

CGS17

In-beam y-ray spectroscopy of ⁹⁴Ag

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Isospin

Observation of similar behaviour of p and n under the nuclear force

Charge symmetry

$$V_{np} = \frac{V_{pp} + V_{nn}}{2}$$

$$V_{pp} = V_{nn}$$

Isospin: p and n considered states of the same particle (*nucleon*) with different projections of the isospin quantum number t_z . The total isospin projection T_z of a nucleus will be:

$$T_z = \sum_{z=1}^{A} t_z = \frac{N - Z}{2}$$

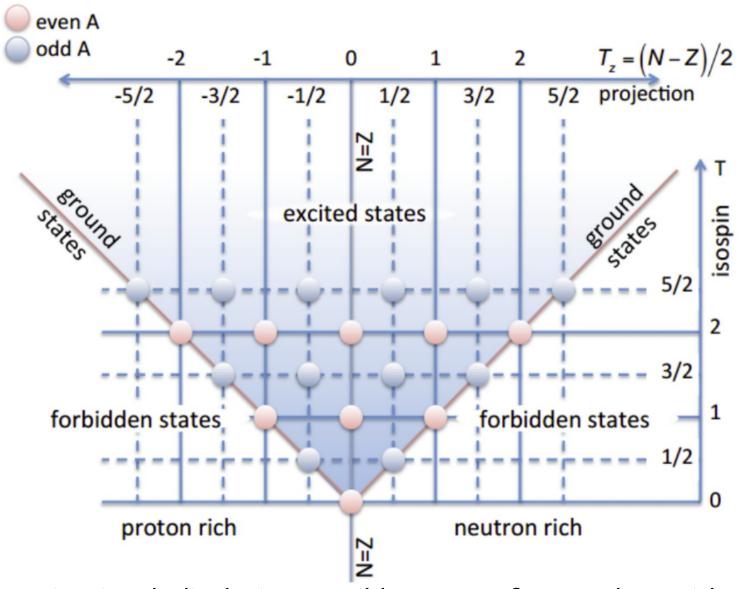
Hence, a nucleus can occupy states with a total isospin T values given by:

$$\frac{|N-Z|}{2} \leqslant T \leqslant \frac{|N+Z|}{2}$$





Bentley isospin triangle



Bentley Isospin triangle displaying possible T states for a nucleus with a given T_z



Isospin symmetry

Isospin-symmetry-breaking probes include:

- Mirror energy differences (MED)
- Triplet energy differences (TED)
- Coulomb energy differences (CED)

