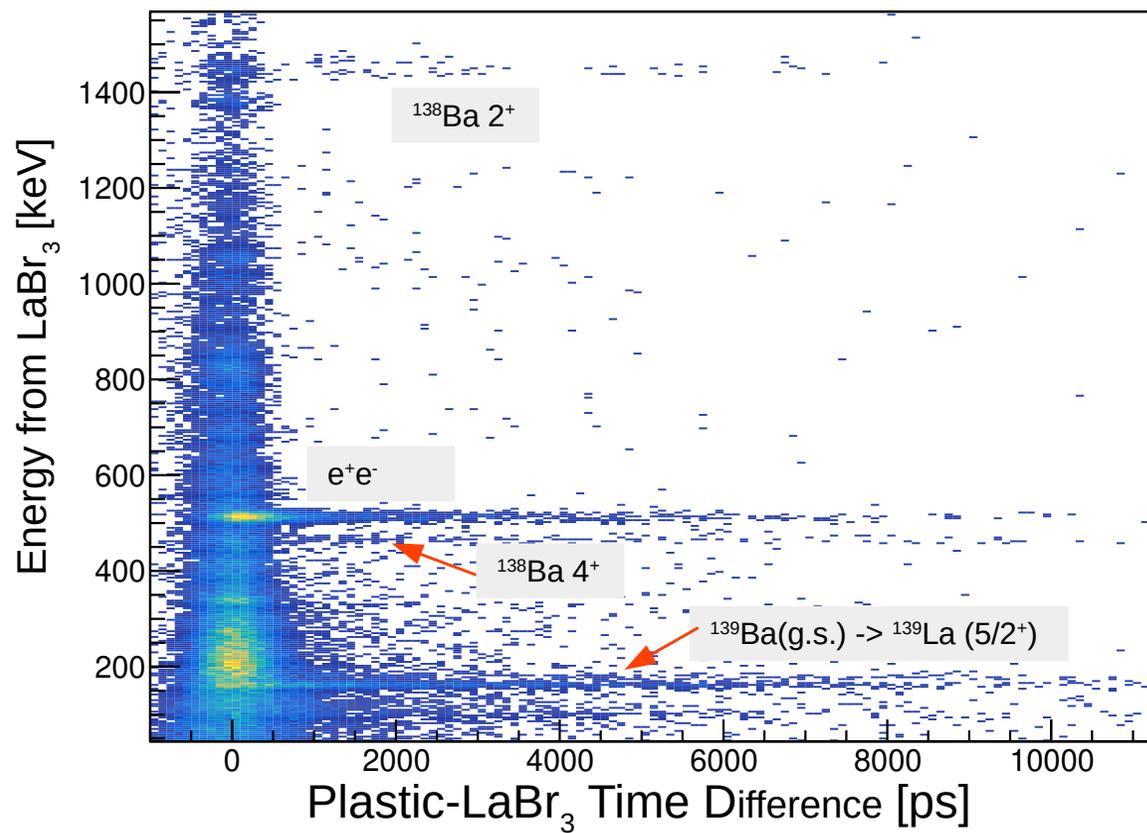
矩心差法

The centroid or center of gravity is the first moment of a time distribution $D(t)$:

$$C^D = \langle t \rangle = \frac{\int t D(t) dt}{\int D(t) dt}$$

The statistical uncertainty is given by the standard deviation $\sigma = \text{FWHM}/2.355$ of the PRF:

