



SELÇUK UNIVERSITY  
FACULTY OF SCIENCE

# XIV. INTERNATIONAL CONFERENCE ON NUCLEAR STRUCTURE PROPERTIES

$\beta$ -decay of the neutron-deficient  
 $^{60}\text{Ge}$  and  $^{62}\text{Ge}$  isotopes at RIKEN

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DE VALÈNCIA

# $\beta$ -decay spectroscopy of exotic nuclei

▣ The study of the properties of **nuclei close to the limits of stability** forms one of the frontiers of modern Nuclear Physics

▣ **Exotic nuclei are known to exhibit new phenomena:**

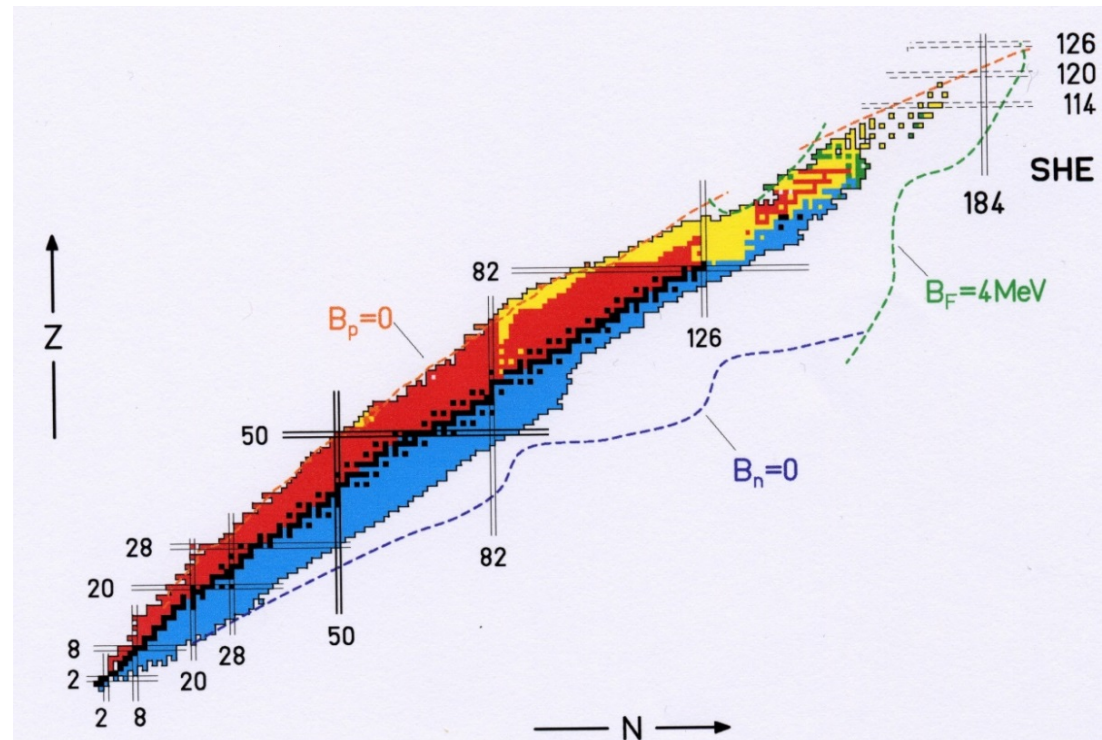
skin/halos, changes of shell structure, new decay modes (particle emissions), shape coexistence...

▣ Many of them lie on the reaction pathways involved in the **production of the chemical elements** in the Universe

▣ Information of great interest for both **Nuclear Structure and Astrophysics**

▣  **$\beta$ -decay spectroscopy with implanted Radioactive Ion Beams:**

Powerful tool to study the structure of **proton-rich nuclei**



# $\beta$ -decay transition strengths

▣  $\beta$ -decay spectroscopy provides a direct access to the absolute values of the  $\beta$ -decay strengths

$$B(F) \propto \left| \langle \psi_f^* | \tau | \psi_i \rangle \right|^2$$

Fermi ( $\Delta S = 0$ )

$$B(GT) \propto \left| \langle \psi_f^* | \sigma \tau | \psi_i \rangle \right|^2$$

Gamow Teller ( $\Delta S = 1$ )

▣ Measured in  $\beta$ -decay experiments

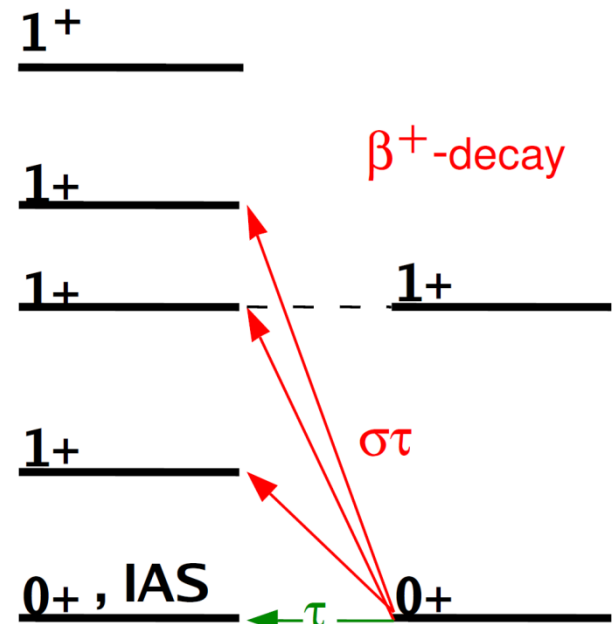
Beta feeding to states  
in the daughter nucleus

$$B_j(GT)^\beta = \frac{K}{\lambda^2} \frac{I_\beta^j(E_j)}{f(Q_\beta - E_j, Z) T_{1/2}}$$