(MED)													⁹¹ Pd	⁹² Pd	⁹³ Pd	94 Pd	⁹⁵ Pd	96 Pd	⁹⁷ Pd	⁹⁸ Pd	⁹⁹ Pd	¹⁰⁰ Pd	10
⁸⁹ Rh														91Rh	92 Rh	93 Rh	94 Rh	95 Rh	96 Rh	⁹⁷ Rh	98 Rh	⁹⁹ Rh	10
,_											87 Ru		l	90 Ru	91Ru	92 Ru		94 Ru	95 Ru		⁹⁷ Ru		
	ΓΕ	D								85 Tc	⁸⁶ Tc	87 Tc	⁸⁸ Tc	⁸⁹ Tc	⁹⁰ Tc	⁹¹ Tc	⁹² Tc	⁹³ Tc	94 Tc	⁹⁵ Tc	⁹⁶ Tc	⁹⁷ Tc	91
									⁸³ Mo		⁸⁵ Mo		⁸⁷ Mo	⁸⁸ Mo	⁸⁹ Mo	⁹⁰ Mo		⁹² Mo				⁹⁶ Mo	
- (CED)								⁸¹ Nb	⁸² Nb	⁸³ Nb	84 Nb			87 Nb			90 Nb	91Nb	92 Nb		94 Nb	NU	96
•								⁸⁰ Zr	81Zr	⁸² Zr	83 Zr	84 Zr	⁸⁵ Zr	86 Zr	⁸⁷ Zr	⁸⁸ Zr	⁸⁹ Zr	⁹⁰ Zr	91Zr	⁹² Zr	⁹³ Zr	⁹⁴ Zr	9.0
					⁷⁶ Y	77 Y	⁷⁸ Y	⁷⁹ Y	⁸⁰ Y	81 Y	82 Y	83 Y	84 Y	85 Y	⁸⁶ Y	87 Y	⁸⁸ Y	89 Y	90 Y	⁹¹ Y	⁹² Y	93 Y	9.
			⁷³ Sr	⁷⁴ Sr	⁷⁵ Sr	⁷⁶ Sr	77 S r	⁷⁸ Sr	⁷⁹ Sr	⁸⁰ Sr	81Sr	82 Sr	⁸³ Sr	84 Sr	⁸⁵ Sr		⁸⁷ Sr		⁸⁹ Sr	90 S r	91Sr	⁹² Sr	9.
			72 Rb	73 Rb	74 Rb	75 Rb	76 Rb	⁷⁷ Rb	78 Rb		⁸⁰ Rb	81Rb		⁸³ Rb		⁸⁵ Rb		⁸⁷ Rb	⁸⁸ Rb	⁸⁹ Rb	90 Rb	91Rb	92
	⁶⁹ Kr	⁷⁰ Kr	⁷¹ Kr	⁷² Kr	⁷³ Kr	⁷⁴ Kr	™Kr	76 Kr	⁷⁷ Kr	⁷⁸ Kr	79 Kr	80 Kr	⁸¹ Kr	⁸² Kr	⁸³ Kr	84 Kr	⁸⁵ Kr	⁸⁶ Kr	⁸⁷ Kr	⁸⁸ Kr	⁸⁹ Kr	90 Kr	9
	⁶⁸ Br	⁶⁹ Br	⁷⁰ Br	⁷¹ Br	⁷² Br	⁷³ Br	⁷⁴ Br	⁷⁵ Br	⁷⁶ Br	⁷⁷ Br	⁷⁸ Br	⁷⁹ Br	⁸⁰ Br	⁸¹ Br	⁸² Br	⁸³ Br	⁸⁴ Br	⁸⁵ Br	⁸⁶ Br	⁸⁷ Br	⁸⁸ Br	⁸⁹ Br	9
⁶ Se	⁶⁷ Se	⁶⁸ Se	⁶⁹ Se	⁷⁰ Se	⁷¹ Se	⁷² Se	⁷³ Se	™Se	⁷⁵ Se	⁷⁶ Se	⁷⁷ Se	⁷⁸ Se	⁷⁹ Se	⁸⁰ Se	81Se	⁸² Se	⁸³ Se	84 Se	⁸⁵ Se	⁸⁶ Se	⁸⁷ Se	⁸⁸ Se	89
³⁵ As	⁶⁶ As	⁶⁷ As	⁶⁸ As	⁶⁹ As	⁷⁰ As	⁷¹ As	⁷² As	⁷³ As	⁷⁴ As	⁷⁵ As	⁷⁶ As	⁷⁷ As	⁷⁸ As	⁷⁹ As	⁸⁰ As	⁸¹ As	⁸² As	⁸³ As	⁸⁴ As	⁸⁵ As	⁸⁶ As	⁸⁷ As	8
