Lifetime measurements of nuclear excited states using a mixed array of HPGe and $LaBr_3(Ce)$ detectors

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Workshop on Physics Opportunities Using Arrays of Fast-Timing Gamma-ray Detectors

19^{th}-20^{th} March 2015

Outline

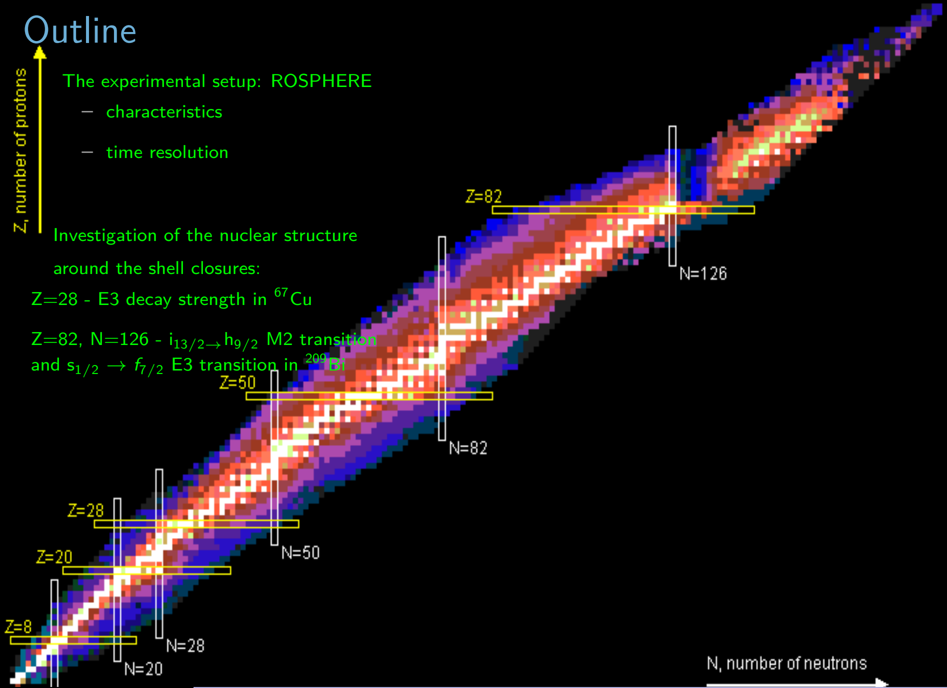
The experimental setup: ROSPHERE

- characteristics
- time resolution

Investigation of the nuclear structure around the shell closures:

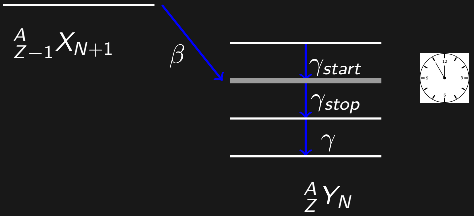
$Z=28$ - E3 decay strength in ^{67}Cu

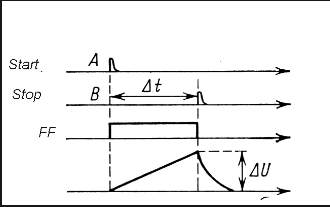
$Z=82$, $N=126$ - $i_{13/2} \rightarrow h_{9/2}$ M2 transition and $s_{1/2} \rightarrow f_{7/2}$ E3 transition in ^{209}Bi



The electronic timing technique

The very basic working principle:





Needs:
- detectors with good energy resolution and timing properties (high light output, fast decay time).
- appropriate electronics.

M. Moszynski, H. Mach, NIM A 277 (1989) 407

N. Marginean et al., EPJ A 46 (2010) 329

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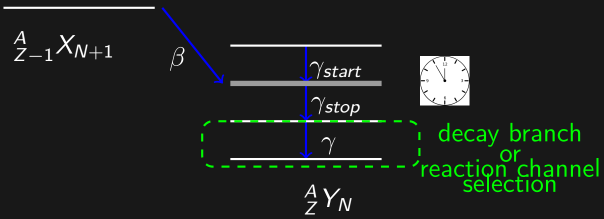

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The experimental setup

Mixed configuration:

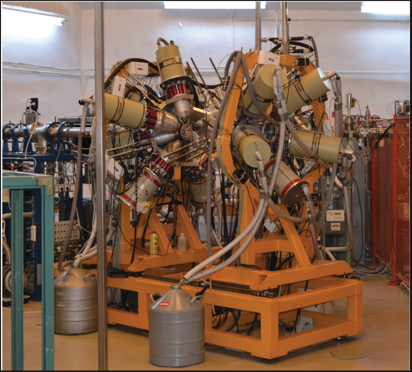
14 HPGe detectors with BGO shields (coaxial or planar)
arranged in 3 rings: 5 @ 37°, 5 @ 143 °, 4 @ 90°

11 $LaBr_3$(Ce) scintillation detectors in positions at : 70°, 110°, 90°.

Characteristics:

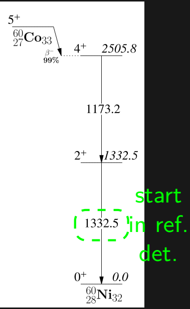
- Absolute efficiency @ 1332 keV (^{60}Co):
  HPGe: 1.10(3)%
  $LaBr_3$(Ce): 1.75(5)%
- Energy resolution: $\Delta R = \frac{FWHM}{E_0}$
  HPGe: 0.1% @ 1332.5 keV (^{60}Co)
  $LaBr_3$(Ce): 2-3% @ 662 keV (^{137}Cs)

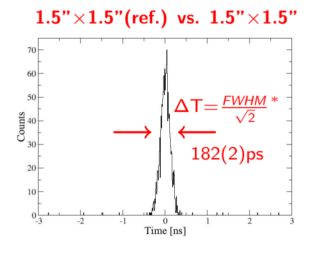
The ROSPHERE array at the Bucharest 9 MV tandem accelerator

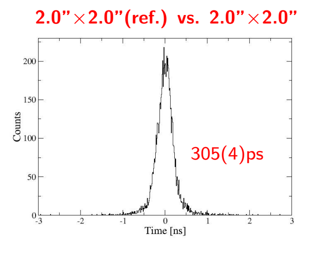


[to be submitted to NIM B]

LaBr$_3$(Ce) time resolution







* for an identical pair of crystals

LaBr$_3$(Ce) sub-array: $\Delta T = 347$ ps

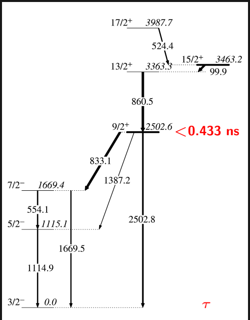
Time resolutions for different crystal shapes and dimensions:

Shape	Dimensions (inch)	Timing resolution (ps)
Cylindrical	1.5"×1.5"	182(2)
Cylindrical	2"×2"	305(4)
Conical	1.5"×1.5"×1"	158(2)
Conical	2"×1.5"×1.5"	210[1]

[to be published in Nucl. Instr. Meth. B]

[1] O.J. Roberts et al., NIM A748 (2014) 91

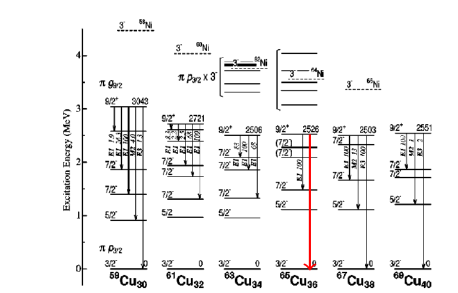
The lifetime of the $9/2^+$ state in ^{67}Cu



If the lifetime is assumed to be equal to the upper limit then one obtains:
$B(E3;9/2^+ \rightarrow 3/2^-) > 11$ W.u.;
$B(E1;9/2^+ \rightarrow 7/2^-) > 1.1\times10^{-6}$ W.u.