$\lambda = g_A/g_V$

Parent half-life

$$B(F)^\beta = K \frac{I_\beta(E)}{f(Q_\beta - E, Z) T_{1/2}}$$



$T_Z=0$

$T_Z=-1$

▣ Advantage: absolute normalization of the strength

# Charge Exchange (CE) reactions

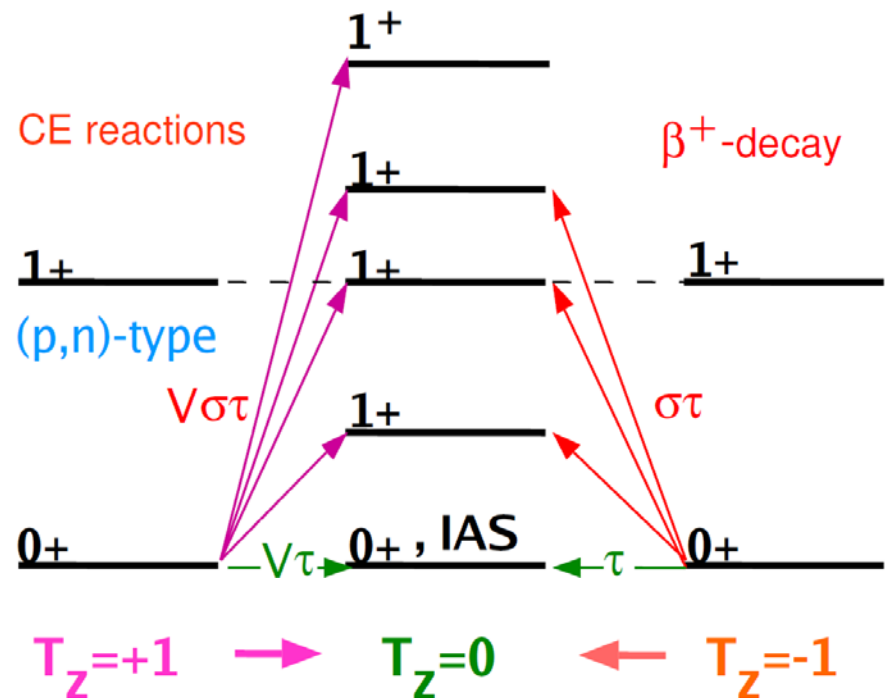
Complementary **(p,n)-type CE reactions**, which are the mirror strong interaction process, also provide information on the  $\beta$ -decay transition strengths

- The CE cross section measured at  $0^\circ$  is proportional to the  $\beta$ -decay strengths (relative values)

$$\left. \frac{d\sigma_{GT}^{CE}}{d\Omega}(0^\circ) \right|_j \cong \hat{\sigma}_{GT}(0^\circ) B_j(GT)$$

$$\frac{d\sigma_F^{CE}}{d\Omega}(0^\circ) \cong \hat{\sigma}_F(0^\circ) B(F)$$

*T.N. Taddeucci et al., NPA 469 (1987) 125-172*



- Advantage: highly excited states can be accessed



# $\beta$ -decay of proton-rich nuclei

Series of experiments aiming at the comparison between  **$\beta$  decay in proton-rich nuclei** and **Charge Exchange (CE) reactions** on the stable mirror target

## Experiments @ GANIL and RIKEN

New and rich spectroscopic information:

$T_{1/2}$ ,  $B_p$ ,  $I_p$ ,  $I_\gamma$ ,  $I_\beta$ ,  $E_X$ , decay schemes,  $B(F)$ ,  $B(GT)$ , mass excesses

  **$^{56}\text{Zn}$** : 1<sup>st</sup> observation of  $\beta$ -delayed  $\gamma$ -proton decay

Orrigo+, PRL 112, 222501 (2014)

  $\beta$ -decay of  $^{48}\text{Fe}$  and  $^{52}\text{Ni}$

Orrigo+, PRC 93, 044336 (2016)