⁴Ge	⁶⁵ Ge	⁶⁶ Ge	⁶⁷ Ge	⁶⁸ Ge	69 Ge	⁷⁰ Ge	71 Ge	⁷² Ge	⁷³ Ge	™Ge	⁷⁵ Ge	⁷⁶ Ge	77 Ge	⁷⁸ Ge	⁷⁹ Ge	80 Ge	81 Ge	82 Ge	83 Ge	84 Ge	⁸⁵ Ge	⁸⁶ Ge	87
³Ga	⁶⁴ Ga	⁶⁵ Ga	⁶⁶ Ga	⁶⁷ Ga	68 Ga	⁶⁹ Ga	™Ga	71Ga	⁷² Ga	⁷³ Ga	⁷⁴ Ga	⁷⁵ Ga	⁷⁶ Ga	⁷⁷ Ga	⁷⁸ Ga	⁷⁹ Ga	⁸⁰ Ga	⁸¹ Ga	⁸² Ga	⁸³ Ga	84 Ga	⁸⁵ Ga	86
² Zn	⁶³ Zn	⁶⁴ Zn	⁶⁵ Zn	⁶⁶ Zn	⁶⁷ Zn	⁶⁸ Zn	⁶⁹ Zn	⁷⁰ Zn	71 Zn	⁷² Zn	⁷³ Zn	74 Zn	⁷⁸ Zn	⁷⁶ Zn	⁷⁷ Zn	⁷⁸ Zn	⁷⁹ Zn	⁸⁰ Zn	⁸¹ Zn	⁸² Zn	⁸³ Zn	⁸⁴ Zn	85
¹Cu	⁶² Cu	⁶³ Cu	⁶⁴ Cu	⁶⁵ Cu	⁶⁶ Cu	⁶⁷ Cu	68 Cu	⁶⁹ Cu	⁷⁰ Cu	71 Cu	⁷² Cu	⁷³ Cu	⁷⁴ Cu	⁷⁵ Cu	⁷⁶ Cu	⁷⁷ Cu	⁷⁸ Cu	⁷⁹ Cu	⁸⁰ Cu	⁸¹ Cu	⁸² Cu		
Ni Ni	⁶¹ Ni	⁶² Ni	⁶³ Ni	⁶⁴ Ni	⁶⁵ Ni	⁶⁶ Ni	⁶⁷ Ni	⁶⁸ Ni	⁶⁹ Ni	⁷⁰ Ni	71 Ni	⁷² Ni	⁷³ Ni	⁷⁴ Ni	⁷⁵ Ni	⁷⁶ Ni	⁷⁷ Ni	⁷⁸ Ni	⁷⁹ Ni				
⁹ Со	⁶⁰ Co	⁶¹ Co	⁶² Co	⁶³ Co	64 Co	⁶⁵ Co	⁶⁶ Co	⁶⁷ Co	⁶⁸ Co	⁶⁹ Co	⁷⁰ Co	⁷¹ Со	⁷² Co	⁷³ Co	™Co	⁷⁵ Co	⁷⁶ Co						
[®] Fe	⁵⁹ Fe	⁶⁰ Fe	⁶¹ Fe	⁶² Fe	⁶³ Fe	64 Fe	65 Fe	⁶⁶ Fe	⁶⁷ Fe	68 Fe	⁶⁹ Fe	⁷⁰ Fe	71 Fe	⁷² Fe	⁷³ Fe	⁷⁴ Fe							
7 Mn	⁵⁸ Mn	⁵⁹ Mn	60 Mn	⁶¹ Mn	⁶² Mn	⁶³ Mn	⁶⁴ Mn	⁶⁵ Mn	66 Mn	⁶⁷ Mn	68 Mn	⁶⁹ Mn	⁷⁰ Mn	⁷¹ Mn									
6Cr	⁵⁷ Cr	58 Cr	⁵⁹ Cr	60 Cr	61Cr	62 Cr	63 Cr	64 Cr	65 Cr	66 Cr	⁶⁷ Cr	68 Cr											
⁵⁵ V	⁵⁶ V	⁵⁷ V	58 V	⁵⁹ V	60 V	⁶¹ V	⁶² V	⁶³ V	64 V	⁶⁵ V	66 V		-										
54 Ti	⁵⁵ Ti	⁵⁶ Ti	57 T i	58 Ti	⁵⁹ Ti	⁶⁰ Ti	⁶¹ Ti	⁶² Ti	⁶³ Ti			-											
3Sc	⁵⁴ Sc	55 Sc	56 Sc	57 Sc	58 Sc	⁵⁹ Sc	60 Sc	61Sc		-													