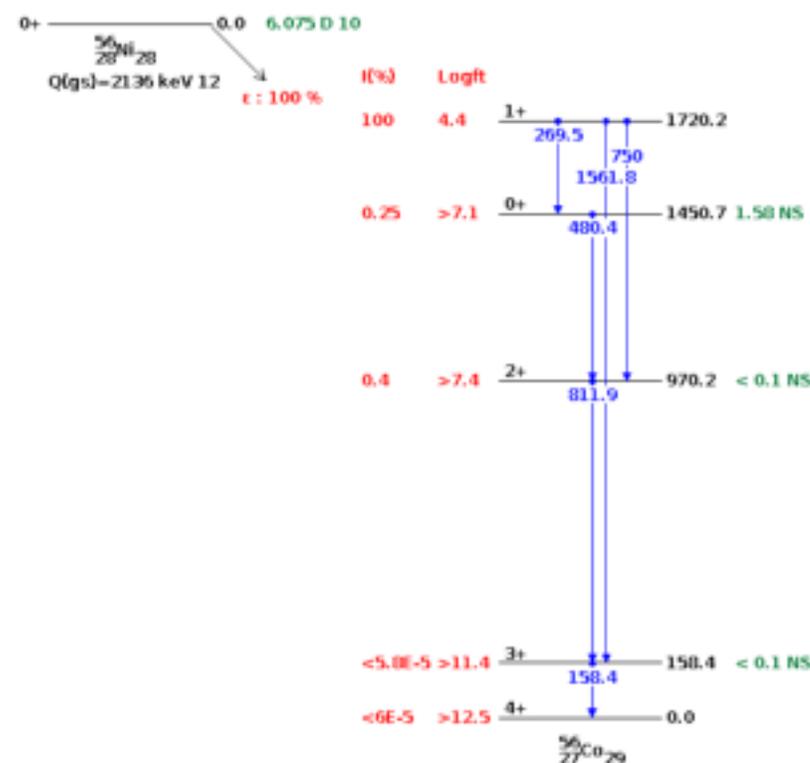




Level Scheme of ^{56}Co

天然Ni (^{58}Ni 丰度 68%)