  **$^{52}\text{Co}$** : 1<sup>st</sup> observation of the 2<sup>+</sup> isomer ( $T_{1/2} = 102_6$  ms)

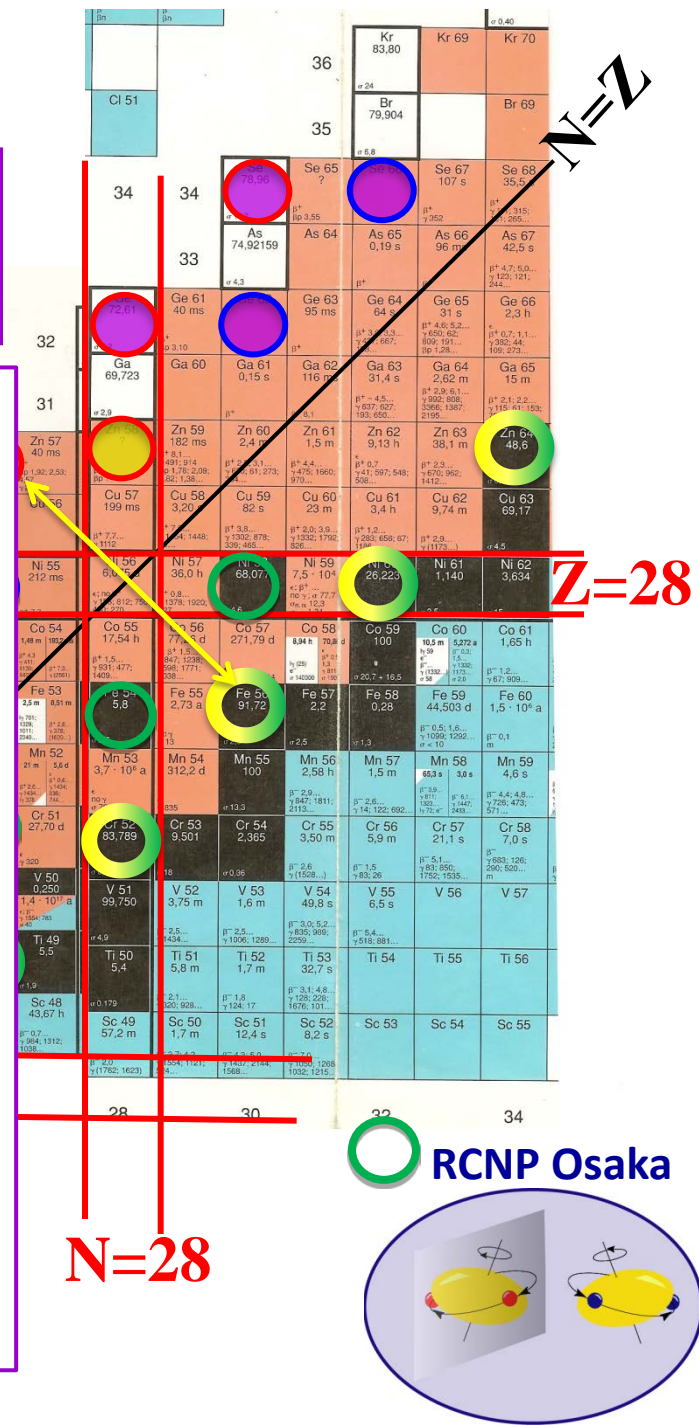
Orrigo+, PRC 94, 044315 (2016)

  **$^{58}\text{Zn}$**  and  $T_{1/2}$  of 16 nuclei with  $T_z = -1, -1/2$

Kucuk, Orrigo+, EPJA 53, 134 (2017)

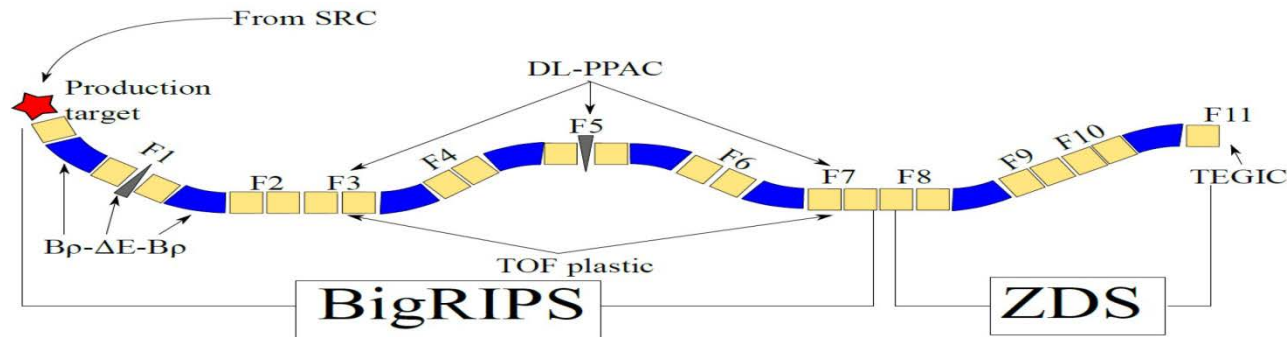
  $\beta$ -decay of  $^{60}\text{Ge}$  and  $^{62}\text{Ge}$

Orrigo+, PRC 103, 014324 (2021)



# $\beta$ -decay of $^{60}\text{Ge}$ and $^{62}\text{Ge}$ @RIKEN

- RIBF@RIKEN**: Primary beam of  $^{78}\text{Kr}$  @345 AMeV fragmented on a 5-mm  $^9\text{Be}$  target
- Separation, selection and identification of the exotic fragments in the **BigRIPS** separator