- it was found to have a large single-particle character (from transfer reactions)

E3 transitions in odd-mass Cu isotopes



[M. Asai et al., PRC 62 (2000) 054313]

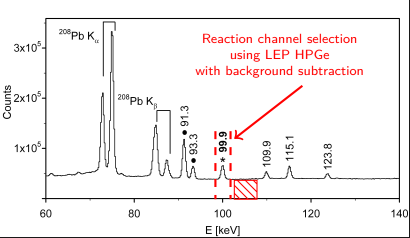
E1 systematics in lighter (A=59, 61, 63) Cu isotopes:

$B(E1) \approx 10^{-5}$ W.u. $\rightarrow$ $B(E3) >> 11$ W.u. for ^{67}Cu $\rightarrow$ **High collectivity!**

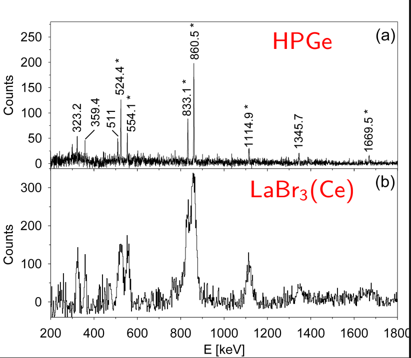
^{67}Cu experiment with ROSPHERE

^{64}Ni(α,p)^{67}Cu reaction @ 18MeV

production cross-section predicted with Talys: 10 mb (≈1% out of the total cross-section)

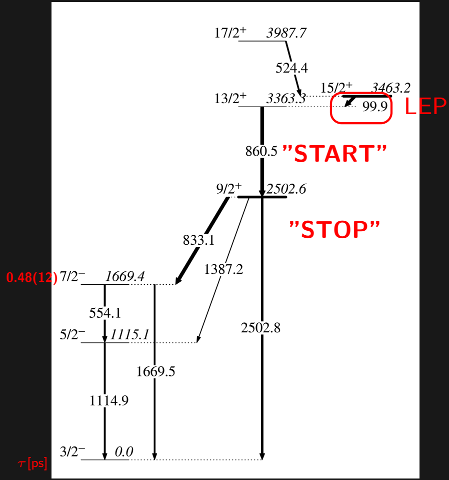


Gated energy spectra:



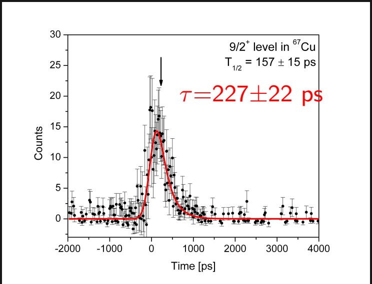
[C.R. Nita, D. Bucurescu, N. Marginean et al., PRC 89 (2014) 064314]

The lifetime of the $9/2^+$ state in ^{67}Cu



Convolution method:

$$f(t) = \int_{-\infty}^{t} P(t' - t_0) e^{-\lambda(t-t')}\, dt'$$



The centroid shift analysis gives:

$\tau = 229 \pm 53$ ps

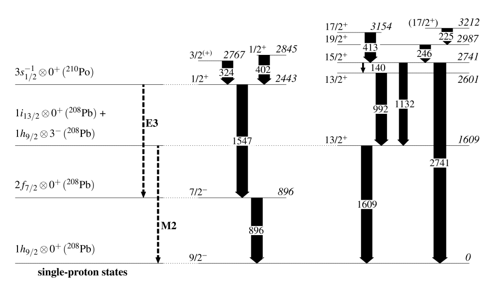
It results that B(E3) $= 16.8 \pm 1.7$ W.u.*

*with the branching ratios adopted from C. Chiara et al., PRC 85 (2012) 024309

[C.R. Nita, D. Bucurescu, N. Marginean et al., PRC 89 (2014) 064314]

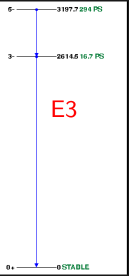
The structure of the first excited states in ^{209}Bi

[to be submitted]

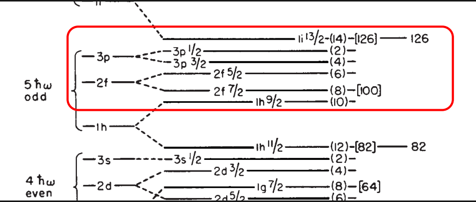


^{209}Bi

$h_{9/2} \otimes 3^-$



^{208}Pb



single-proton states

[source: M.G. Mayer, The Shell Model, Nobel Prize Lecture]