$^{58}\text{Ni}(n,3n)^{56}\text{Ni}$



E(level) [†]	J ^π	T _{1/2} [Ⓔ]	XREF	Comments
0.0	4 ⁺	77.236 d 26	ABCDEFGHIJK	% α +% β^+ =100 $\mu = 3.85 \text{ J}$ (2005Sc24); $Q = +0.25 \text{ 9}$ (2005Sc24) J^π : $J=4$ from atomic beam (1976Fu06) and $\pi=+$ from $L=4$ in $^{54}\text{Fe}(\alpha, d)$. $T_{1/2}$: from evaluation of $T_{1/2}$ by 2004WoZZ. Others: 77.12 d 7 (1978La21), 77.12 d 10 (1977An13), 78.4 d 5 (1974Cr05), 77.2 d 8 (1954Bu58), 77.30 d 9 (1989Al24), 78.76 d 12 (1972Em01), 77.3 d 3 (1957Wr37), 77.08 d 8 (1989Le17), 77.28 d 4 (1989Sc17), and 77.29 d 3 (1990Al29), 77.210 d 28 and 77.290 d 40 (1992Fu02).
158.38 3	3 ⁺	$< 0.1^{\text{A}}$ ns	A CDEFGHIJK	XREF: I(167)I(166). J^π : $J=3$ from $\gamma\gamma(\theta)$ in ^{56}Ni α decay and $\pi=+$ from $L(\alpha, d)=2$.
576.50 7	5 ⁺	0.28 ^C ps +7-5	BCDEFGHIJK	$T_{1/2}$: others: 0.33 ps +22-10 (p,ny), 0.33 ps +22-11 (^3He ,py). J^π : configuration= $(\pi 1f_{7/2})(\nu 1p_{3/2})5^+$. See also $J=5$ from $\gamma\gamma(\theta)$ ($^{12}\text{C}, n\text{p}\gamma$) and $\pi=+$ from $L(\alpha, d)=4$.
829.61 5	4 ⁺	> 1.7 ps	CDE GHIJK	XREF: I(840). $T_{1/2}$: others: > 0.76 ps (p,ny), > 1.4 ps (d, $\alpha\gamma$). J^π : $J=4$ from $\gamma(\theta)$ of 671 γ to 3 ⁺ 158 in $^{54}\text{Fe}(\alpha, n\text{p}\gamma)$ and $\pi=+$ from $L(p, ^3\text{He})=4$.
970.23 4	2 ⁺	0.12 ps +12-6	A CDE GHIJK	XREF: I(961). $T_{1/2}$: others: 0.076 ps +21-14 (p,ny), < 0.1 ns in ^{56}Ni α decay, and 0.139 ps +31-24 (d, $\alpha\gamma$). J^π : $J=2$ from $\text{p}\gamma(\theta)$ of 812 γ to 3 ⁺ 158 in $^{54}\text{Fe}(\alpha, \text{He}, \text{p}\gamma)$ and $\pi=+$ from $L(^3\text{He}, p)=2$.
1009.13 7	5 ⁺	0.38 ^C ps +14-9	CDE GHIJK	XREF: I(1001). $T_{1/2}$: others: 0.44 ps +25-12 in $^{56}\text{Fe}(p, \text{ny})$, 0.27 ps +18-9 in $^{54}\text{Fe}(\alpha, \text{He}, \text{p}\gamma)$.
1114.51 5	3 ⁺	0.19 ps +9-6	C E GHIJK	J^π : from analyzing power in $^{58}\text{Ni}(\text{pol } d, \alpha)$ and $L(d, \alpha)=4$. XREF: I(1106). $T_{1/2}$: others: 0.24 ps +4-2 (^3He ,py), 0.139 ps +28-24 (d, $\alpha\gamma$). J^π : $J=3$ from $^{56}\text{Fe}(p, n)$, (p,ny), M1+E2 γ to 4 ⁺ .
1450.68 4	0 ⁺	1.58 ^B ns 6	A C GHIJK	XREF: I(1444). E(level): anti-analog state of 0 ⁺ g.s. in ^{56}Fe in $^{56}\text{Fe}(p, n)$, (p,ny). $T_{1/2}$: others: > 2.0 ps (^3He ,py), > 0.4 ps (p,ny). J^π : $J=0$ from $\gamma\gamma(\theta)$ in ^{56}Ni α decay, $\pi=+$ from $L(p, ^3\text{He})=0$.
1585 10			C	