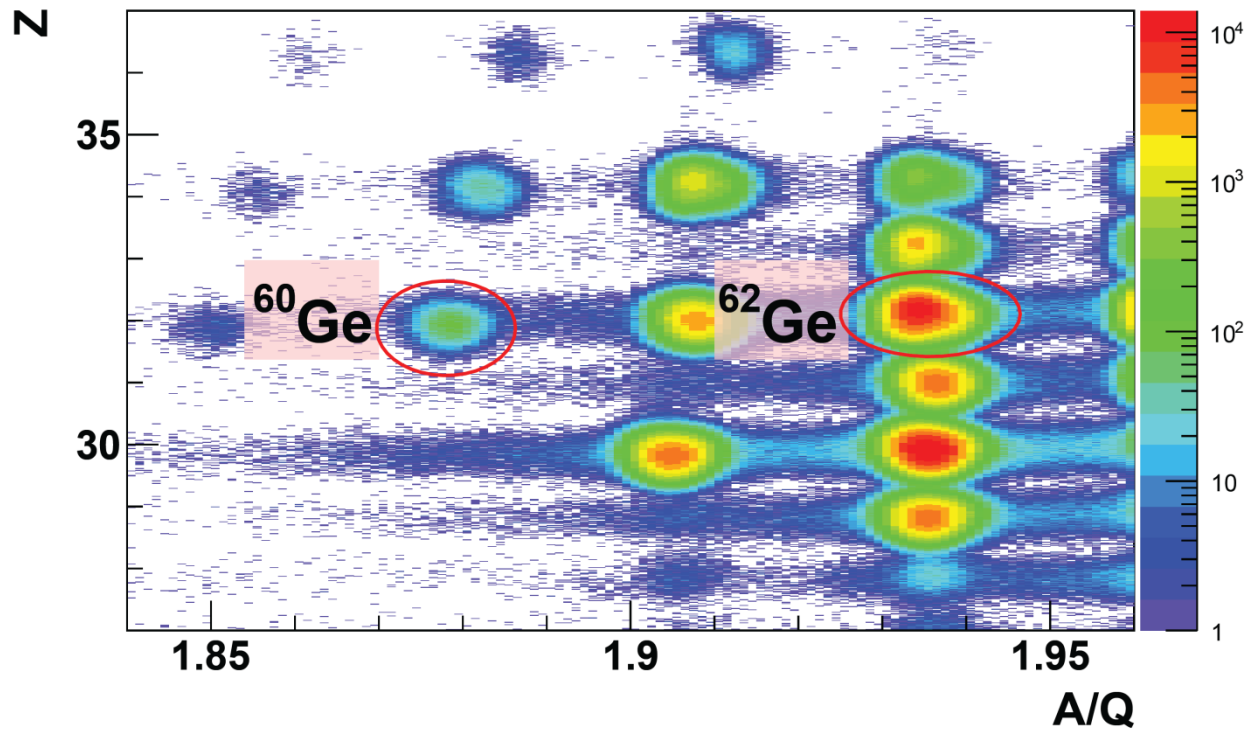
- WAS3ABi** detects both implanted fragments and subsequent charged-particle ( $\beta$  and protons) decays
- The **EURICA** cluster array detects both prompt and  $\beta$ -delayed  $\gamma$  rays