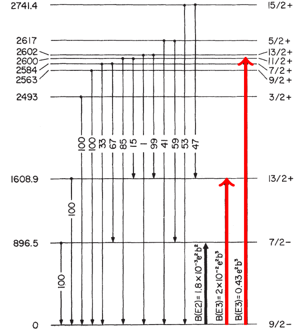
The structure of J^{π}=13/2^{+}, 1/2^{+} states in ^{209}Bi

π ($1i_{13/2} \rightarrow 1h_{9/2}$) transition:

	Broglia et al.	Hertel el al.	Bohr, Mottelson
B(E3) e^2 fm^6	1.24(32) $\times 10^4$	2.2(8) $\times 10^4$	1.5(5) $\times 10^4$

- The E3 admixture has been determined to be 10% based on a measured mixing ratio of -0.33(10).
- Breene et al., combined this measured mixing ratio with a value of B(E3;1609$\rightarrow$0)=1.5(5)$\pm 10^4$ $e^2 fm^6$, quoted by Bohr and Mottelson to derive a value of $T_{1/2}$=270(180) ps.
- NO direct $T_{1/2}$ measurement!

Coulomb excitation exp.



[Hertel el al., PRL 23 (1969) 488]

13/2^{+} state, dominant $i_{13/2}$ single-particle character:

$$|13/2^+_1\rangle = |0^+(^{208}Pb) \otimes \pi(i_{13/2})\rangle + |3^- \otimes \pi(h_{9/2})\rangle$$

1/2^{+} state, 2p-1h state:

$$|\ 1/2^+_1\rangle = |0^+(^{210}Po) \otimes \pi(s_{1/2})\rangle + |3^- \otimes \pi(f_{7/2})\rangle$$

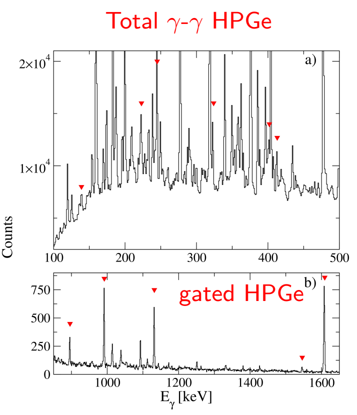
s.p.

coupling to the one λ=3 phonon state in ^{208}Pb

^{209}Bi experiment with ROSPHERE

^{208}Pb(^{7}Li, 2nα)^{209}Bi reaction @ 32 MeV

$\sigma_{^{209}Bi} \approx 3\,\%$ of the total cross-section

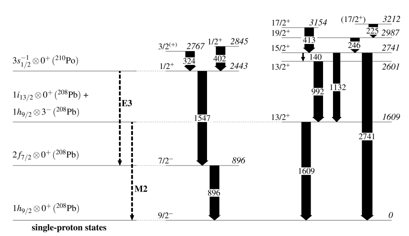


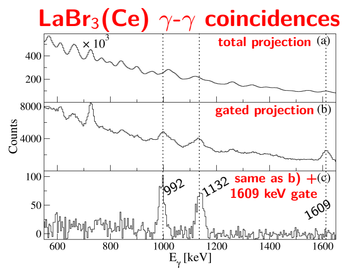
Lifetime measurements in ^{209}Bi

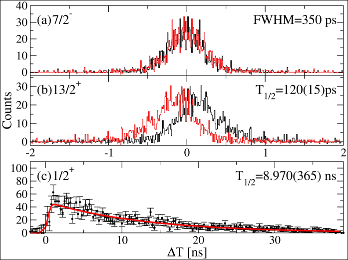
[to be submitted]

low E_γ

HPGe gates







Lifetime measurements in ^{209}Bi - results

J_i^π	$T_{1/2}$ ps	$L\lambda$	Transition	$B(L\lambda)$ e^2fm^6 or $\mu_N^2 fm^2$	$B(L\lambda)$ W.u.
$13/2^+$	120(15)	E3	$(^{208}\text{Pb } 3^- \otimes \pi 1h_{9/2}) \rightarrow (^{208}\text{Pb } 0^+ \otimes \pi 1h_{9/2})$ +	$1.1(4)\times10^4$	4.4
			$(^{208}\text{Pb } 0^+ \otimes \pi 1i_{13/2}) \rightarrow (^{208}\text{Pb } 0^+ \otimes \pi 1h_{9/2})$		
		M2	$(^{208}\text{Pb } 0^+ \otimes \pi 1i_{13/2}) \rightarrow (^{208}\text{Pb } 0^+ \otimes \pi 1h_{9/2})$	$3.8(3)\times10^1$	0.7
$1/2^+$	8970(365)	E3	$(^{210}\text{Po } 0^+ \otimes \pi 3s_{1/2}) \rightarrow (^{208}\text{Pb } 0^+ \otimes \pi 2f_{7/2})$	$6.4(2)\times10^3$	2.5

