Experiments probing isospin symmetry

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CENTER FOR EXOTIC NUCLEAR STUDIES

Contents

Introduction

Isospin

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

- Charge independence $$V_{np}=\frac{V_{pp}+V_{nn}}{2}$$
- Charge symmetry $$V_{pp}=V_{nn}$$

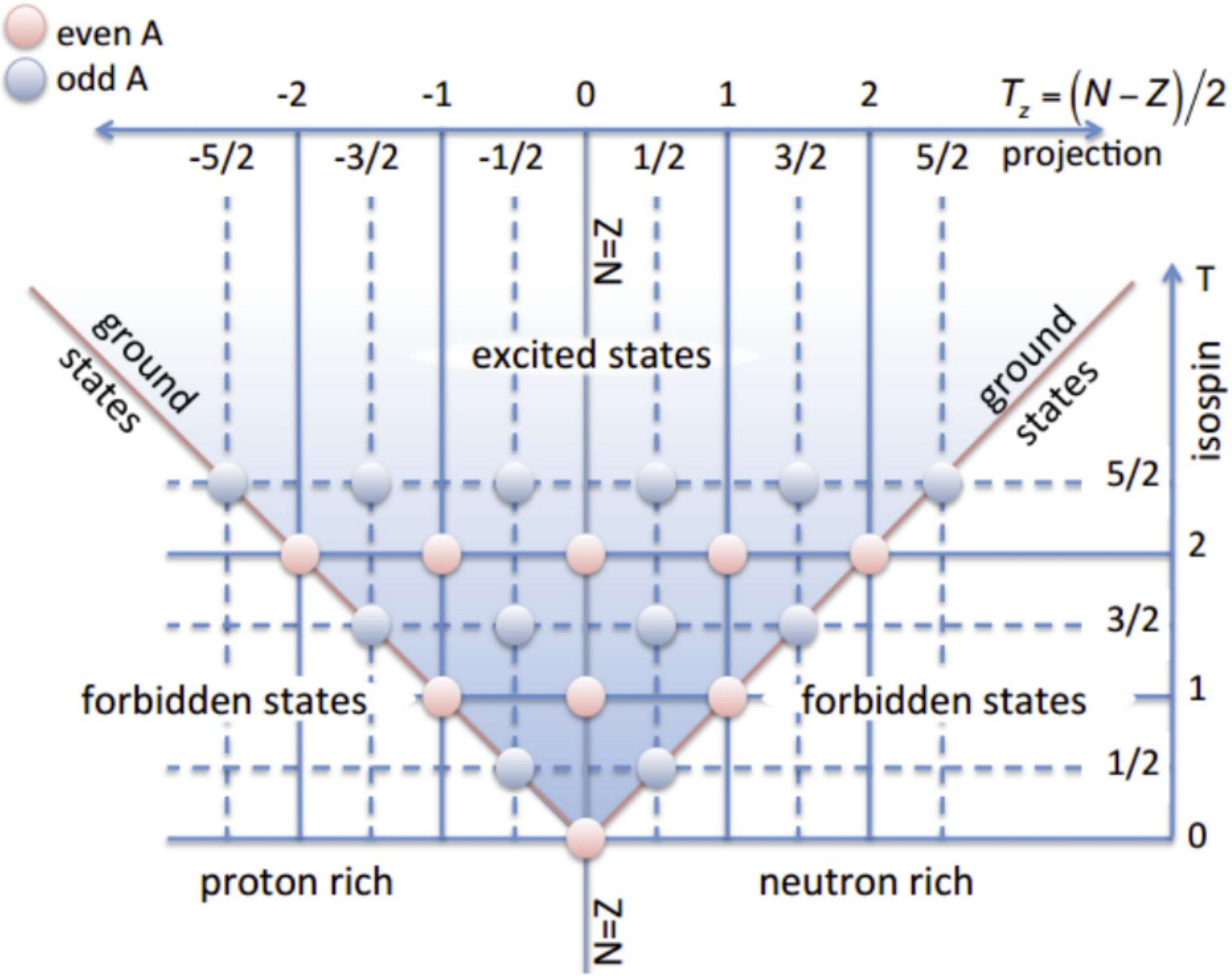
Isospin: p and n considered states of the same particle (*nucleon*) with different projections of the isospin quantum number t_z. The total isospin projection T_z of a nucleus will be:

$$T_z=\sum^{A} t_z=\frac{N-Z}{2}$$

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

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

Isospin

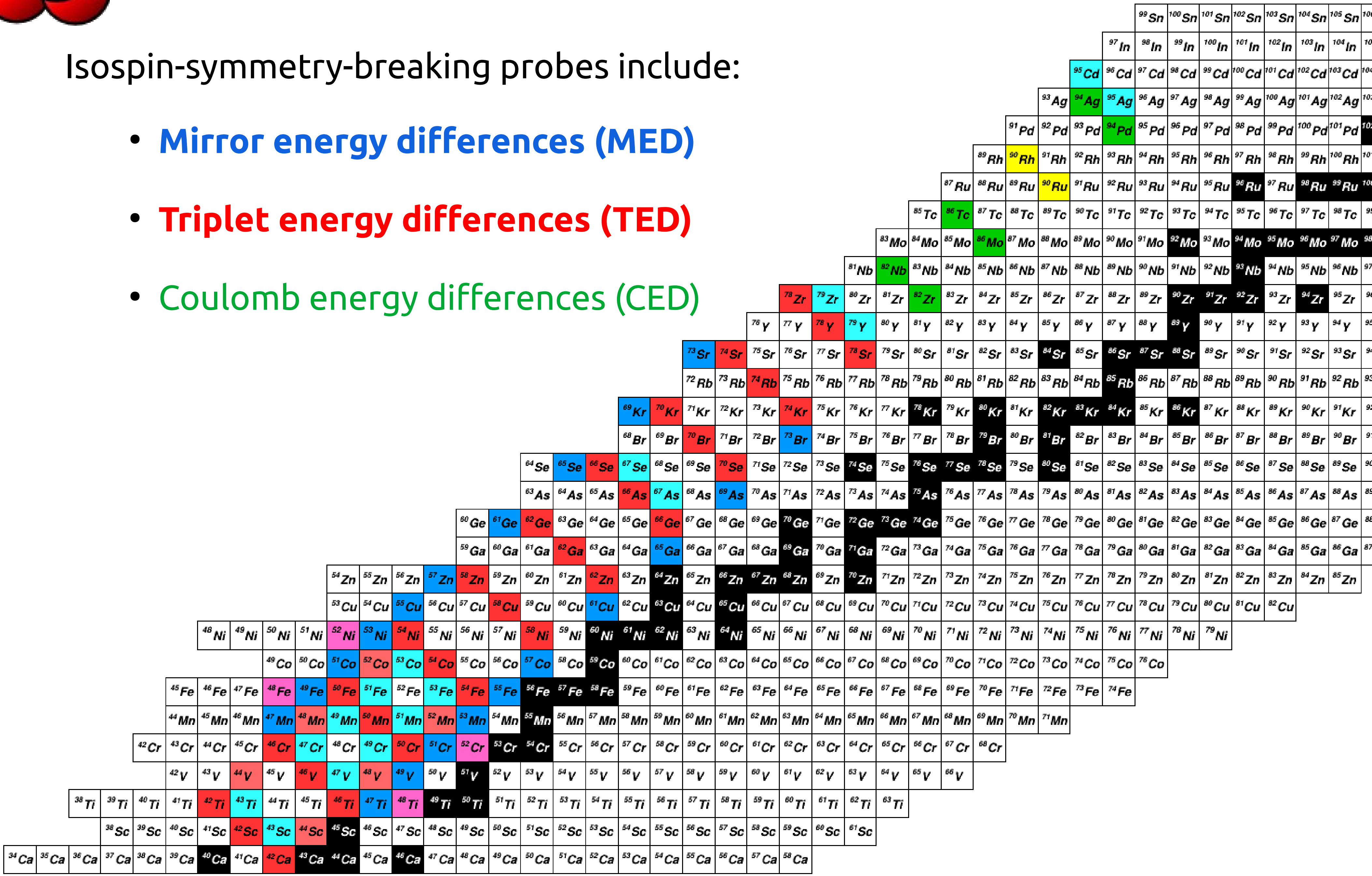


Bentley Isospin triangle displaying possible T states for a nucleus with a given T_z

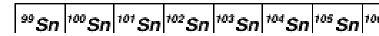
Isospin symmetry

Isospin-symmetry-breaking probes include:

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



Isospin symmetry



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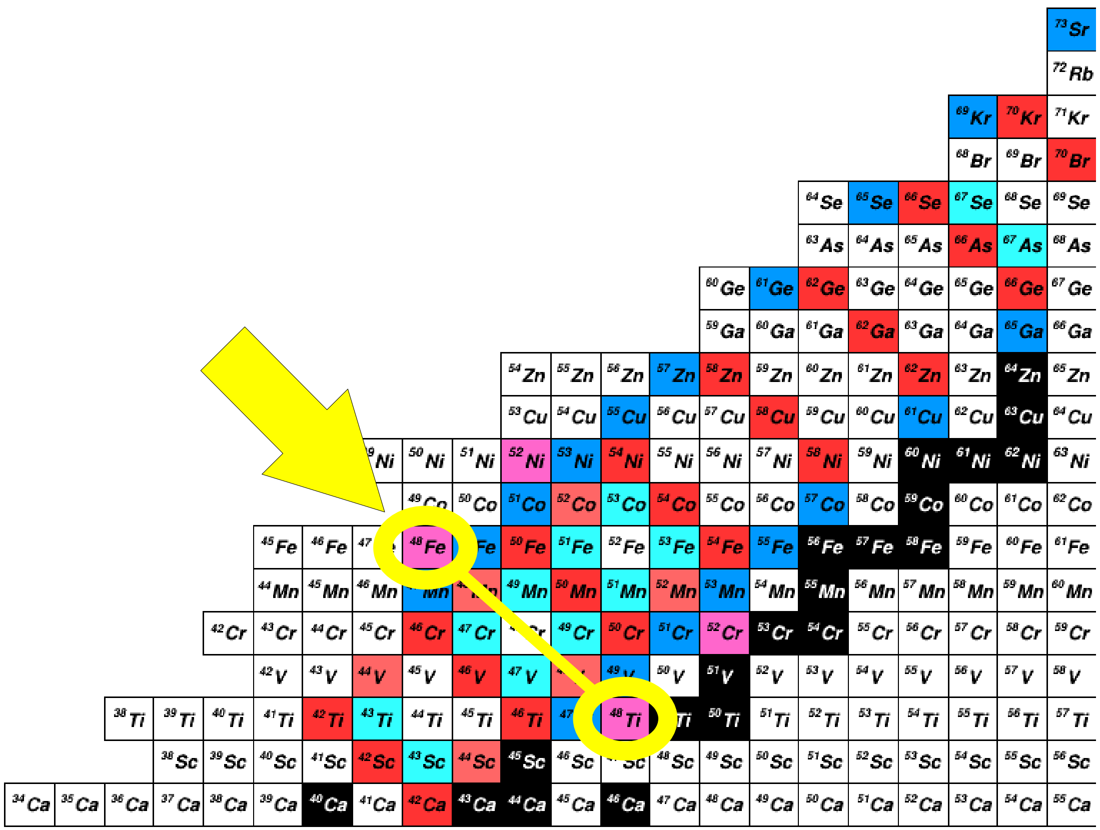

Spectroscopy of the $T = 2$ mirror nuclei ^{48}Fe/^{48}Ti using mirrored knockout reactions.

R. Yajzey[a,b], M. A. Bentley[a], E. C. Simpson[c], T. Haylett[a], S. Uthayakumaar[a], D. Bazin[d,e], J. Belarge[d], P. C. Bender[d], P.J. Davie
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L. Morris[a], D. R. Napoli[g], X. Pereira-Lopez[a], F. Recchia[d,i], J. A. Tostevin[h], R. Wadsworth[a], D. Weisshaar[d]

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[c]Research School of Physics, The Australian National University, Canberra ACT 2600, Australia
[d]National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA
[e]Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA
[f]School of Physics and Astronomy, University of Edinburgh, Edinburgh EH9 3FD, UK
[g]INFN, Laboratori Nazionali di Legnaro, I-35020 Legnaro, Italy
[h]Department of Physics, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom
[i]Dipartimento di Fisica e Astronomia dell'Università and INFN, Sezione di Padova, I-35131 Padova, Italy

Abstract

A sequence of excited states has been established for the first time in the proton-rich nucleus ^{48}Fe (Z=26, N=22). The techniqu mirrored (i.e. analogue) one-nucleon knockout reactions was applied, in which the $T_z = \pm 2$ mirror pair, ^{48}Fe/^{48}Ti were populated one-neutron/one-proton knockout from the secondary beams ^{49}Fe/^{49}V, respectively. The analogue properties of the reactions w used to help establish the new level scheme of ^{48}Fe. The inclusive and exclusive cross sections were determined for the popula states. Large differences between the cross sections for the two mirrored reactions were observed and have been interpreted in te of different degrees of binding of the mirror nuclei and in the context of the recent observations of suppression of spectrosco strength as a function of nuclear binding. Mirror energy differences (MED) have been determined between the analogue T = states and compared with the shell model predictions. MED for this mirror pair, due to their location in the shell, are especi sensitive to excitations out of the $f_{7/2}$ shell, and present a stringent test of the shell-model prescription.