# $\beta$ -decay of $^{60}\text{Ge}$ and $^{62}\text{Ge}$ @RIKEN

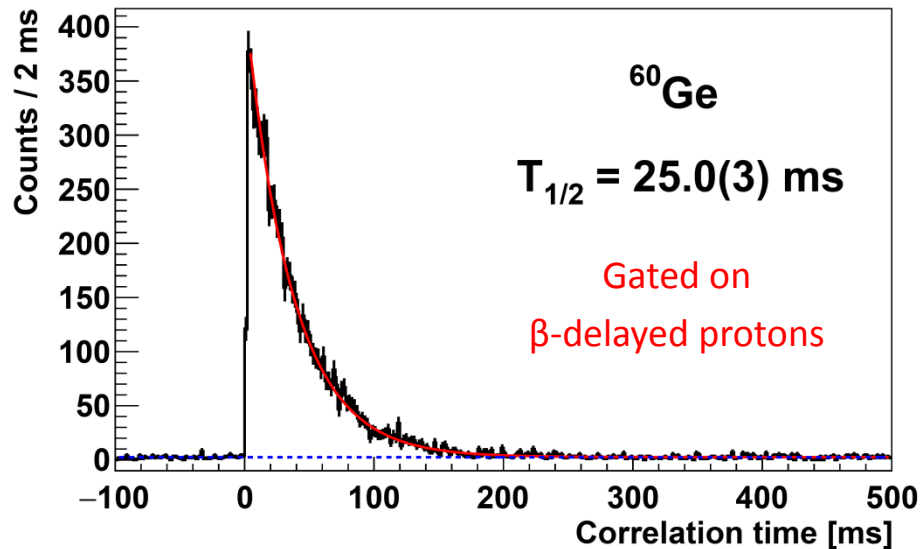
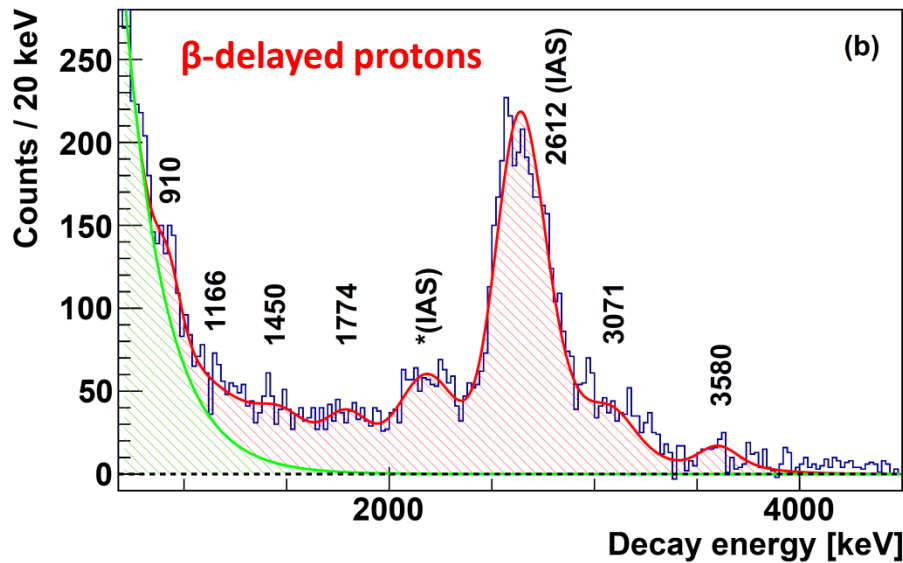
■ The RIKEN high-intensity (up to 250 pnA)  $^{78}\text{Kr}$  beam allowed us to achieve unprecedented statistics:

- $^{60}\text{Ge}$  implants =  $1.5 \times 10^4$
- $^{62}\text{Ge}$  implants =  $2.1 \times 10^6$



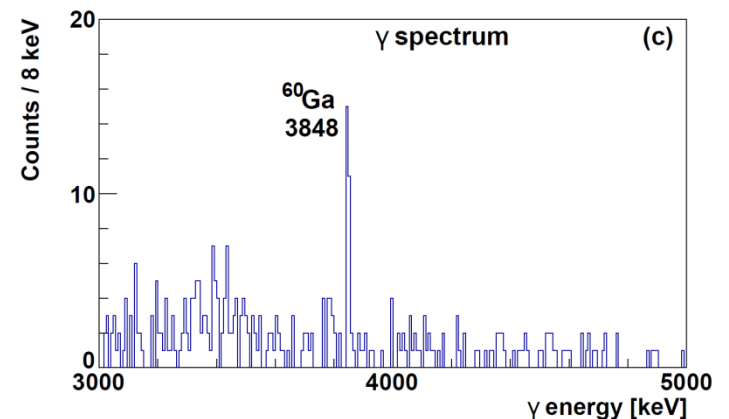
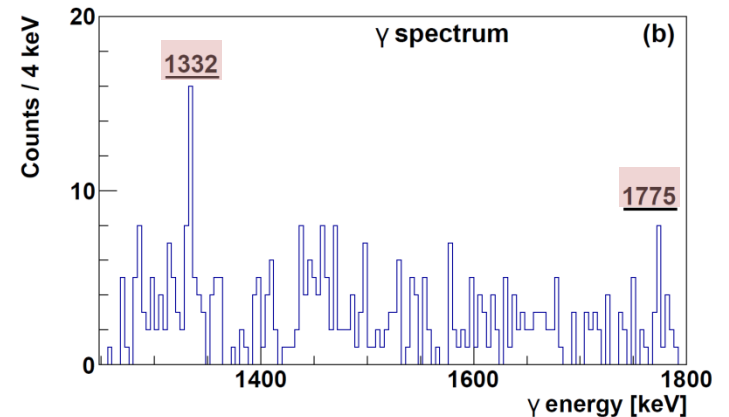
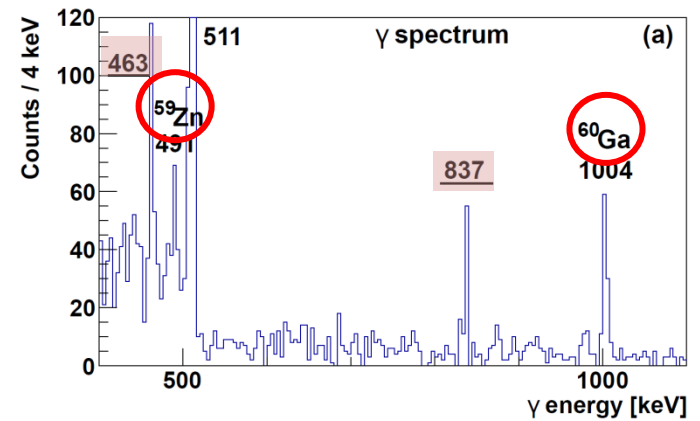
*S.E.A. Orrigo et al., Phys. Rev. C 103, 014324 (2021)*