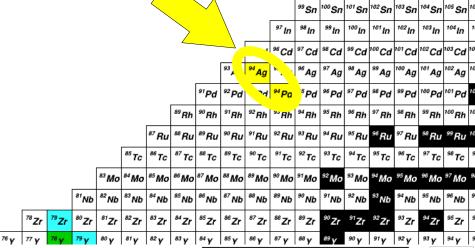


Isospin symmetry

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Regular Article - Experimental Physics

In-beam γ -ray spectroscopy of 94 Ag

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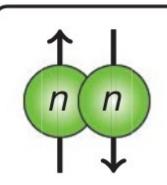
Nucleon pairing

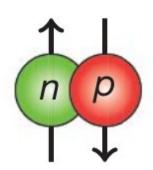
- Like-nucleon pairing (nn and pp) is the dominant pairing correlation.
- In N~Z systems, np pairings are possible.

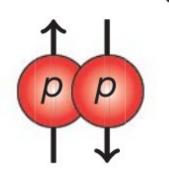
a

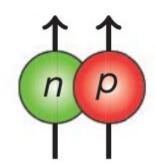
$$T = 1, J = 0$$

b T = 0, J > 0









- Evidence of spin-aligned T=0 np pairing is elusive.
 - Rotational alignment in ⁸⁸Ru
 - Yrast sequence in ⁹²Pd

B. Cederwall et al., Nature 461, (2011) 6871.

- Theory studies suggested similar effect in N=Z A>90 ⁹⁴Ag and ⁹⁶Cd

G.J.Fu, J.J Shen, Y.M. Zhao and A. Arima, PRC 87 (2013) 044312 Z.X.Xu, C. Qi, J. Blomqvist, R.J. Liotta and R. Wyss, Nucl. Phys. A 877 (2012) 51-58 S. Zerquine and P. Van Isacker, PRC 83 (2011) 064314.



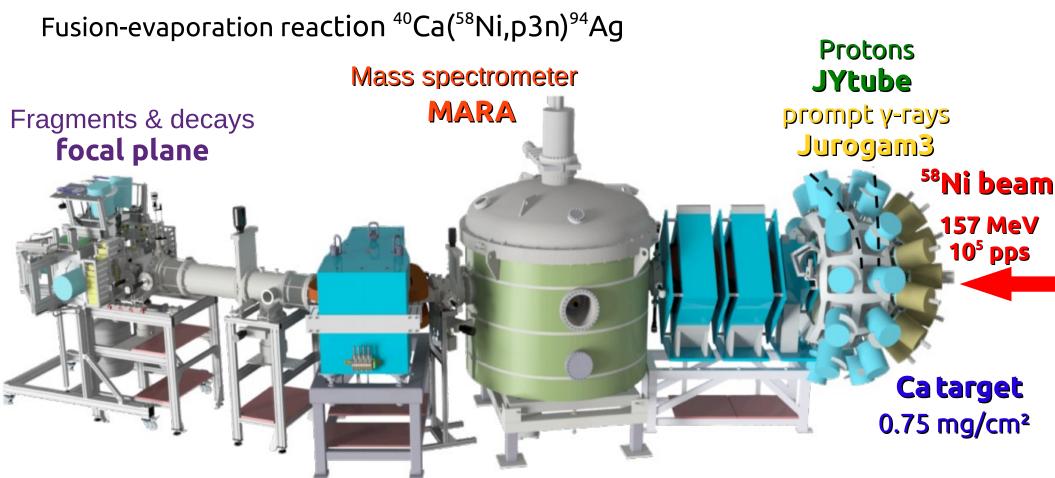
Current knowledge on 94Ag

- Several experimental studies have been focused on ⁹⁴Ag:
 - [1] J. Park et al., PRC 99, 034313 (2019).
 - [2] K. Moschner et al., EPJ web conf. 93, (2015) 01024.
 - [3] M. La Commara et al., Nucl. Phys. A 708 (2002) 167-180.
 - [4] I. Mukha et al., PRC 70 (2004) 044311.
 - [5] I. Mukha et al., PRL 95 (2005) 022501.
 - [6] K. Schmidt et al., Z. Phys. A 350 (1994) 99-100.
 - [7] C. Plettner et al., Nucl. Phys. A 733 (2004) 20-36.
 - [8] E. Roeckl, Int. J. Mod. Phys. E 15, 2 (2006) 368-373.
 - [9] O.L. Pechenaya et al., PRC 76 (2007) 011304(R).
 - [10] T. Kessler et al., Nucl. Instrum. Methods PRB 266 (2008) 4420-4424.
 - [11] A. Kankainen et al., PRL 101 (2008) 142503.
 - [12] K. Kaneko et al., AIP Conference Proceedings 1090 (2009) 611.
 - [13] J. Cerny et al., PRL 103 (2009) 152502.
 - [14] David G. Jenkins, PRC 80 (2009) 054303.
 - [15] I. Mukha et al., arXiv:1008.5346 [nucl-ex] (2009).
 - [16] Mamta Aggarwal, PLB 693 (2010) 489-493.
- However, current knowledge is limited to:
 - 0⁺ ground state, half life of 27(2) ms [1,2]
 - Two isomeric states:
 - (7⁺) [3] half life of 0.50(1) ms [1,4] located at 6.7 MeV [5]. β , β -delayed p and p
 - (21⁺) [3] half life of 0.39(4) ms [4]