1. Introduction

The attractive strong nuclear force that acts between protons and neutrons is virtually invariant to the charge of the individual nucleons. This yields one of the fundamental concepts in nuclear physics - the concept of isospin and the resulting influence of isospin symmetry in nuclear structure [1, 2]. Isospin enables us to describe two types of fermion, the proton and neutron, as two different states of the nucleon and, in this formalism, all nucleons have isospin quantum number $t = \frac{1}{2}$ with different projections for a proton ($t_z = -\frac{1}{2}$) and for a neutron ($t_z = +\frac{1}{2}$). Moreover, the nucleus has a total isospin projection on the z-axis T_z, and the total isospin of the individual nucleons, denoted by quantum number T, is given by:

$$T_z = \sum t_z = \frac{N-Z}{2} \quad (1)$$

$$\frac{|N-Z|}{2} \leq T \leq \frac{|N+Z|}{2}. \quad (2)$$

In the absence of isospin breaking interactions, states of the same isospin, T, in a set of nuclei of the same mass number (isobaric analogue states, IAS) will be degenerate. Differences in excitation energies of IAS will result from the Coulomb interaction and from any charge-dependent components of the

forces lift the degeneracy of analogue states, break isospin sy metry and may result in isospin mixing of the states in quest (e.g. [3]).

The concept of charge symmetry of the nuclear force quires that the neutron-neutron (V_{nn}) and proton-proton (V interactions are identical, and any interactions where $V_{nn} \neq$ (e.g. arising from the Coulomb force) are known as isovec interactions. The study of mirror nuclei, with exchanged nu bers of neutron and protons, is an immensely powerful met to investigate isovector phenomena and how they relate to clear structure more generally. Differences in excitation en gies between mirror nuclei, known as mirror energy differen (MED), are given by

$$MED_J = E^*_{J,T,-T_z} - E^*_{J,T,+T_z}$$

where E^*_{J,T,T_z} is the excitation energy of a state with spin J, t isospin T, and isospin projection T_z. MED derive entirely fr isovector effects, and there have been extensive studies i MED in the fp shell, coupled to detailed shell-model calcu tions – e.g. [4–9]. The developments of the shell-model cal lations have enabled reliable interpretation of MED in term electromagnetic phenomena, of both multipole and monop origin, which are expected to provide the largest contributio the MED [3]. These studies have yielded detailed informat on the effective isospin non-conserving interactions that br

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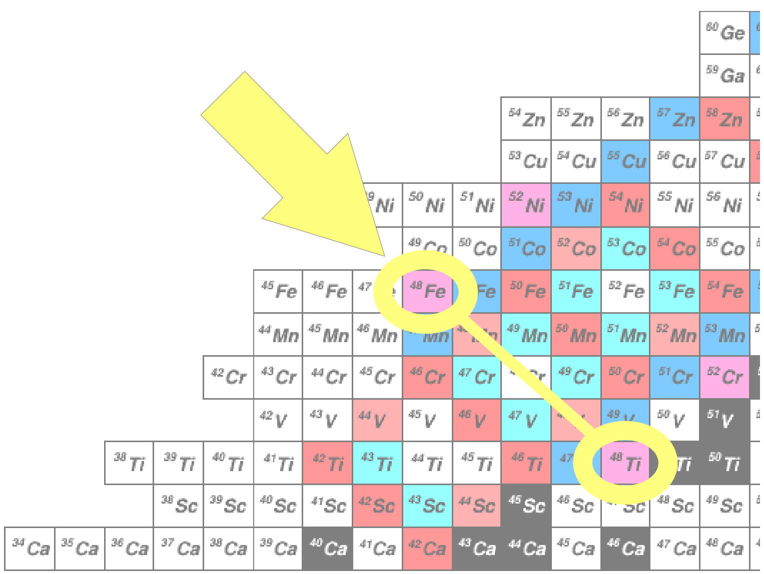
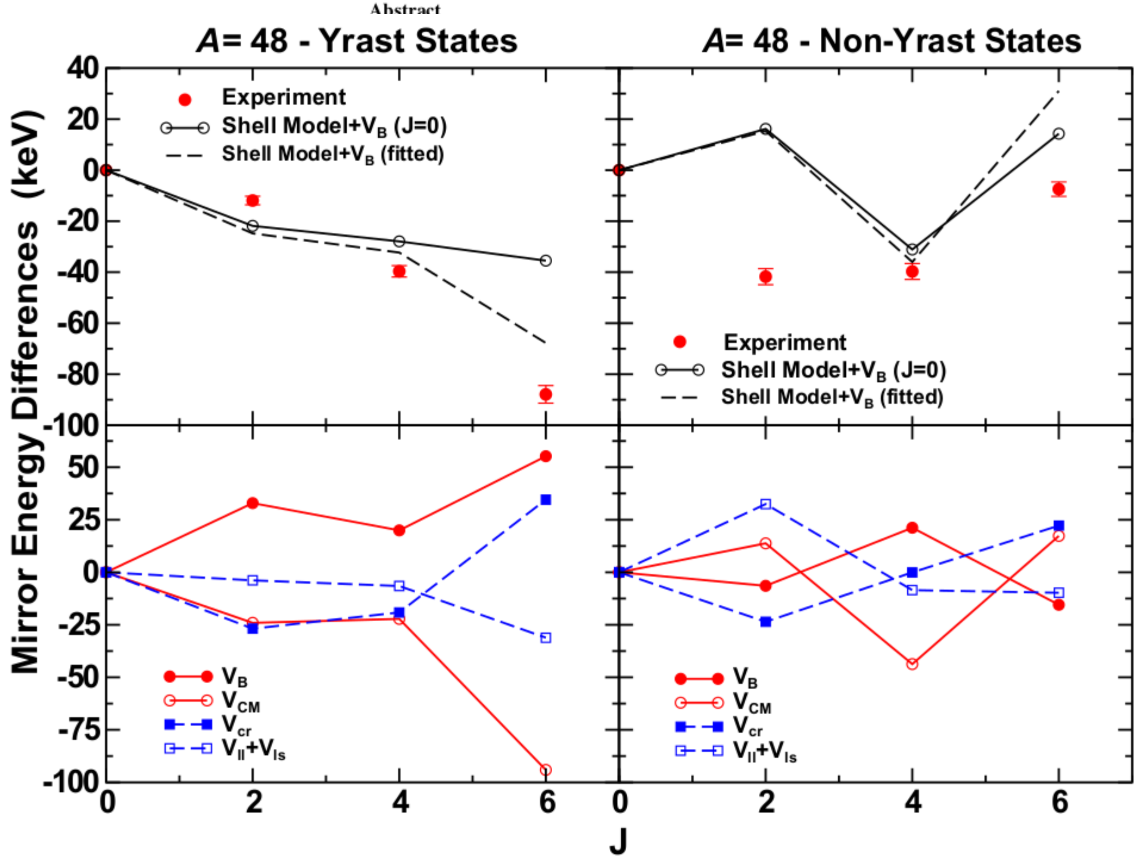
Abstract





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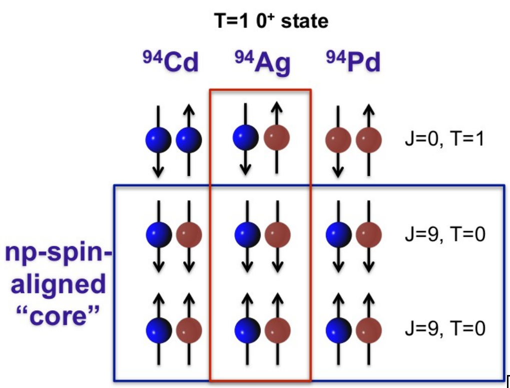

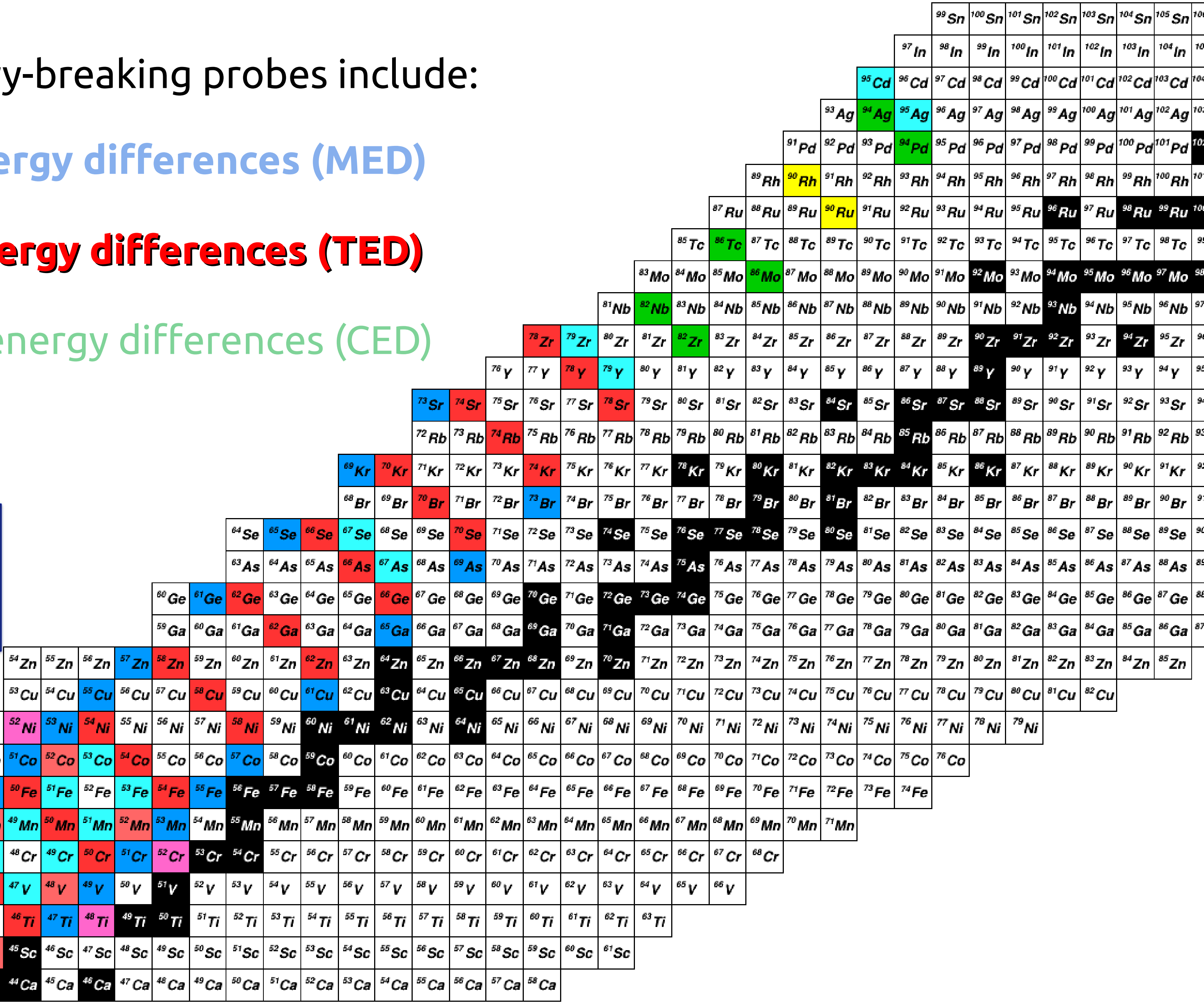

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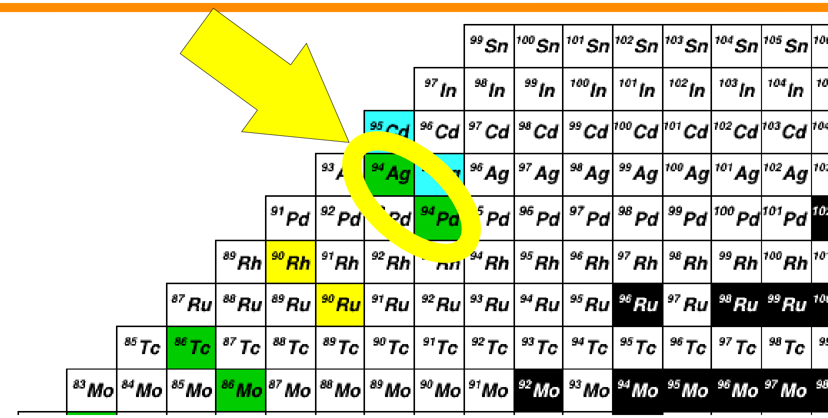

In-beam spectroscopy of excited states of ^{94}Ag

X. Pereira-López[a,b], M.A. Bentley[a], R.Wadsworth[a], S. M. Lenzi[c,e], P. Ruotsalainen[d], U. Forsberg[a,f], H. Badram[d], A. Blazhev[i], T. Calverley[d], B. Cederwall[h], D. Cox[d], T. Grahn[d], P. Greenlees[d], J. Hilton[d], D.G. Jenkins[a], R. Julin[d], S. Juutinen[d], J. Konki[d], M. Leino[d], R. Llewelyn[a], K. Moschner[i], B.S. Nara Singh[g], J. Pakarinen[d], P. Papadakis[d], J. Partanen[d], P. Rahkila[d], M. Sandzelius[d], J. Sarén[d], C. Scholey[d], S. Stolze[d], S. Uthayakumaar[a], J. Uusitalo[d], R. Yajzey[a]