# $\beta$ decay of $^{60}\text{Ge}$



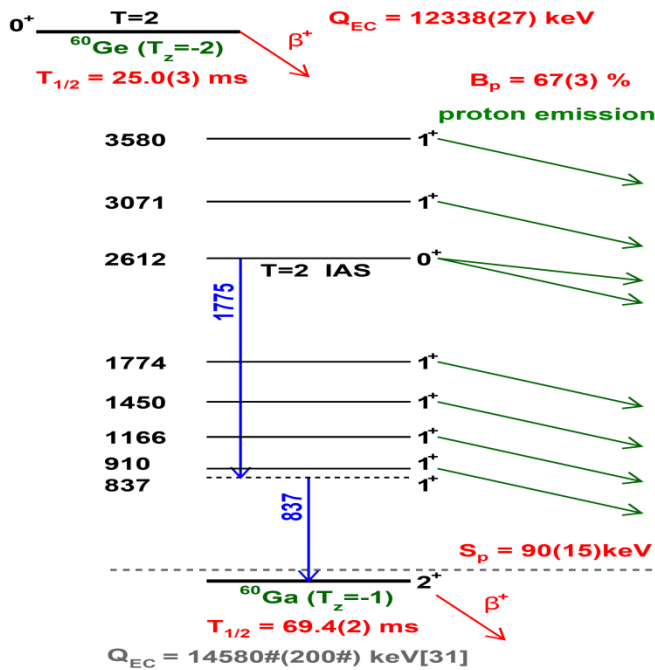
S.E.A. Orrigo et al., Phys. Rev. C 103, 014324 (2021)

## $\beta$ -delayed $\gamma$ rays

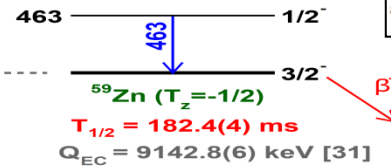




# $\beta$ decay of $^{60}\text{Ge}$



$S_p = 2836.8(7) \text{ keV} [31]$



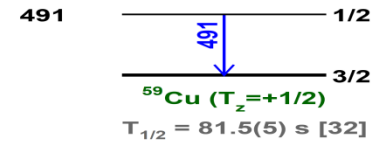
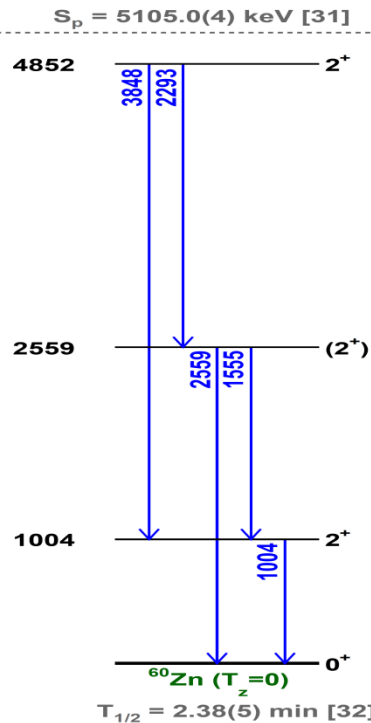
$E_X \text{ (keV)}$	$I_\beta \text{ (%)}$	$B(F)$	$B(GT)$
3580(27)	1.9(2)		0.14(1)
3071(28)	3.2(3)		0.18(2)
2611.8(9) <sup>a</sup>	45.3(20)	3.1(1)	
1774(23)	4.2(3)		0.11(1)
1450(25)	5.1(4)		0.11(1)
1166(28)	4.0(5)		0.074(9)
910(20)	2.8(4)		0.044(6)
837.2(2)	7(2)		0.11(3)

<sup>a</sup>IAS.