Experimental setup

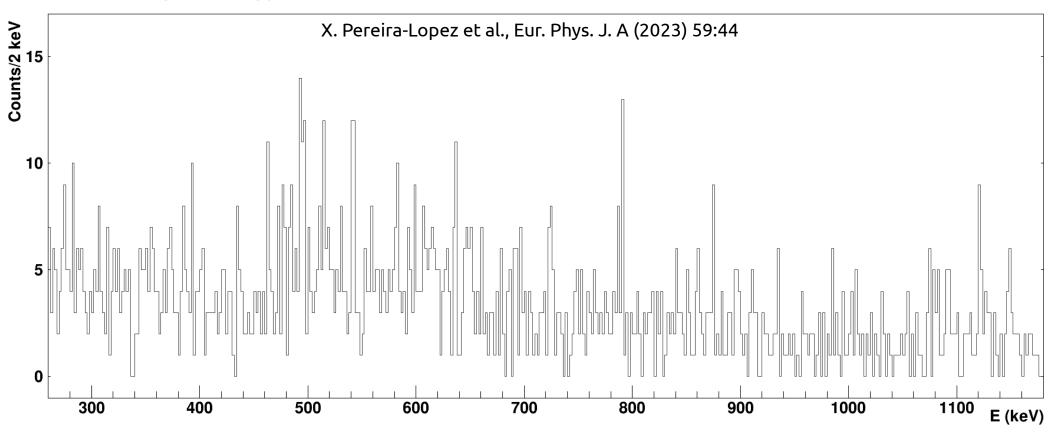


• All detector signals are time stamped to allow temporal correlations.



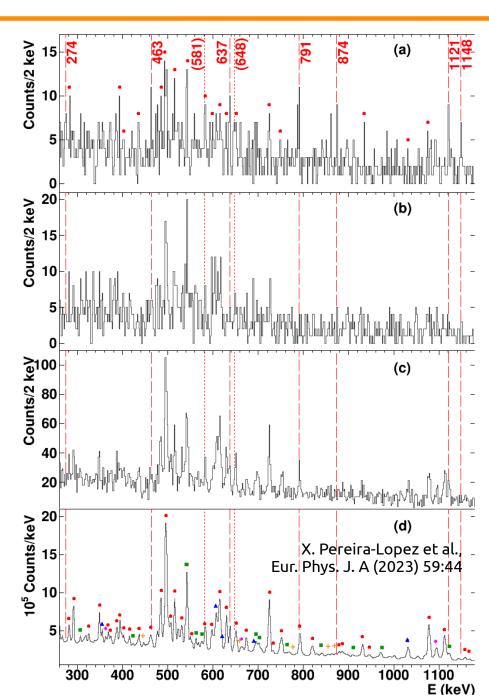


- 94Ag transitions were identified in the Doppler corrected γ-ray spectra for:
 - Prompt emission
 - short-lived A=94 fragments (decay within 60ms)
 - One or less charged particles
 - High energy β (E > 3 MeV)