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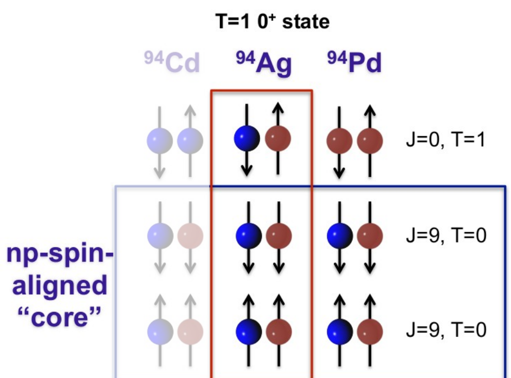
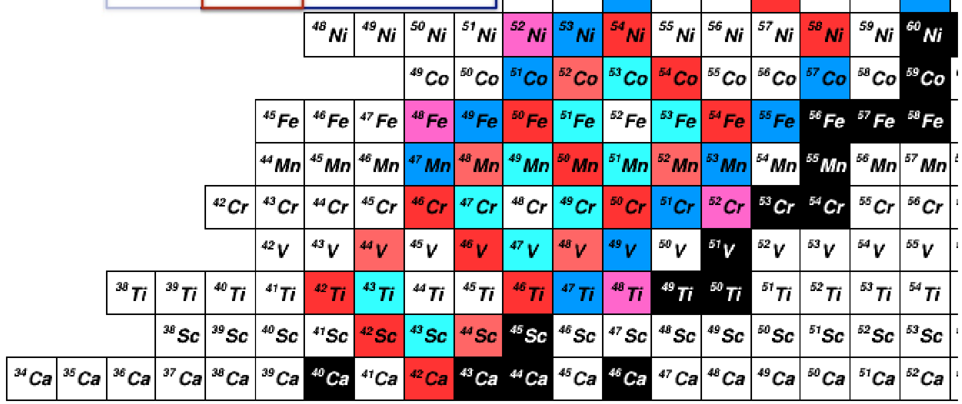
Abstract

A recoil beta tagging experiment has been performed to study the excited $T = 0$ and $T = 1$ states in odd-odd $N = Z$ ^{94}Ag, using the ^{40}Ca(^{58}Ni,p3n)^{94}Ag reaction. The experiment was conducted using the MARA recoil separator and JUROGAM3 array at the Accelerator Laboratory of the University of Jyväskylä. Through correlating fast, high-energy beta decays at the MARA focal plane with prompt γ-rays emitted at the reaction target, a number of transitions between excited states in ^{94}Ag have been identified. The timing characteristics of these transitions confirm that they fall within decay sequences that feed the short-lived $T = 1$ ground state of ^{94}Ag. The transitions are proposed to correspond to decays within, and between, the sets of states with $T = 0$ and $T = 1$. Some of these transitions can be used to suggest, tentatively, through isospin-symmetry arguments, the excitation energies of one or more $T = 1$ states and hence extract Coulomb Energy Differences (CED). Shell-model predictions of CED are presented and compared with the tentative experimental CED value(s).

Keywords:

Introduction - The study of nuclei along the $N = Z$ line affords a unique opportunity to study one of the key underpinning concepts in nuclear physics - the exchange symmetry between at, or near, the ground state, which has properties of a fully paired structure. These are the isobaric analogue of the $T = 1$ ground-state sequences of the neighbouring even-even isobars.



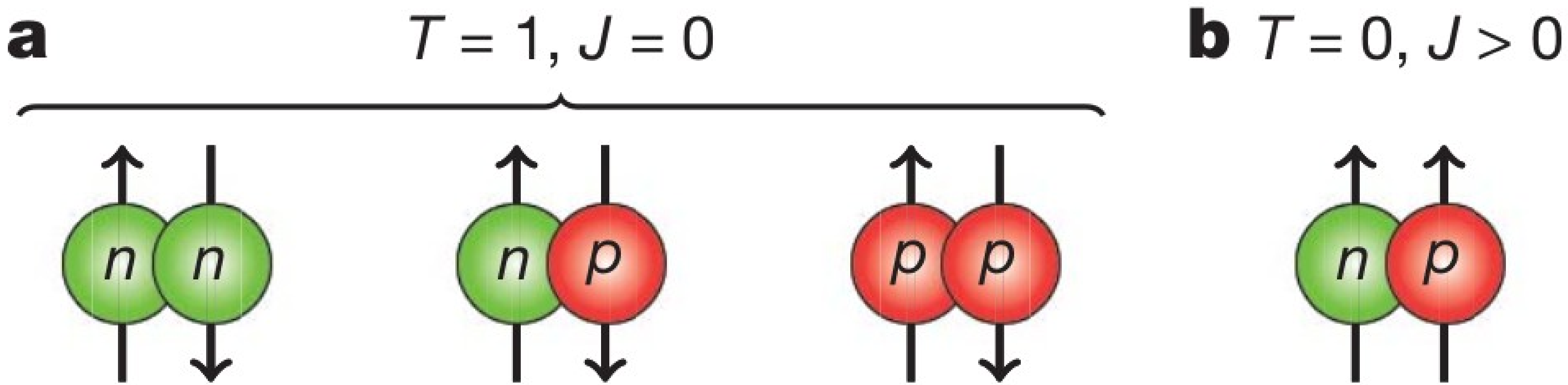


Experiment:

In-beam spectroscopy of ^{94}Ag

Nucleon pairing

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



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

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

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

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. Zerguine and P. Van Isacker, PRC 83 (2011) 064314.

Current knowledge on ^{94}Ag

- Several experimental studies have been focused on ^{94}Ag:

[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

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Experimental setup

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

JYVÄSKYLÄN YLIOPISTO
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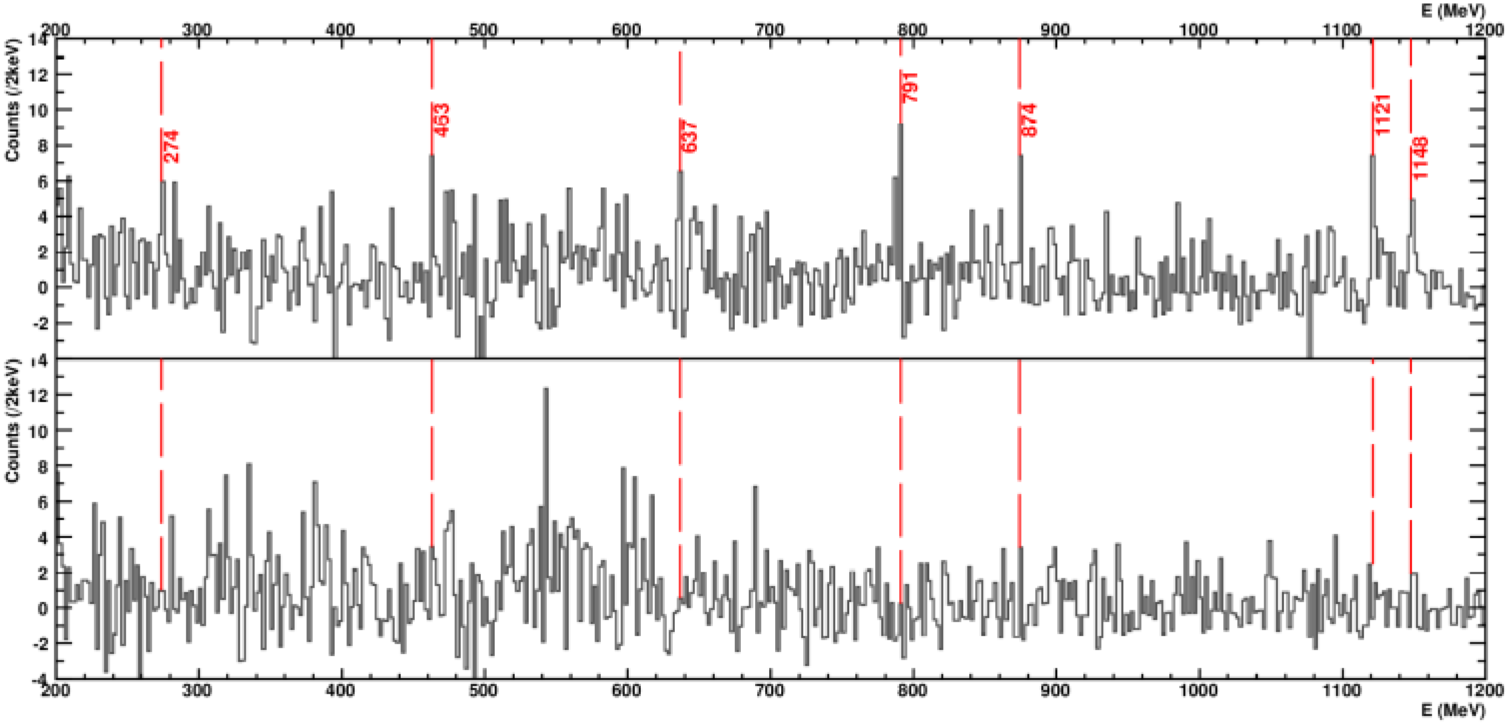
^{94}Ag transitions



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.

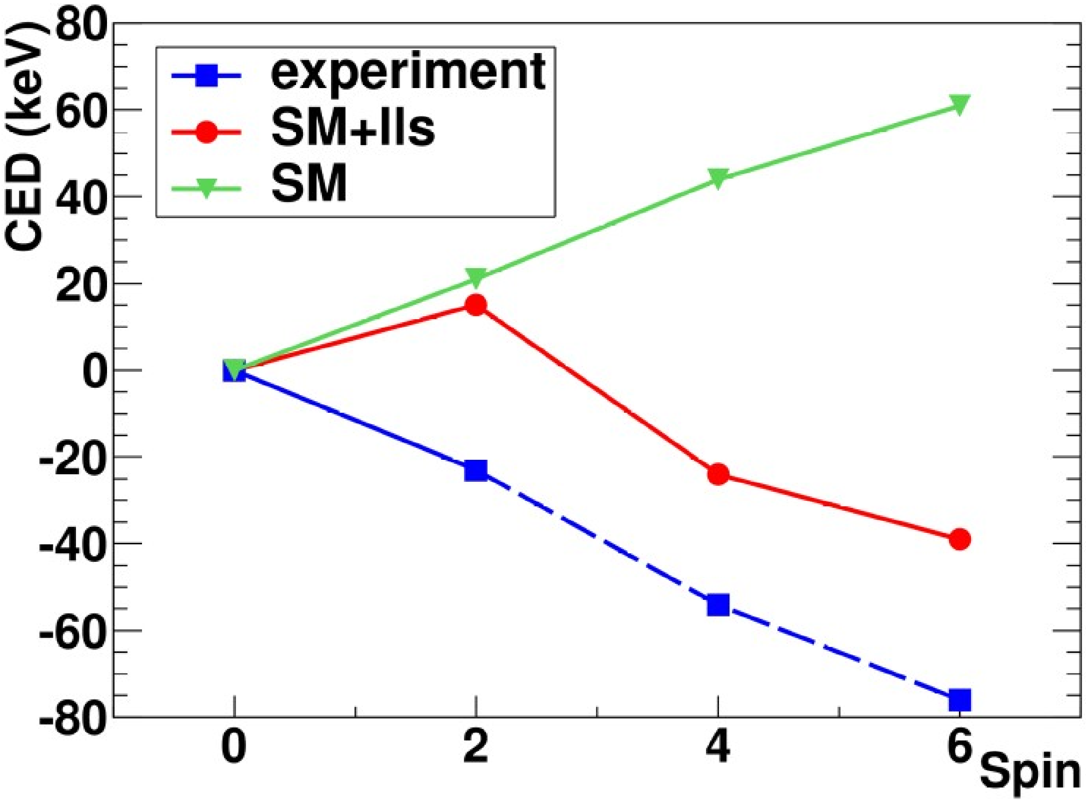
- Most contaminants identified as γ from ^{94}Ru
  - evidence of ^{94}Rh, ^{94}Tc and ^{90}Mo also observed
- They come from either:
  - false correlations
  - misidentified p3n events

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.