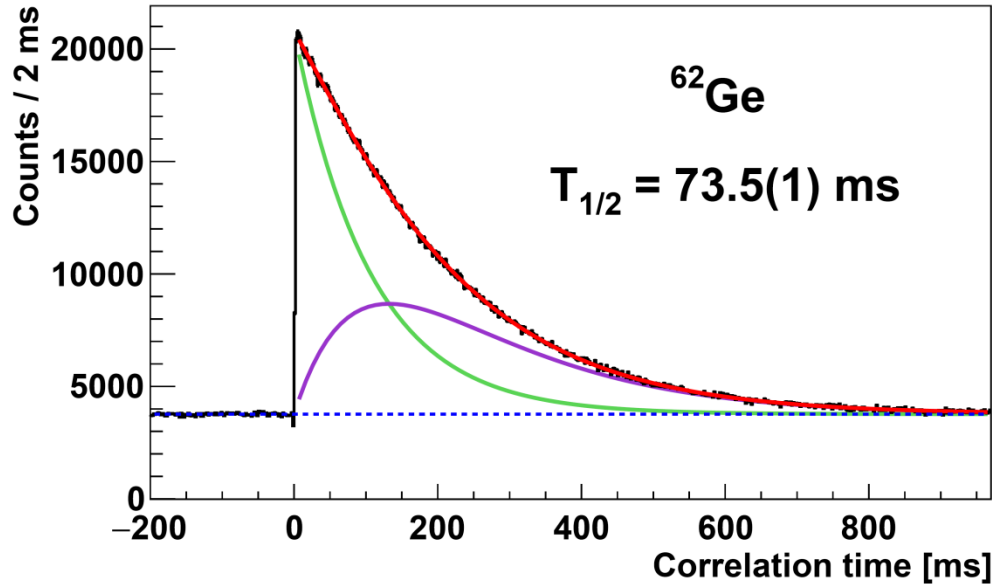


$^{60}\text{Ga}$

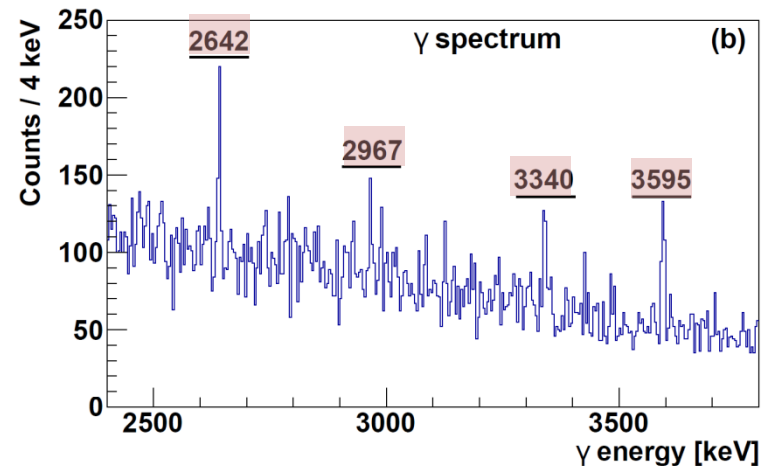
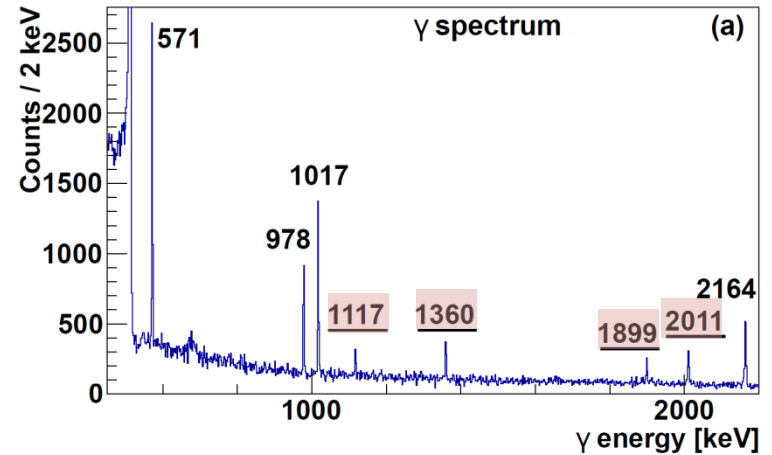
Nucleus at the p-dripline  
 New decay scheme:  
 totally unknown before