以3倍半衰期的规律而言，要获得强度最高的 ^{56}Ni 产物，需要对 ^{58}Ni 辐照18days

测量⁹⁰Zr激发态寿命

⁹⁰Nb ε decay 1990Me15,1982Wa24

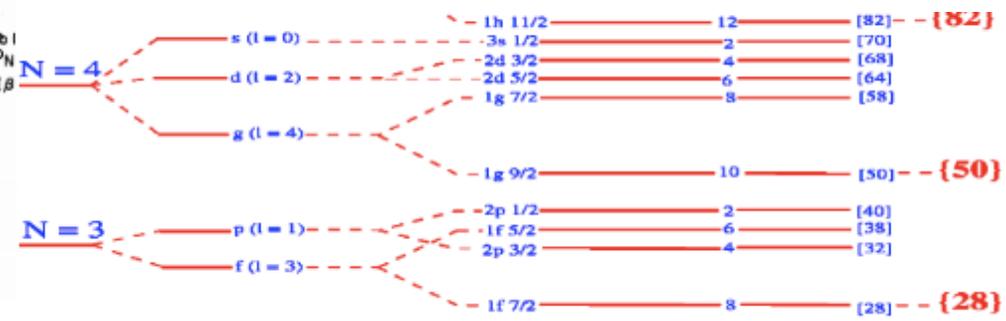
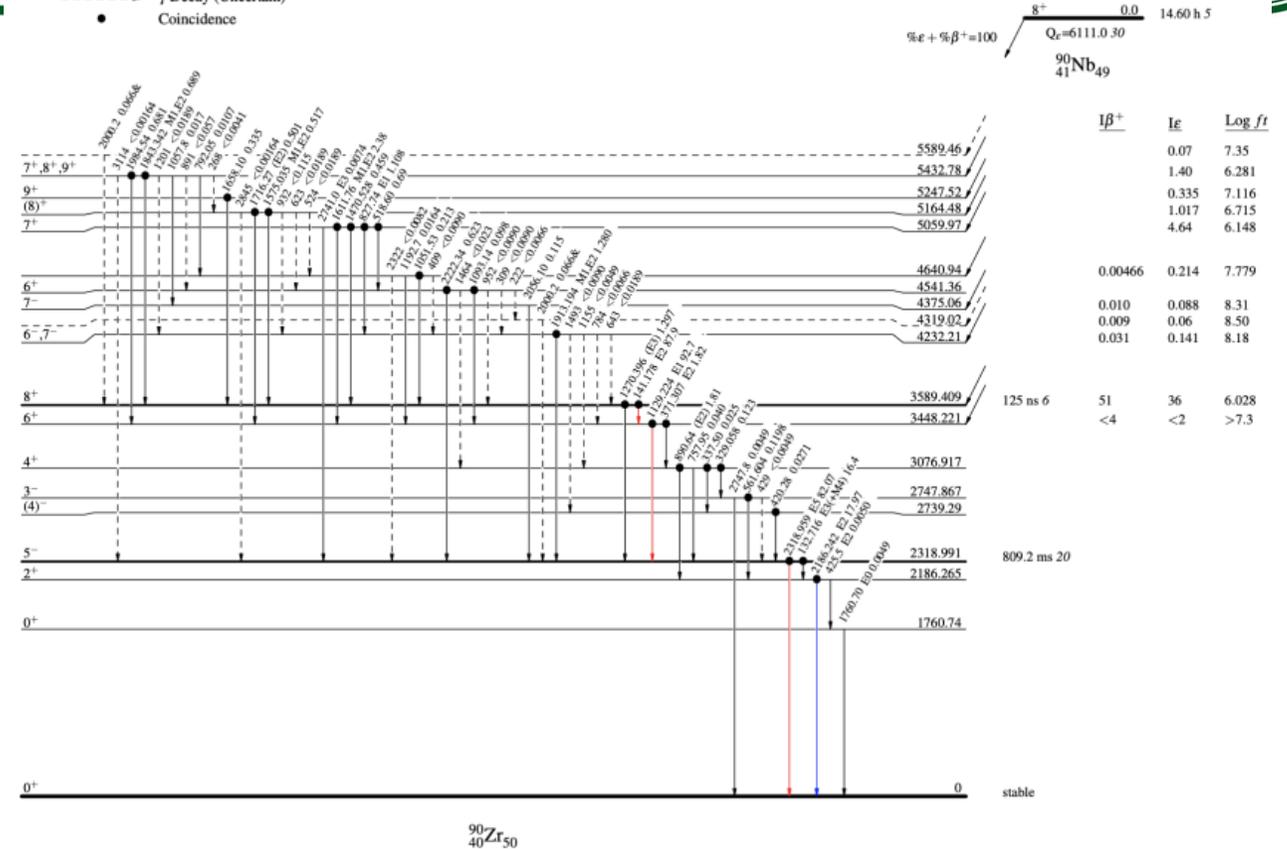
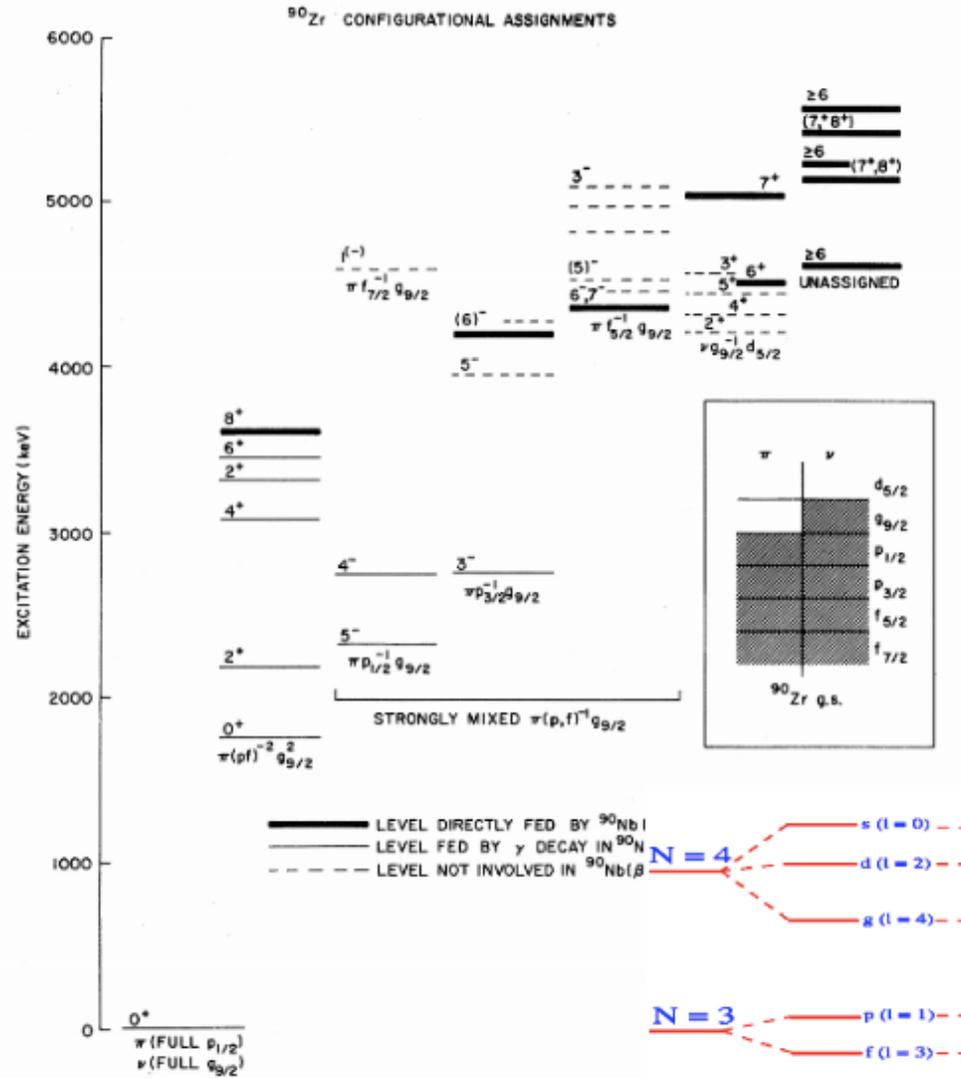


Legend

- $I_\gamma < 2\% \times I_\gamma^{\max}$
- $I_\gamma < 10\% \times I_\gamma^{\max}$
- $I_\gamma > 10\% \times I_\gamma^{\max}$
- - - γ Decay (Uncertain)
- Coincidence

Decay Scheme

Intensities: $I_{(\gamma+ec)}$ per 100 parent decays
& Multiply placed: undivided intensity given





(3) ^{209}Bi 辐照实验

用白光中子束流轰击 ^{209}Bi 靶， (n, γ) 反应可以产生 ^{210}Bi ， (n, xn) 反应可以产生 $(210-x)$ Bi核素，其中 ^{205}Bi - ^{206}Bi 的半衰期在天的量级， ^{202}Bi - ^{204}Bi 的半衰期在小时量级。根据不同目标衰变母核的半衰期，可以灵活选择辐照时间；亦可以根据其他实验的束流时间，选择研究合适的衰变母核，测量子核Pb核素的激发态寿命，充分符合“伴随”测量实验的要求。