CEDs

- γ-γ was not possible.
- Based on comparison with ^{94}Pd
  - 791, 874 and 637 keV in ^{94}Ag

    analog states of
  - 814, 905 and 659 keV in ^{94}Pd
- Negative CEDs
  - Observed only for ^{70}Br-^{70}Se
- Compared to SM calculations
  - JUN45, fpg model space
  - decresing trend
  - ~35 keV shift

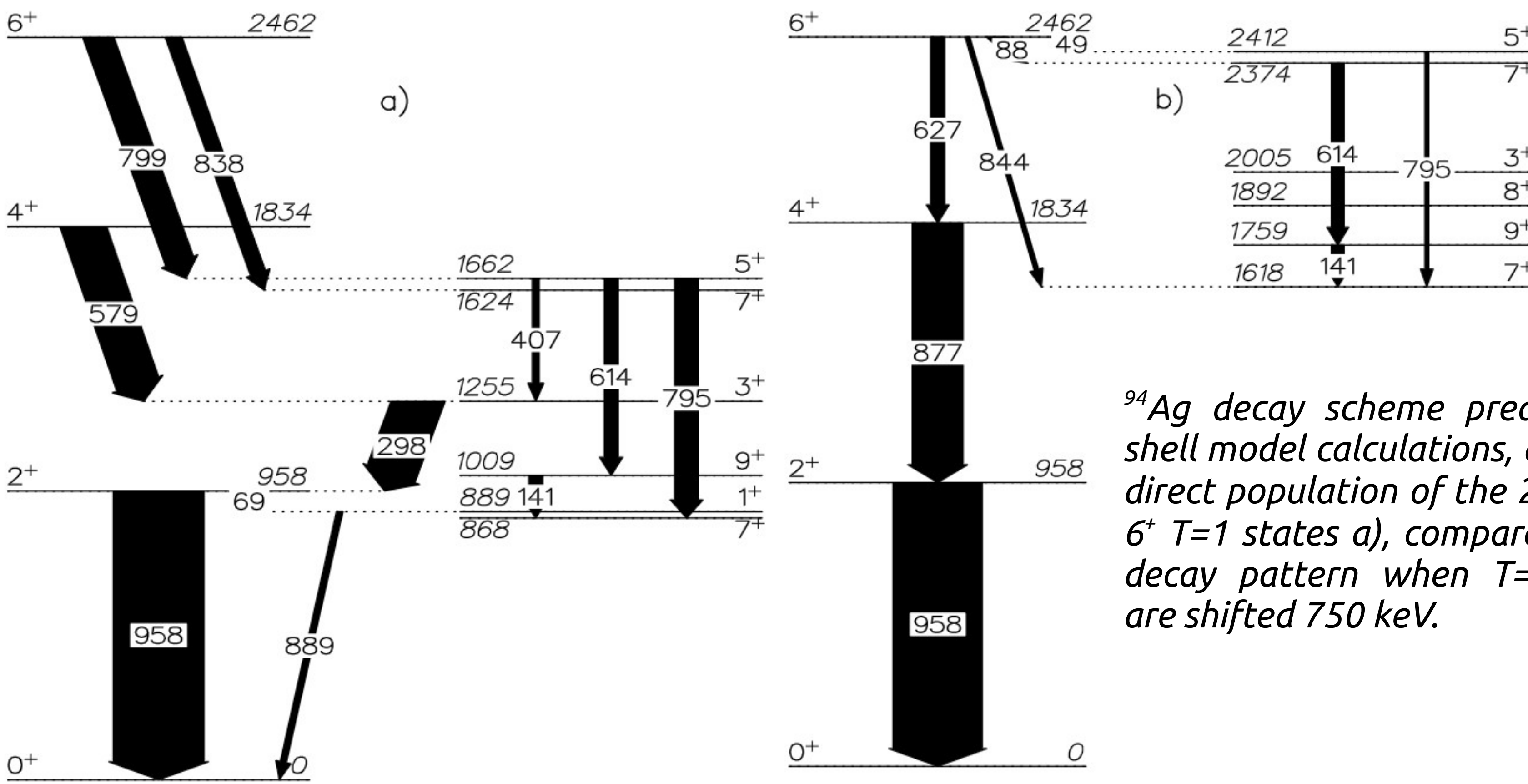


CEDs as function of J between tentatively assigned T=1 levels in ^{94}Ag and analog states in ^{94}Pd. ***Experimental values*** *in blue squares,* ***SM model prediction*** *in red circles.*

Shell model predictions

- SM suggest that we should only see $2^+ \rightarrow 0^+$ T=1 decay.
- 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.
- Further work is required

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



[94]Ag decay scheme predicted by shell model calculations, assuming direct population of the 2^+, 4^+ and 6^+ T=1 states a), compared to the decay pattern when T=0 states are shifted 750 keV.

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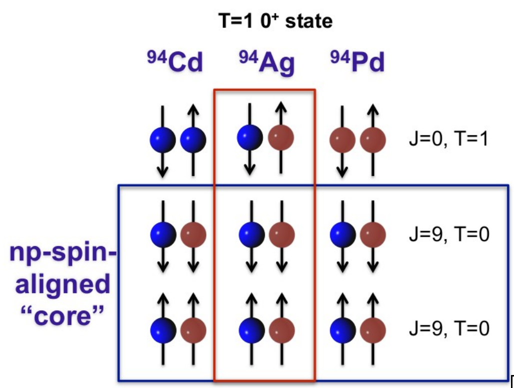
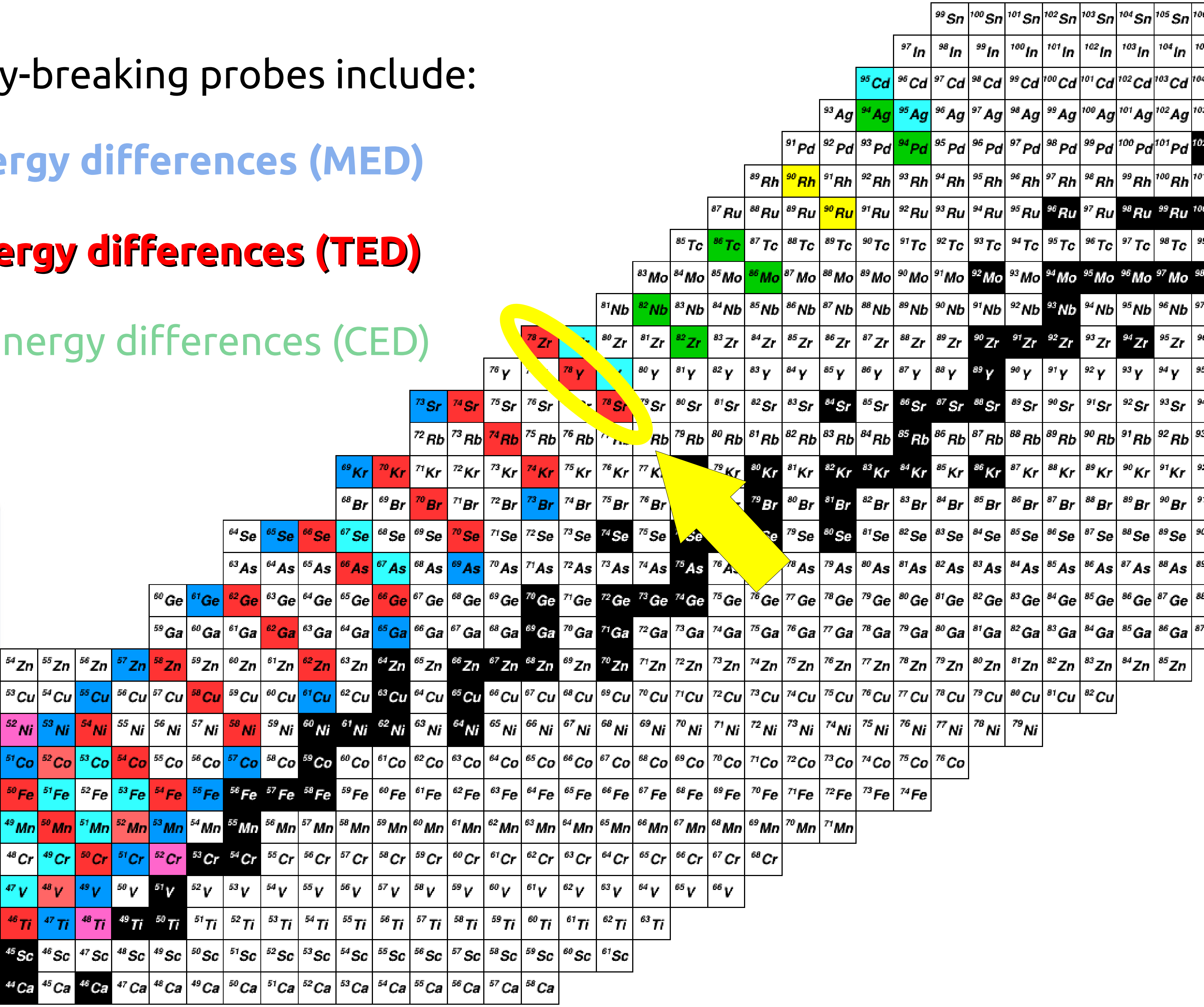
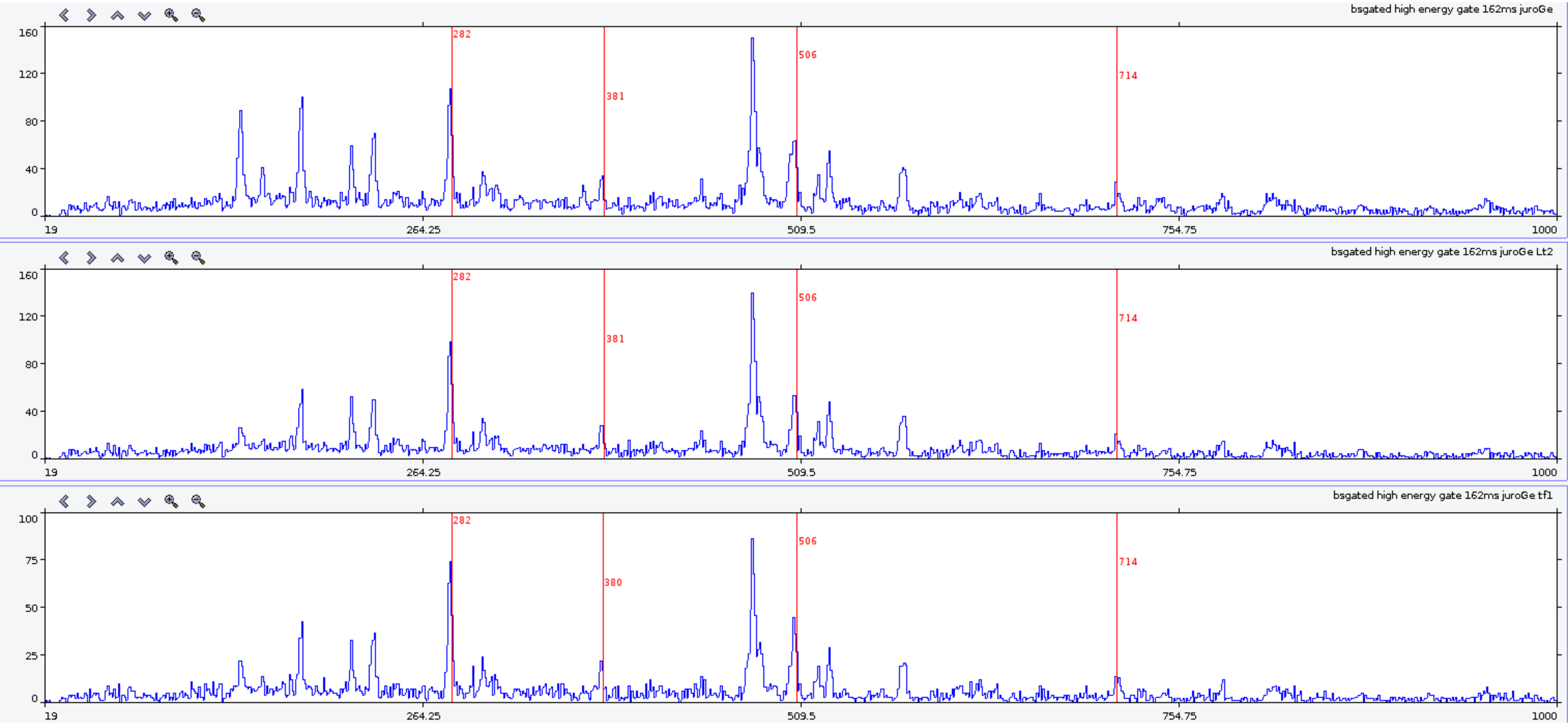




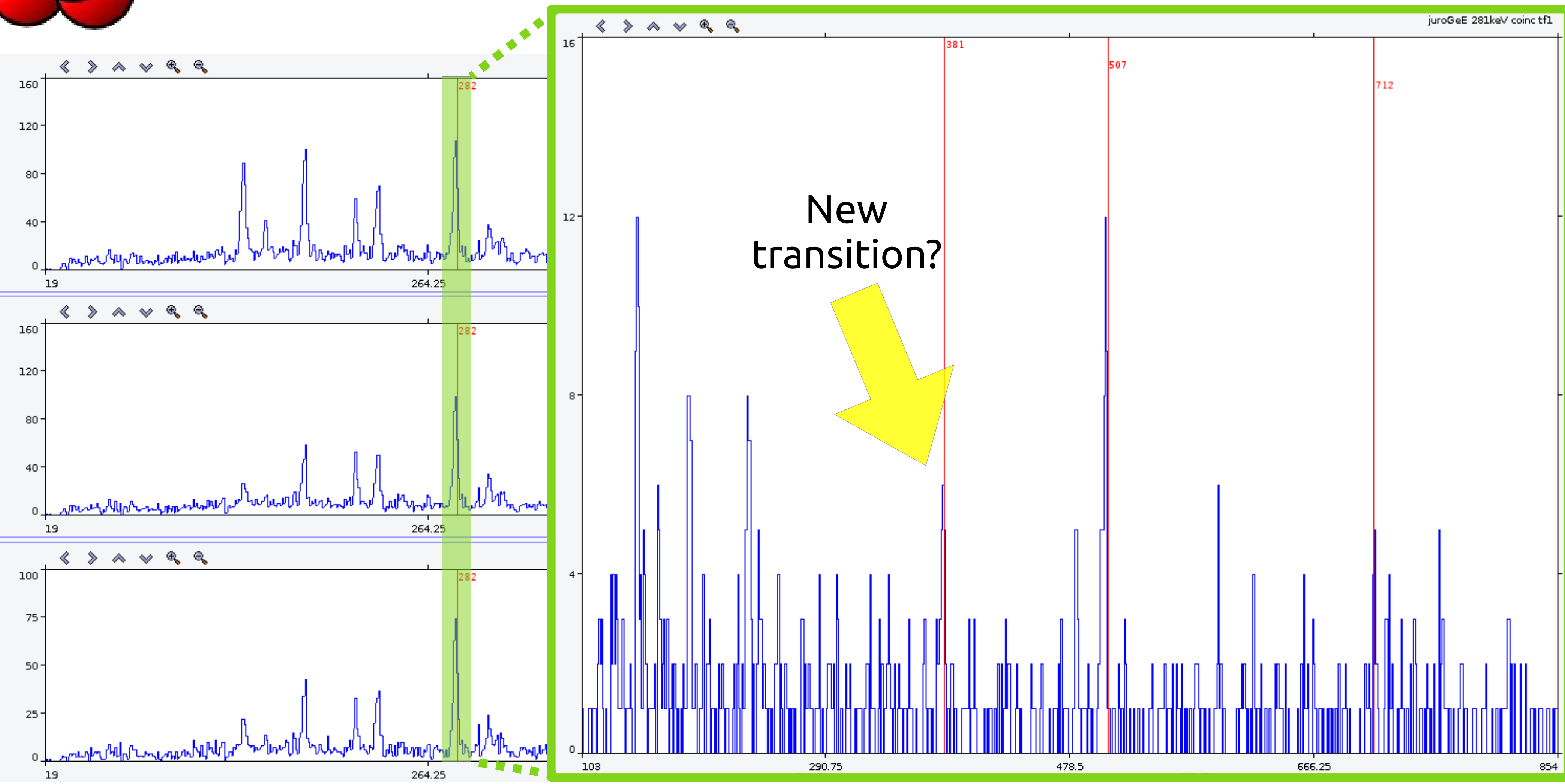
In-beam spectroscopy of ^{78}Zr

^{78}Y transitions



- Prompt emission
- short-lived A=78 fragments
- One charged particles
- High energy β