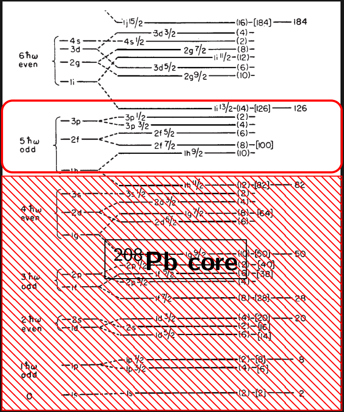
For the $13/2^+ \rightarrow 9/2^-$ (g.s.) the single-particle and the collective components cannot be disentangled from the measured B(E3) value.

Particle-vibration core coupling calculations needed.

Shell-model calculations for $J^{\pi}=13/2^{+}$ state in ^{209}Bi

KHPE

π valence space

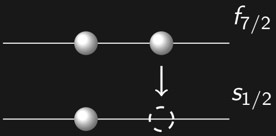


- the Shell-model predicts "pure" single-particle configurations defined by $h_{9/2}$, $f_{7/2}$, $i_{13/2}$ orbitals for the g.s. $(9/2^{-})$, 897 keV state $(7/2^{-})$ and 1609 keV state $(13/2^{+})$;

- for the M2 decay, using standard gyromagnetic factors, $B(M2)_{SM} = 760\ \mu_N^2 fm^2$;

- for $g_s^{eff} = 0.35\ g_s^{stand.}$ determined by I. Hamamoto for the ^{208}Pb region gives $\rightarrow B(M2) = 125\ \mu_N^2 fm^2$;

Shell-model calculations for $J^{\pi}=1/2^{+}$ state in ^{209}Bi



- to gain insight into the 1/2+ state composition, proton orbitals below Z=82, i.e. $2d_{5/2}$, $2d_{3/2}$, $3s_{1/2}$, $1h_{11/2}$, have to be considered along with orbitals above Z=82, $1h_{9/2}$, $2f_{7/2}$, $1i_{13/2}$ in order to account for the proton excitation on top of ^{208}Pb core.

Shell-model wave-function:

$$| 1/2^{+}_{1}\rangle=[s^{-1}_{1/2}(h^{2}_{9/2})_{0^{+}}]\ (88\%) + [\pi\ s^{-1}_{1/2}(f^{2}_{7/2})_{0^{+}}]\ (8\%) + [\pi\ s^{-1}_{1/2}(i^{2}_{13/2})_{0^{+}}]$$

- the theoretical B(E3) computed in the same valence space is equal to $0.302 \times 10^{3}\ e^{2}fm^{6}$.

- it represents a pure single particle estimation which does not take into account the core polarization induced by the $(h_{9/2} \otimes 3^{-}(^{208}Pb))$ weak-coupling (4%).

Conclusions

We have successfully measured lifetimes of about 100 ps using the triple-γ coincidences with the ROSPHERE array in the mixed configuration.

The triple-gamma coincidences method proved to be a powerful tool that enables the measurement of nuclear lifetimes in cases when the final decay branch is difficult to select or the statistics is poor.

Thank you to all collaborators!

Marginean N.[3], Bruce A.M.[1], Roberts O.J.[1,2], Bucurescu D.[3], Deleanu D.[3], Filipescu D.[3], Florea N.[3], Gheorghe I.[3], Ghita D.G.[3], Glodariu T.[3], Lica R.[3], Marginean R.[3], Mihai C.[3], Negret A.[3], Podolyak Zs.[4], Regan P.H.[4], Sava T.[3], Stroe L.[3], Suvaila R.[3], Toma S.[3]

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