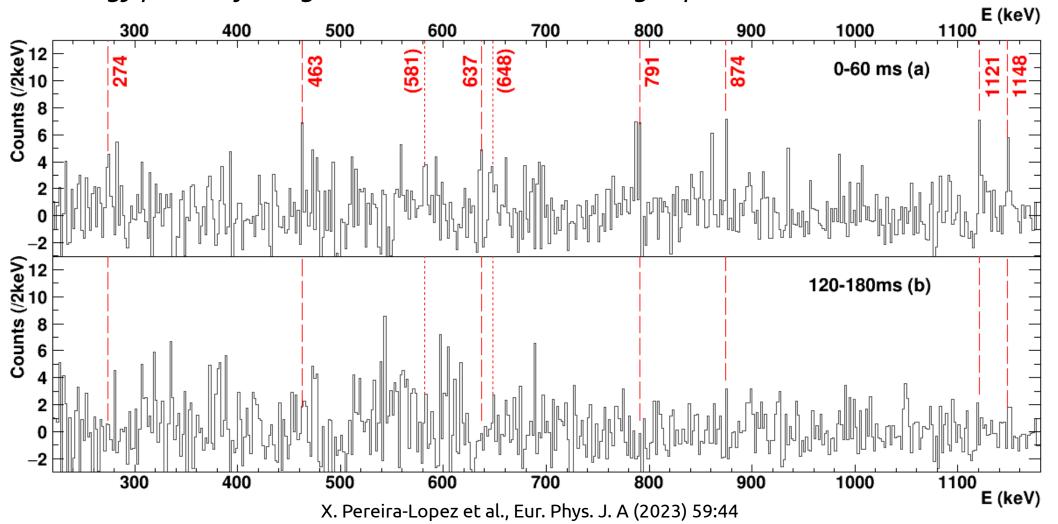


- Comparison with spectra recorded for
 - b) higher charged particle multiplicity
 - c) Longer lived A=94 recoils
 - decay between 120 and 180 ms
 - d) A=94 recoil
- γ-rays at 273, 463, 637, 791, 874, 1121 and 1148 keV seem to grow respect to other A=94 contaminants when gating on the reaction channel leading to ⁹⁴Ag.
 - Most contaminants are ⁹⁴Ru transitions.
 - evidence of ⁹⁴Rh, ⁹⁴Tc and ⁹⁰Mo
 - They come from either:
 - false correlations
 - misidentified p3n events





Background substracted Doppler corrected spectra for prompt γ -rays for A=94 recoils decaying withing 60ms (a) or 120-180ms (b), in coincidence with a high energy β and rejecting events with 2 or more charged particles in JYtube.

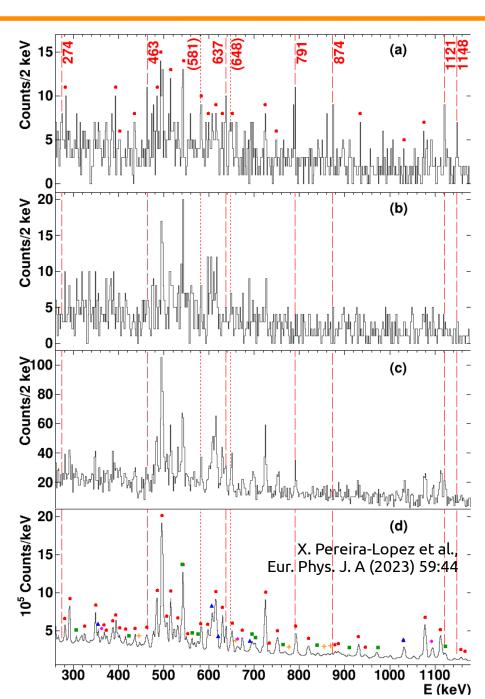




- Comparison with spectra recorded for
 - b) higher charged particle multiplicity
 - c) Longer lived A=94 recoils
 - decay between 120 and 180 ms
 - d) A=94 recoil

γ-rays observed in this work are associated with a short lived A=94 nucleus, produced via one charged particle evaporation channel and whose half-life is consistent with currently accepted value for 94 Ag ground state β -decay.

Not enough statistics for γ-γ analysis.