^{78}Y transitions



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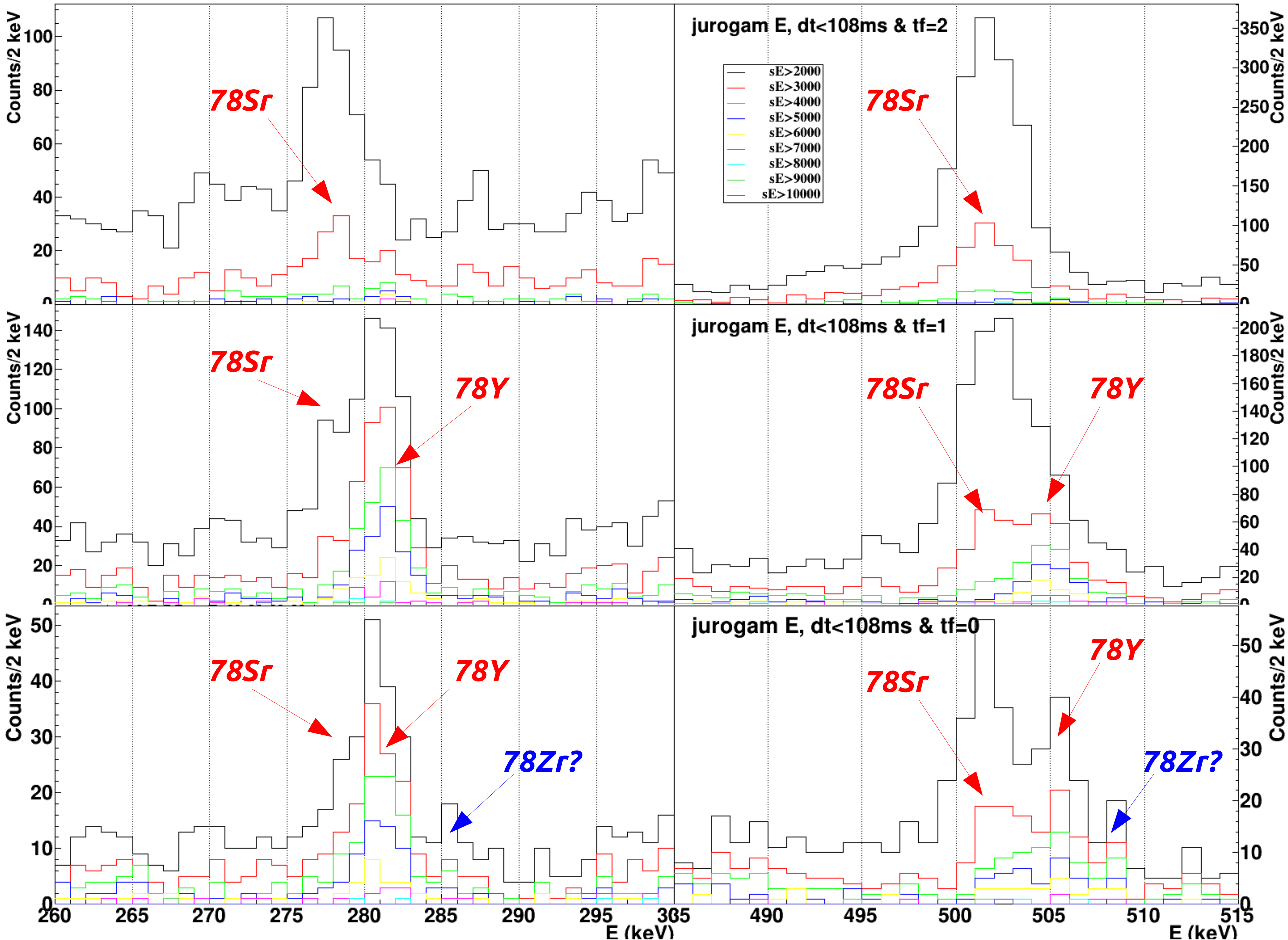
^{78}Zr transitions ?



Outlook

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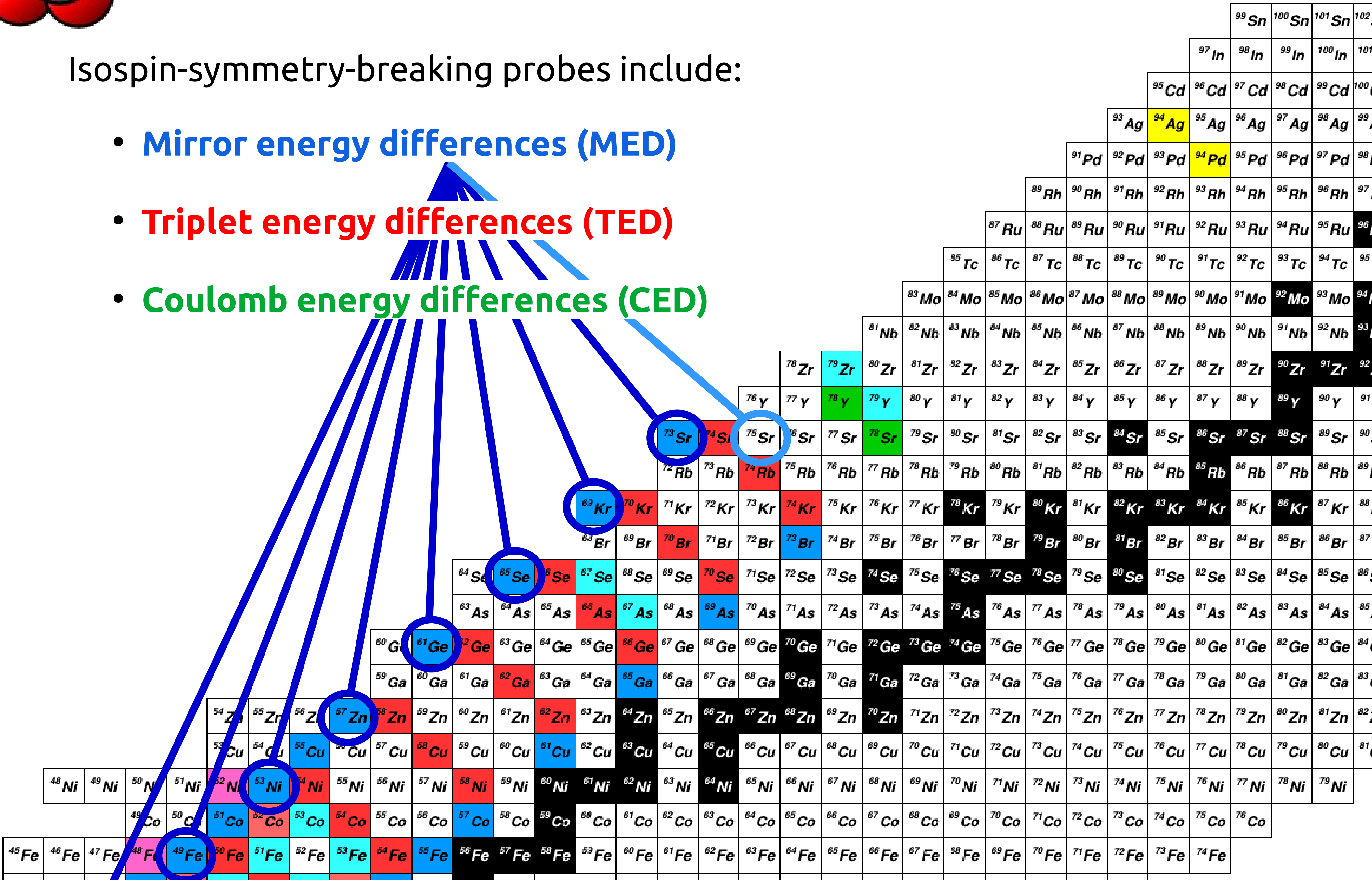

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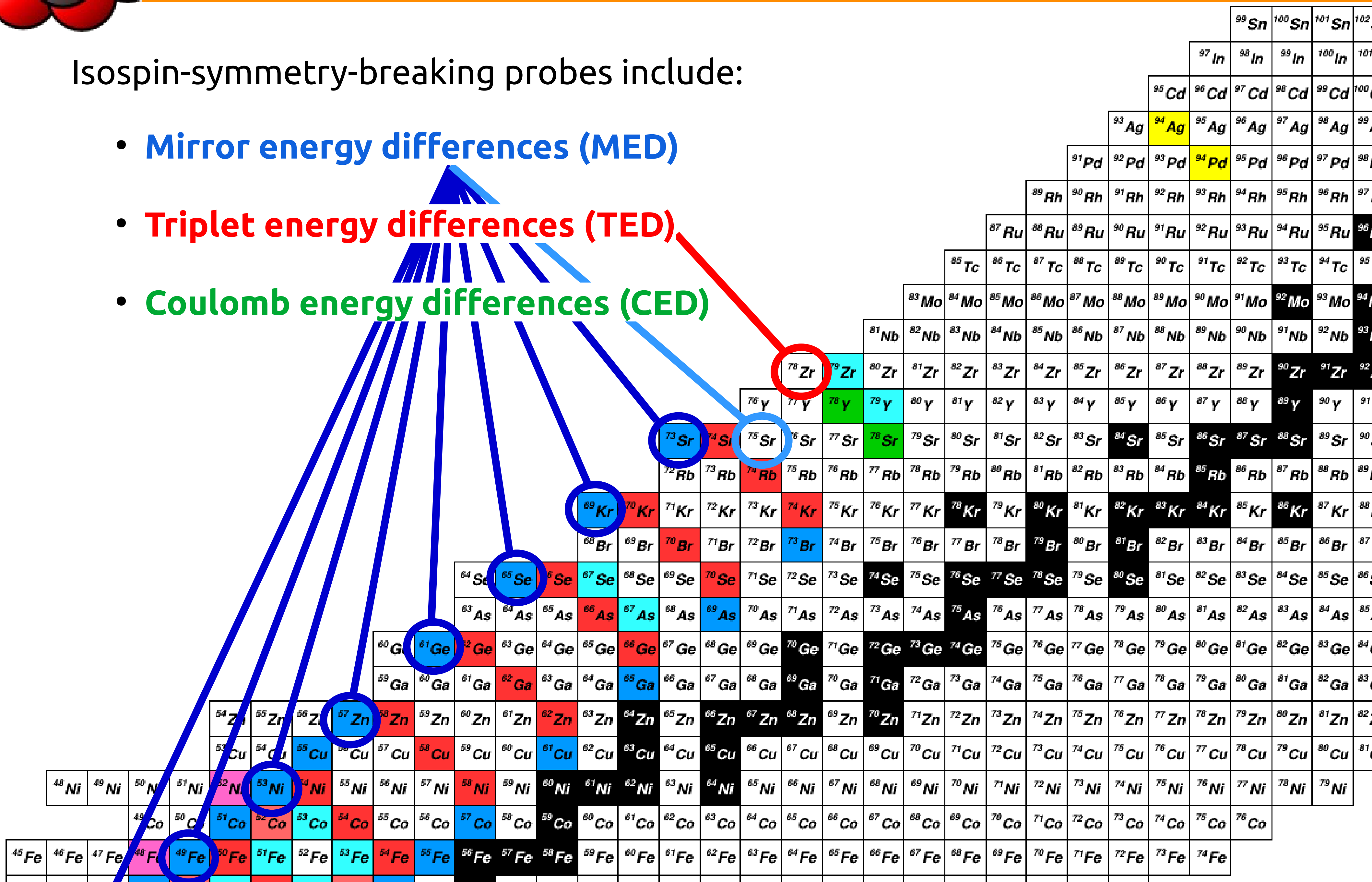