# $\beta$ decay of $^{62}\text{Ge}$

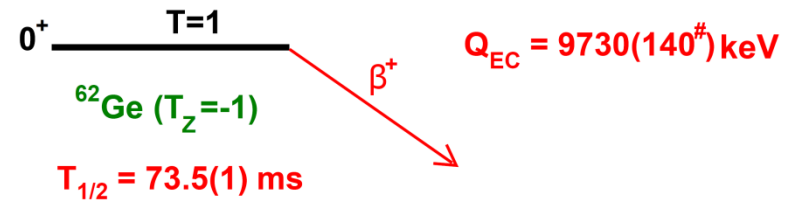


## $\beta$ -delayed $\gamma$ rays



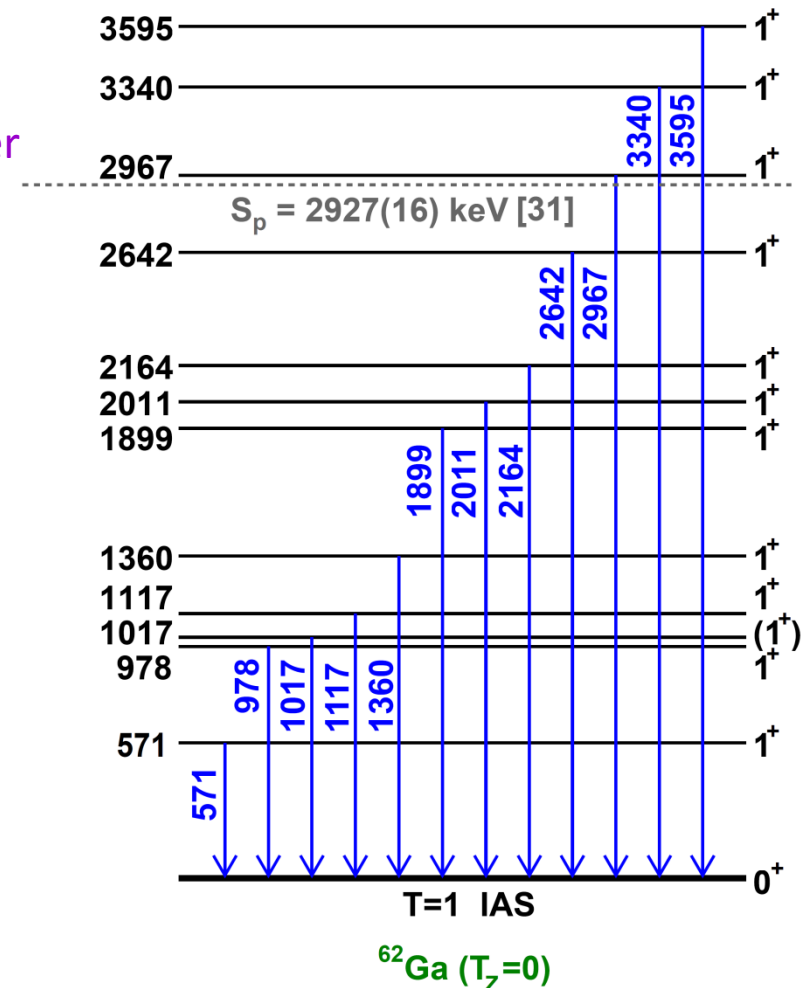
*S.E.A. Orrigo et al., Phys. Rev. C 103, 014324 (2021)*

# $\beta$ decay of $^{62}\text{Ge}$



■ No  $1^+ \rightarrow 1^+$  transitions  $\Rightarrow$   
 confirmed the *quasi-rule* of Warburton and Weneser  
 (suppression of M1 isoscalar transitions between  
 $J^\pi = 1^+, T = 0$  states)

■ No evidence of enhanced low-lying Gamow-Teller  
 strength in  $^{62}\text{Ga}$  due to isoscalar p-n pairing  
 [E. Grodner et al., PRL 113, 092501 (2014)]



$E_\gamma$ (keV)	$I_\gamma$ (%)	$E_X$ (keV)	$I_\beta$ (%)	$B(F)$	$B(GT)$
3594.7(5)	0.6(1)	3594.7(5)	0.6(1)		0.07(1)
3339.6(5)	0.30(6)	3339.6(5)	0.30(6)		0.030(7)
2966.8(5)	0.35(6)	2966.8(5)	0.35(6)		0.028(5)
2641.8(5)	0.4(1)	2641.8(5)	0.4(1)		0.029(7)
2164.1(4)	2.6(2)	2164.1(4)	2.6(2)		0.13(1)
2010.9(4)	0.96(8)	2010.9(4)	0.96(8)		0.045(5)
1899.3(4)	0.58(6)	1899.3(4)	0.58(6)		0.025(3)
1359.7(2)	0.70(5)	1359.7(2)	0.70(5)		0.022(2)
1117.4(2)	0.41(4)	1117.4(2)	0.41(4)		0.011(2)
1017.1(1)	2.6(1)	1017.1(1)	2.6(1)		0.067(6)
978.3(1)	1.8(1)	978.3(1)	1.8(1)		0.047(4)
571.3(1)	3.4(1)	571.3(1)	3.4(1)		0.068(6)
		g.s. <sup>a</sup>	85.3(3) <sup>b</sup>	2.0	

<sup>a</sup>IAS.  
<sup>b</sup>The ground state-to-ground state feeding is  $I_\beta^{\text{IAS}} = (100 - \sum_i I_\gamma^i)$ .

S.E.A. Orrigo et al., Phys. Rev. C 103, 014324 (2021)

# Summary

## $\beta$ decay of very neutron-deficient nuclei @RIKEN

- Measured  $T_{1/2}$  with improved precision:

$^{60}\text{Ge}$  25.0(3) ms,  $^{60}\text{Ga}$  69.4(2) ms,  $^{62}\text{Ge}$  73.5(1) ms

## $T_z = -2$ $^{60}\text{Ge}$

- Mainly  $\beta$ -delayed proton emission,  $B_p = 67(3)\%$ , populating  $^{59}\text{Zn}$
- $\beta$ -delayed  $\gamma$ -emission in competition, observed 3 new  $\gamma$ -rays
- $^{59}\text{Zn}$ : 1<sup>st</sup> observation of the 1<sup>st</sup> excited state, determined  $E_x = 463.3(1)$  keV

## $T_z = -1$ $^{62}\text{Ge}$

- Mainly direct population of the  $^{62}\text{Ga}$  g.s. [g.s. to g.s. feeding of 85.3(3)%]
- 12  $\gamma$ -rays (8 of them for the 1<sup>st</sup> time)
- The suppression of isoscalar  $1^+ \rightarrow 1^+$  transitions is confirmed (*quasi-rule*)
- The negligible role of  $T = 0$  p-n pairing condensate in  $A = 62$  is confirmed

*Thank you for your attention!*