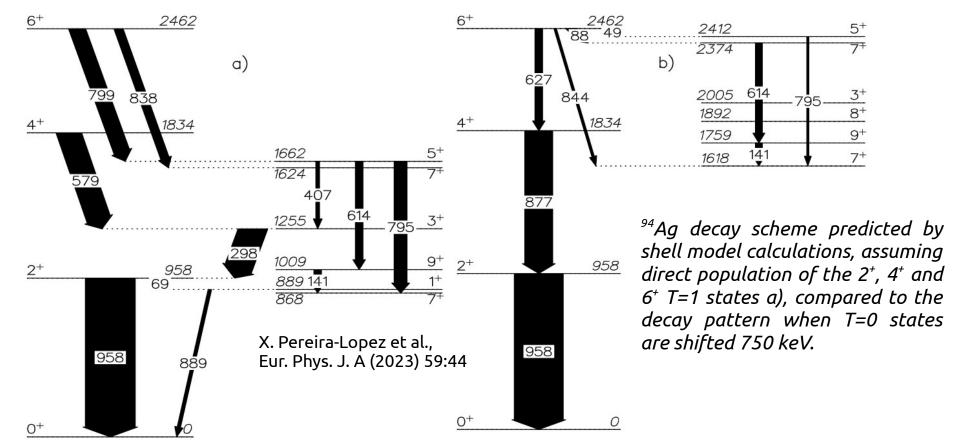




Shell model predictions

- Shell model calculations using JUN45 interaction in the fpg model space.
 - \circ Dominant decay patterns assuming direct population of the 2⁺, 4⁺ and 6⁺ T=1 states
- However, if T=0 lie 750 keV higher, E2 sequence from 6⁺ becomes dominant.
- Location of T=0 strongly influenced by np aligned $g_{9/2}$ matrix element.

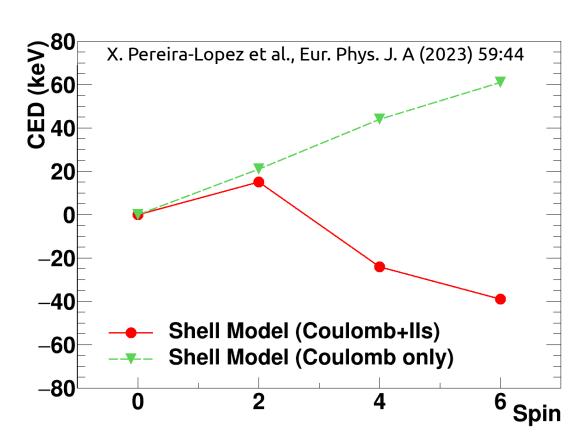
Z.X.Xu, C. Qi, J. Blomqvist, R.J. Liotta and R. Wyss, Nucl. Phys. A 877 (2012) 51-58





CEDs

- Based on comparison with ⁹⁴Pd
 - 791, 874 and 637 keV in ⁹⁴Ag
 tentative analog of
 - 814, 905 and 659 keV in ⁹⁴Pd
- Negative CEDs
 - Observed only for ⁷⁰Br-⁷⁰Se
- Compared to SM calculations
 - decresing trend
 - ∘ ~35 keV shift
- SM cast doubts on this tentative assignment



CEDs as function of J between tentatively assigned T=1 levels in ⁹⁴Ag and analog states in ⁹⁴Pd. **Shell model predictions with and without single particle monopole effects** in red circles and green triangles.



Conclusions

- Seven γ -ray transitions observed are associated with a short lived A=94 nucleus, produced via one charged particle evaporation channel and whose half-life is consistent with accepted value for 94 Ag ground state β -decay.
 - $^{\circ}$ First observation of γ -ray transitions from 94 Ag excited states.
 - Level scheme remains unclear.
- Shell model calculations were presented, showing the separation between T=1 and T=0 strongly influences the decay pattern.
 - Work required to determine the relative position of T=0 and T=1 states.
 - provide insight into the np spin-aligned pairing in this nucleus
- Possible correspondence between observed transitions and analogue states in neighbouring T=1 isobar nucleus ⁹⁴Pd is discussed.
 - Shell model predicted CEDs are presented.



Collaborators

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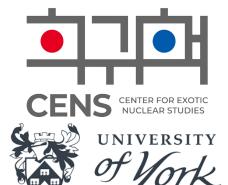
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Regular Article - Experimental Physics

In-beam γ -ray spectroscopy of 94 Ag

- X. Pereira-López^{1,2,a}, M. A. Bentley^{1,b}, R. Wadsworth¹, P. Ruotsalainen³, S. M. Lenzi^{4,5}, U. Forsberg^{1,6},
- K. Auranen³, A. Blazhev⁷, B. Cederwall⁸, T. Grahn³, P. Greenlees³, A. Illana³, D. G. Jenkins¹, R. Julin³, H. Jutila³,
- S. Juutinen³, X. Liu⁸, R. Llewelyn¹, M. Luoma³, K. Moschner⁷, C. Müller-Gatermann^{7,9}, B. S. Nara Singh^{10,11},
- F. Nowacki¹², J. Ojala³, J. Pakarinen³, P. Papadakis¹³, P. Rahkila³, J. Romero^{3,14}, M. Sandzelius³, J. Sarén³,
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