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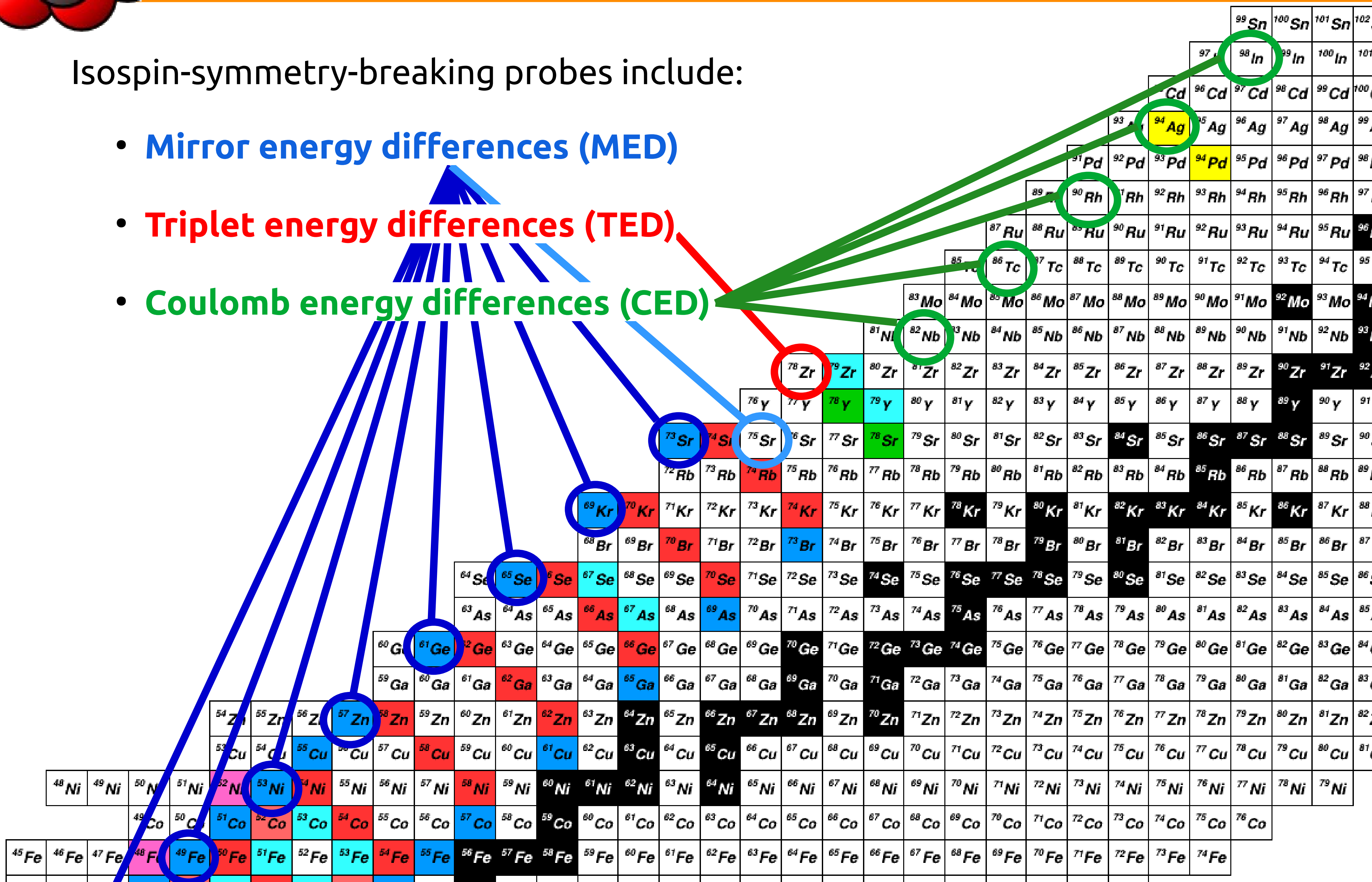

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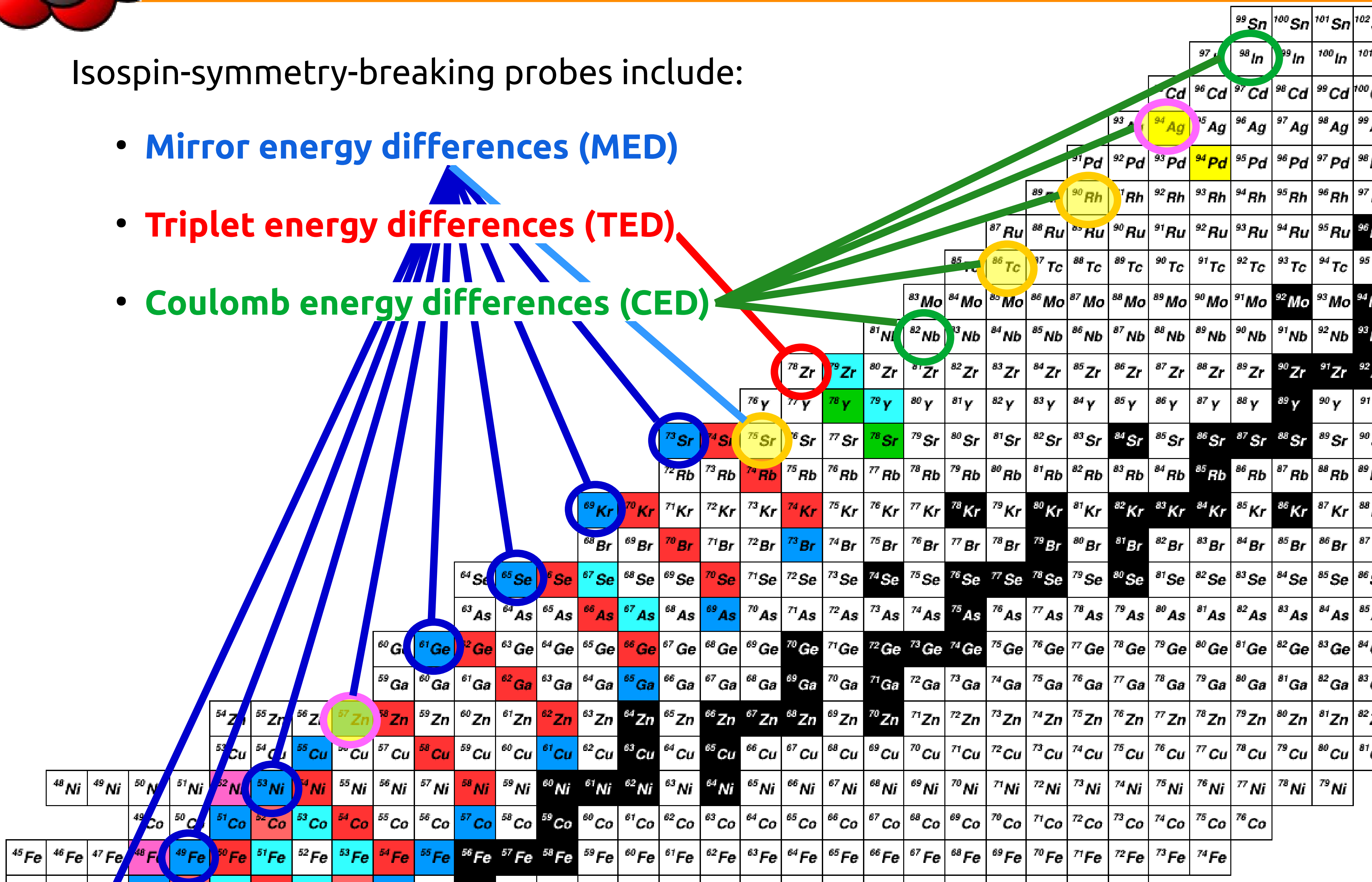

Isospin symmetry

- **V_{CM}, Coulomb monopole:** effect of recoupling angular momenta of pairs of protons.
- **V_{cr}, Radial contribution:** is the monopole Coulomb contribution associated with changes in the nuclear radius with J.
- **$V_{ll}+V_{ls}$:** Shifts in the SM single-particle energy levels due to Coulomb and magnetic effects
- **V_B, isospin non-conserving contribution**

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…[f], E. Lun…
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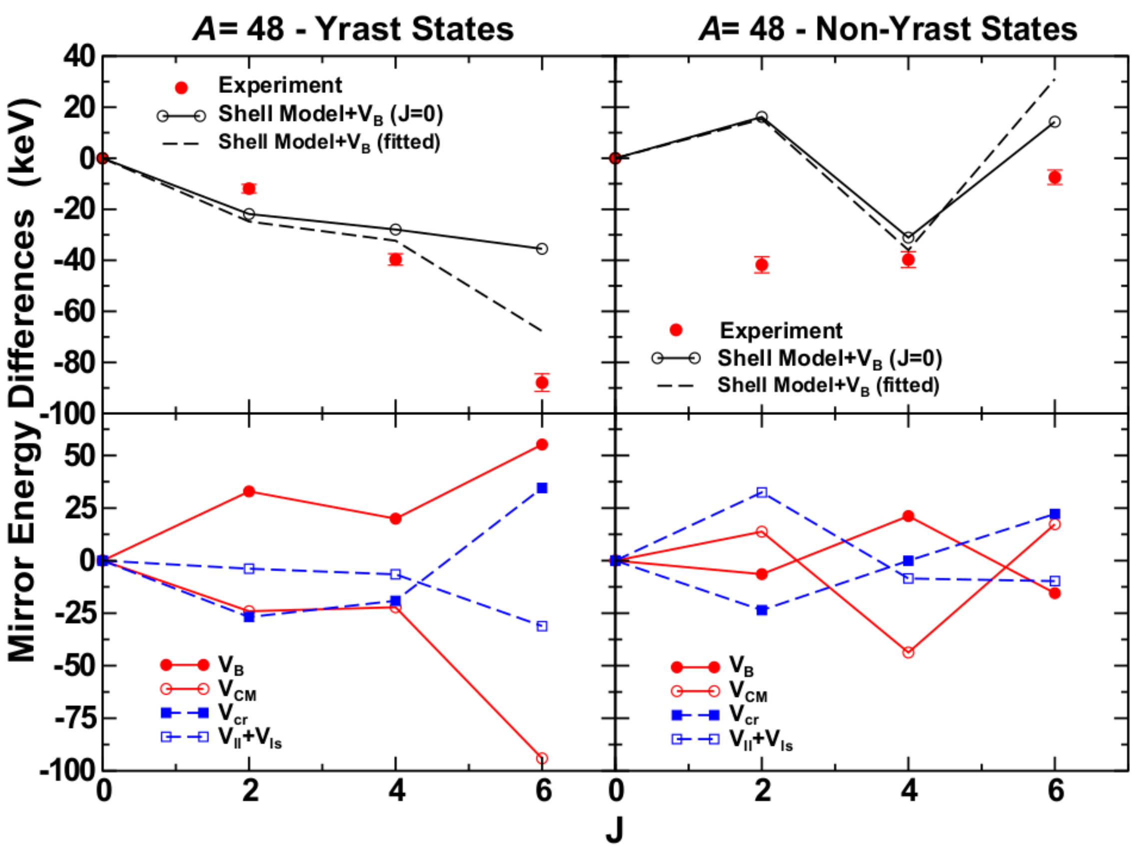
[h]Department of Physics, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdo…
[i]Dipartimento di Fisica e Astronomia dell'Università and INFN, Sezione di Padova, I-35131 Padova, Italy



…ce of excited states has been established for the first time in the proton-rich nucleus ^{48}Fe (Z=26, N=22). The t… (i.e. analogue) one-nucleon knockout reactions was applied, in which the $T_z = \pm 2$ mirror pair, ^{48}Fe/^{48}Ti were p… …on/one-proton knockout from the secondary beams ^{49}Fe/^{49}V, respectively. The analogue properties of the rea… …elp establish the new level scheme of ^{48}Fe. The inclusive and exclusive cross sections were determined for th… …rge differences between the cross sections for the two mirrored reactions were observed and have been interpre… …nt degrees of binding of the mirror nuclei and in the context of the recent observations of suppression of sp… …s a function of nuclear binding. Mirror energy differences (MED) have been determined between the analo… …l compared with the shell model predictions. MED for this mirror pair, due to their location in the shell, are… …o excitations out of the $f_{7/2}$ shell, and present a stringent test of the shell-model prescription.

…luction

…ttractive strong nuclear force that acts between protons …ons is virtually invariant to the charge of the individual … This yields one of the fundamental concepts in nu… …sics - the concept of isospin and the resulting influence … symmetry in nuclear structure [1, 2]. Isospin enables …cribe two types of fermion, the proton and the neutron, …fferent states of the nucleon and, in this formalism, …ons have isospin quantum number $t = \frac{1}{2}$ with differ… …ctions for a proton ($t_z = -\frac{1}{2}$) and for a neutron ($t_z =$ … …reover, the nucleus has a total isospin projection on … T_z, and the total isospin of the individual nucleons, …y quantum number T, is given by:

$$= \sum t_z = \frac{N-Z}{2} \quad (1)$$

$$\frac{-Z|}{2} \leq T \leq \frac{|N+Z|}{2}. \quad (2)$$

…sence of isospin breaking interactions, states of the …pin, T, in a set of nuclei of the same mass number …analogue states, IAS) will be degenerate. Differences …ion energies of IAS will result from the Coulomb in… …teraction and from any charge-dependent components of the …

forces lift the degeneracy of analogue states, break is… …metry and may result in isospin mixing of the states … (e.g. [3]).

The concept of charge symmetry of the nuclea… …quires that the neutron-neutron (V_{nn}) and proton-p… interactions are identical, and any interactions where… (e.g. arising from the Coulomb force) are known a… interactions. The study of mirror nuclei, with excha… …bers of neutron and protons, is an immensely power… to investigate isovector phenomena and how they r… clear structure more generally. Differences in excit… …gies between mirror nuclei, known as mirror energy… (MED), are given by

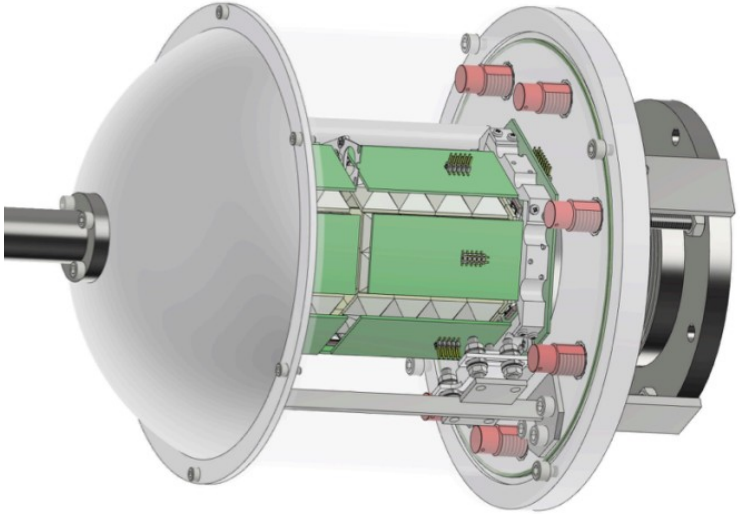
$$MED_J = E^*_{J,T,-T_z} - E^*_{J,T,+T_z}$$

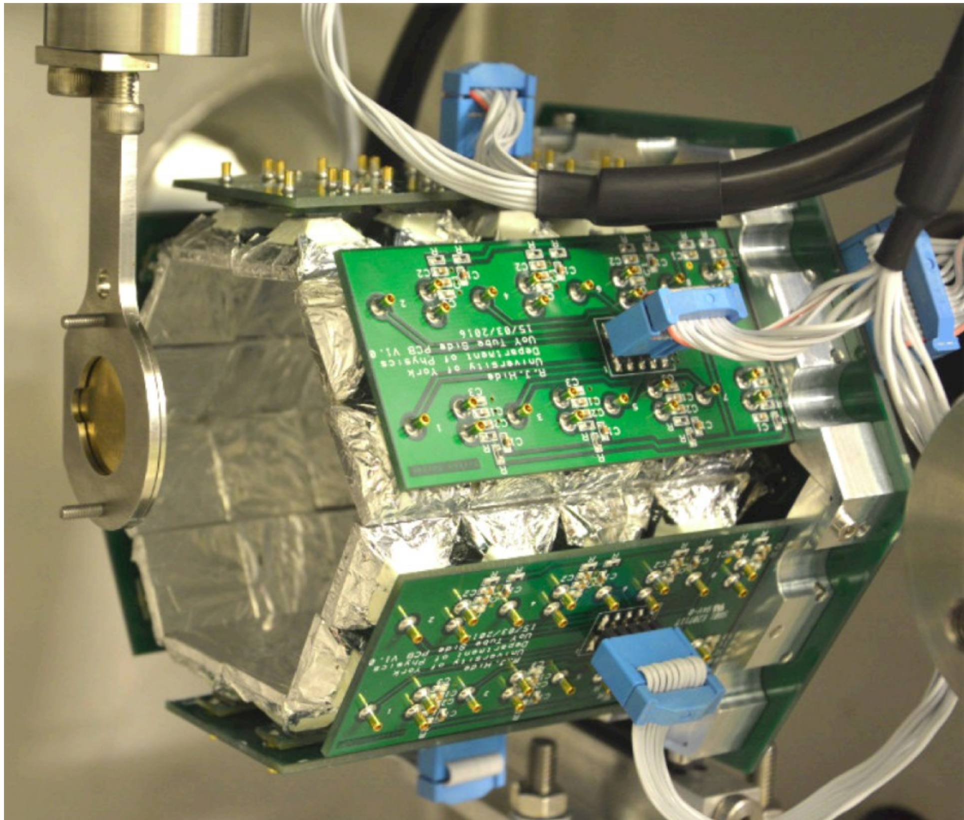
where E^*_{J,T,T_z} is the excitation energy of a state with … isospin T, and isospin projection T_z. MED derive e… isovector effects, and there have been extensive … MED in the fp shell, coupled to detailed shell-mo… …tions – e.g. [4–9]. The developments of the shell-m… …lations have enabled reliable interpretation of MED… electromagnetic phenomena, of both multipole and… origin, which are expected to provide the largest con… the MED [3]. These studies have yielded detailed i… on the effective isospin non-conserving interaction…

Experimental setup

JYtube

- 96 plastic scintillator crystals.
- Hexagonal shape
- Placed around the target
- Detect evaporated charged particles
    - 65 % efficiency
- Used as a veto detector

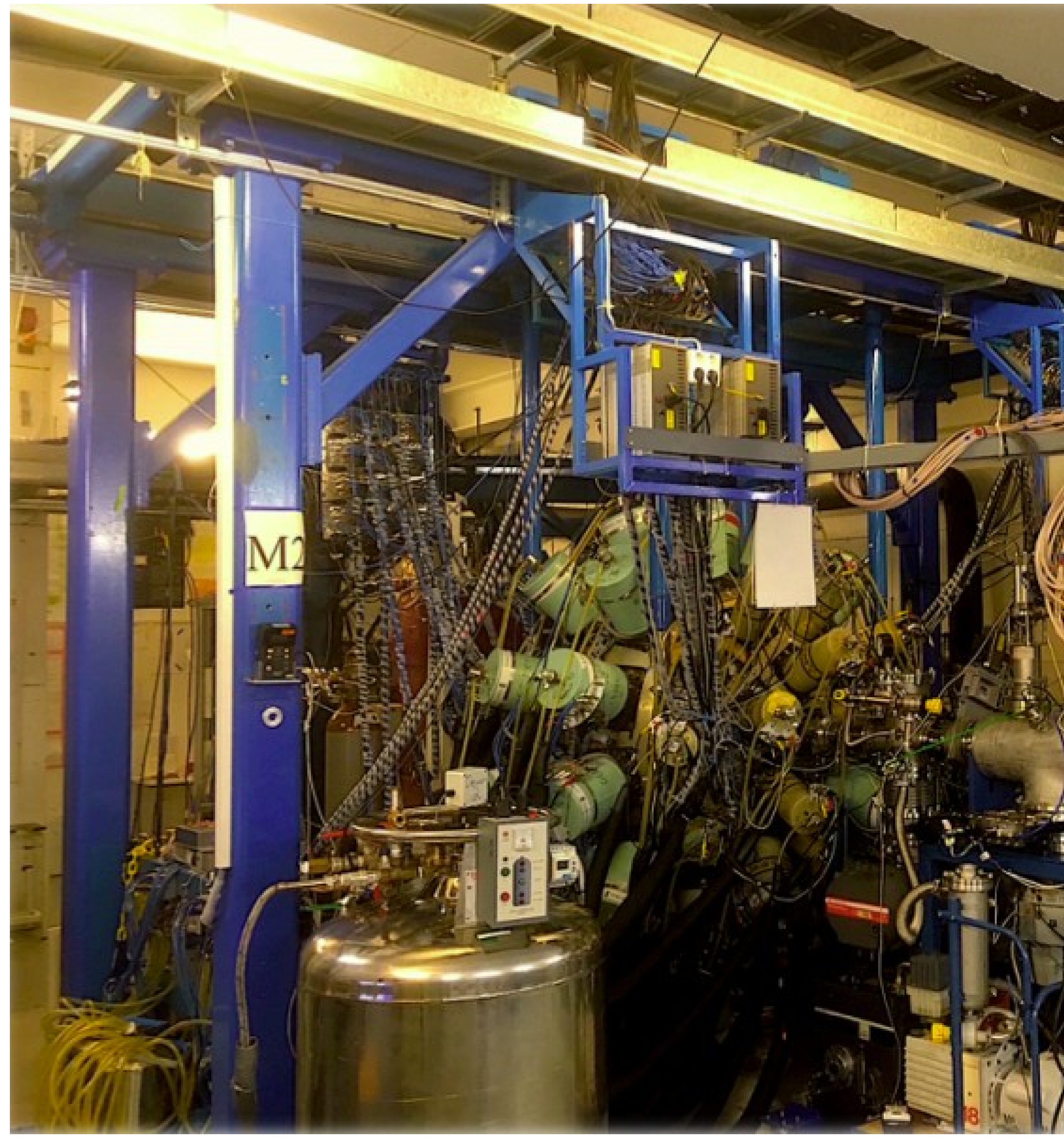




Experimental setup

Jurogam3

- HP Ge detector array
  - 15 single-crystals
  - 24 clover detectors
- BGO Compton suppresion shields
- Placed around the target
  - compact configuration
  - 6% efficiency @ 1.3 MeV
- Prompt γ-rays



Experimental setup

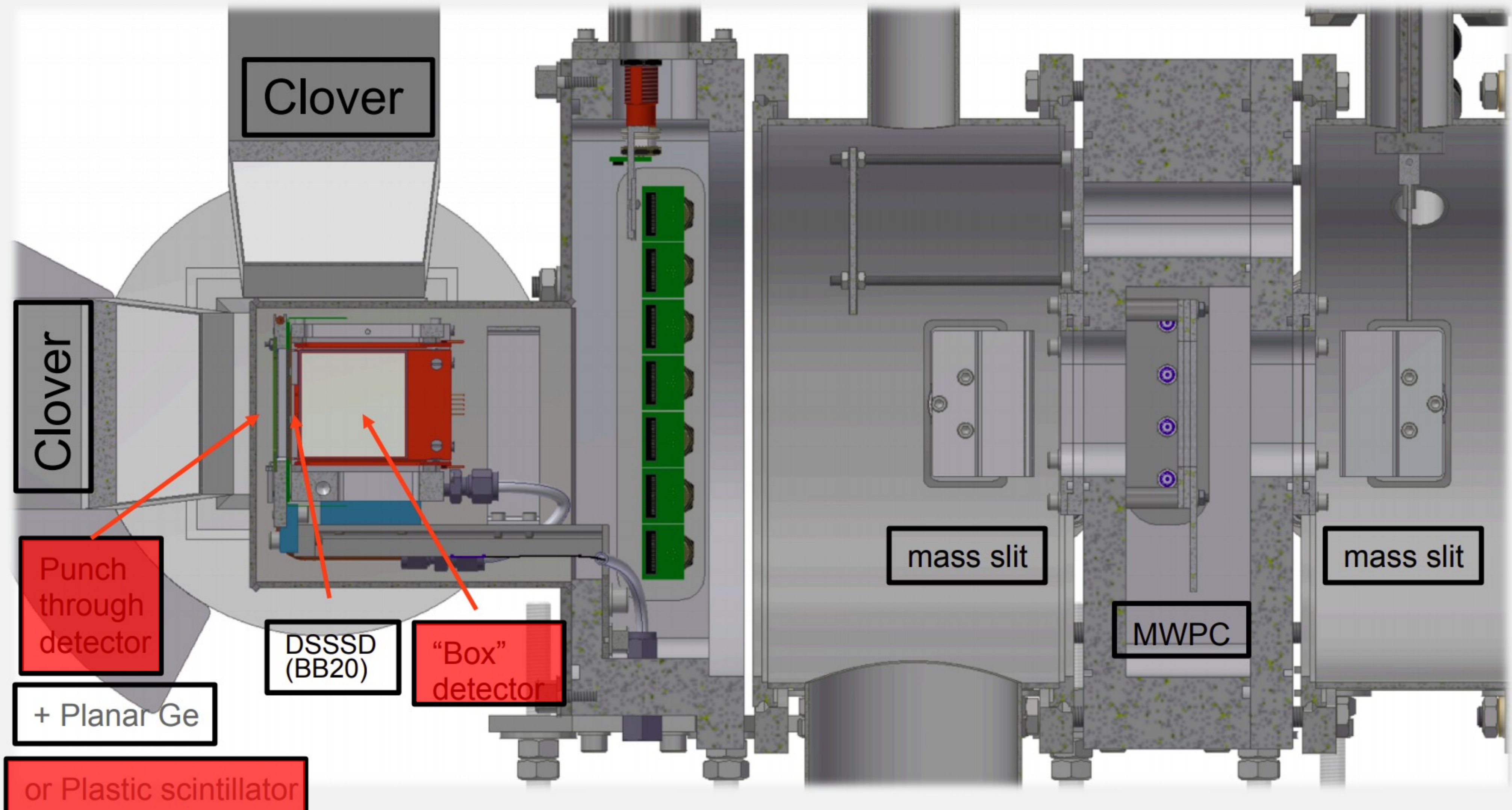
MARA

- Perform A/q identification
- Maximise transmission of A=94 fragments to the focal plane detection system.
  - Electric & magnetic field settings
  - Mass slits

Quadrupole triplet, electrostatic deflector and magnetic dipole (from right to left)

Experimental setup

GREAT focal plane



^{94}Ag half-life

- The half-life of the recoils in coincidence with these γ-rays was estimated using the Schmidt method.

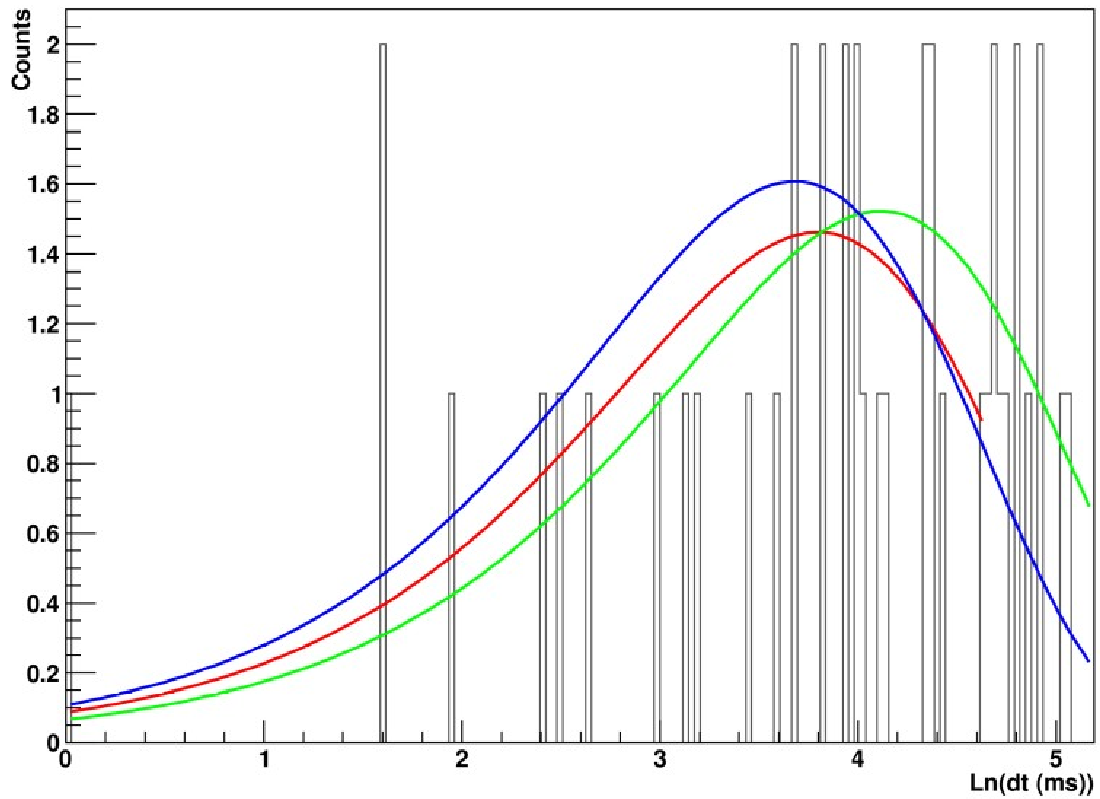
  K.-H. Schmidt, Eur.Phys.J. A 8, (2000) 141-149

  - β threshold raised to 5 MeV

    - contaminant bias

  - Decay of daughter ^{94}Pd

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.

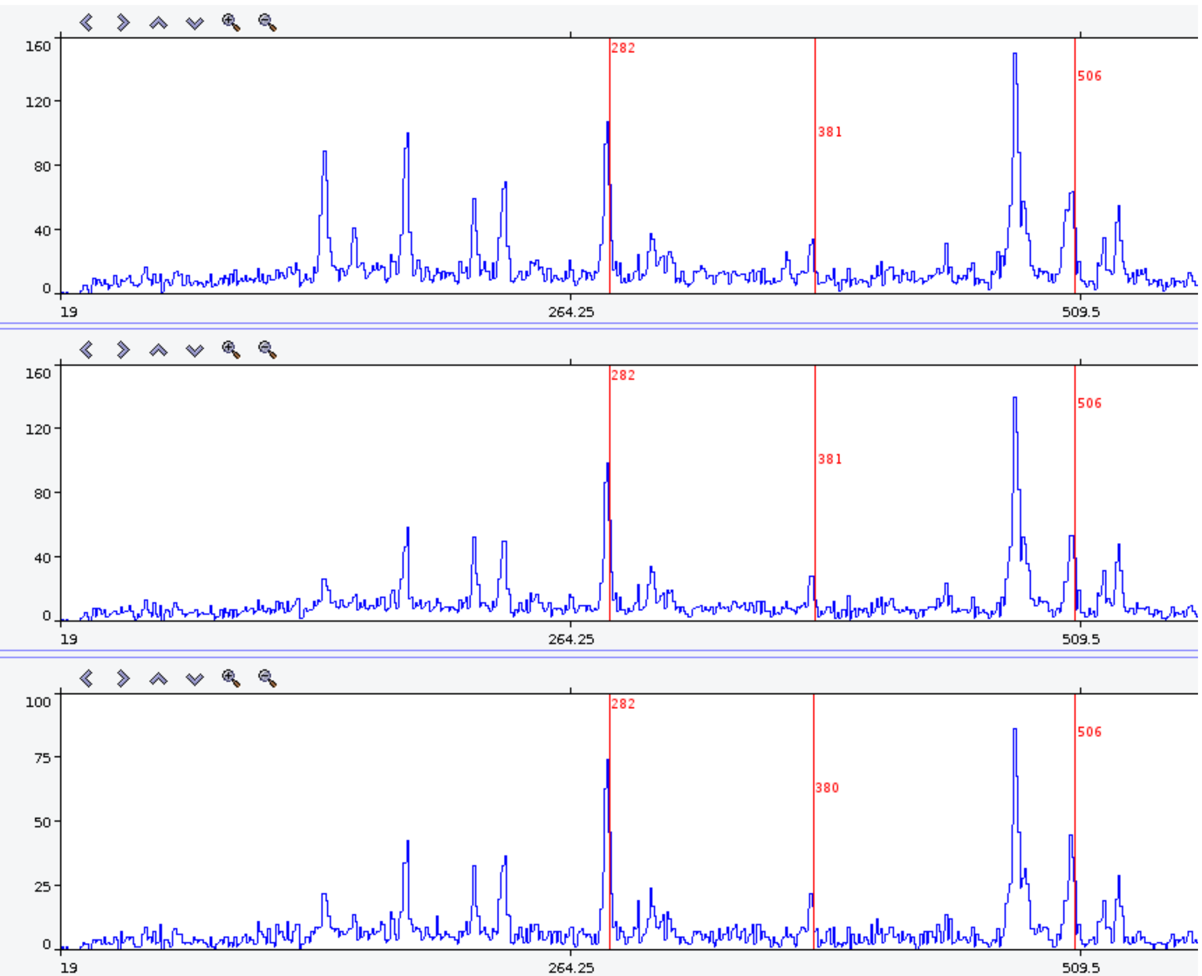


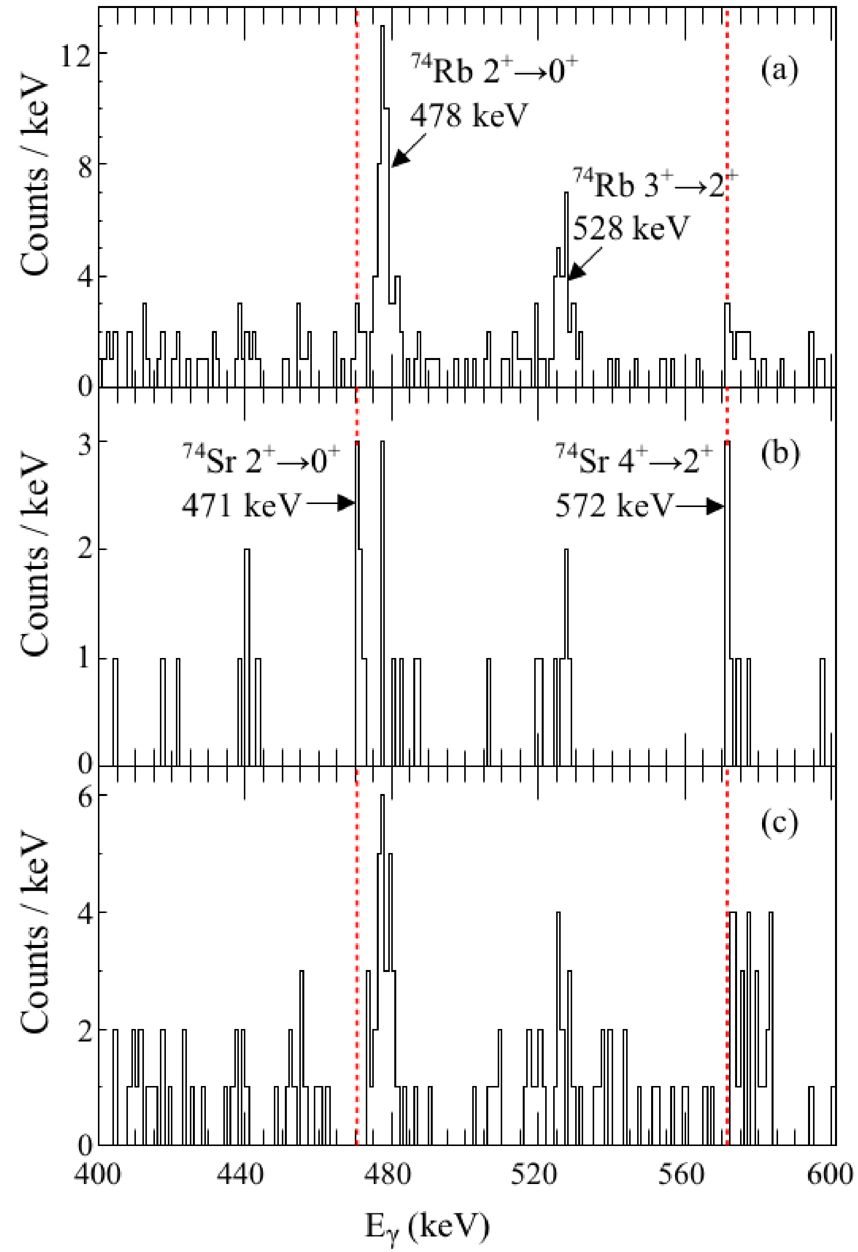
Natural logarithm of the decay time measured for recoils associated with γ-rays tentatively assigned to ^{94}Ag. ***Green*** *and* ***red*** *curve represent the log-likelihood fit to the decay data within* ***120*** *and* ***180*** *ms from implantation, from whose a half life of* ***41(12)*** *and* ***30(12)*** *ms is estimated.* ***Blue*** *curve is a calculation corresponding to the current accepted value of* ***27(2)*** *ms.*

Conclusions

- Seven γ-ray transitions 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.
    - They represent the first observation of γ-ray transitions from ^{94}Ag excited states.
- Results compared with neighbouring T=1 isobar nucleus ^{94}Pd.
- CEDs are extracted and discussed with shell model calculations.
    - Level scheme remains unclear.
- Future experiments to locate 7^+ T=0 isomer may provide important information on this regard.

^{74}Sr new transitions?

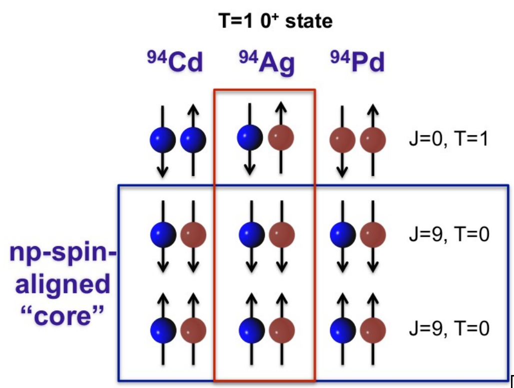


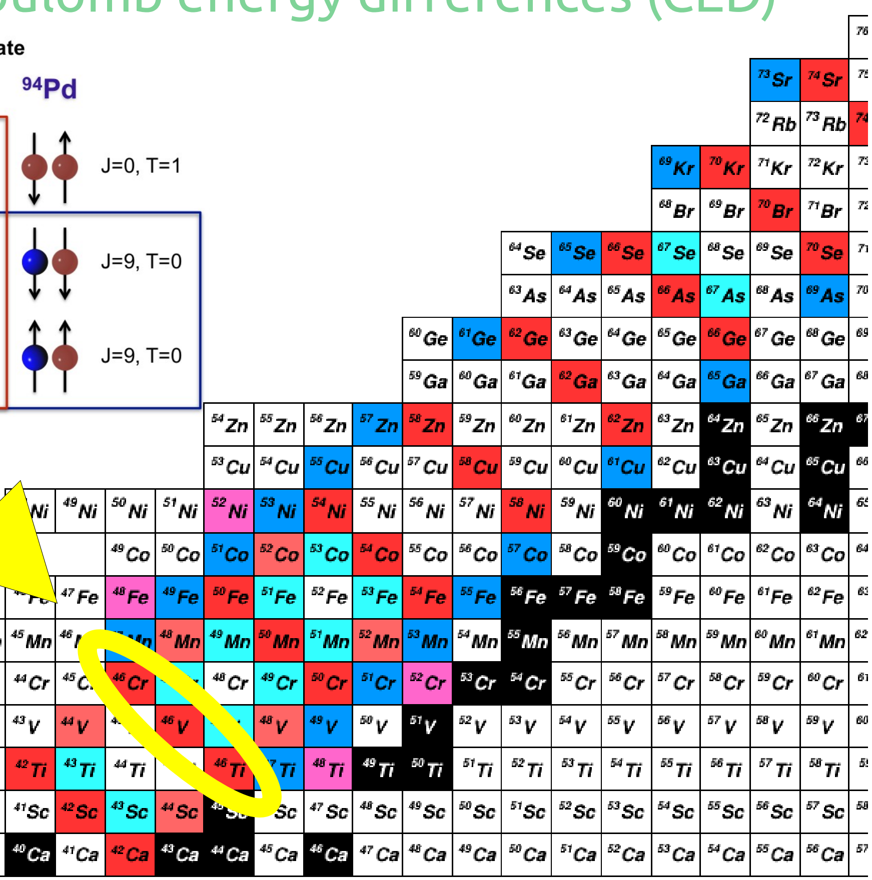


Isospin symmetry

Isospin-symmetry-breaking probes include:

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





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Isospin dependence of electromagnetic transition strengths among a isobaric triplet

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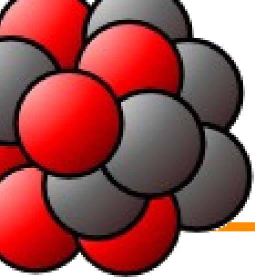

Isospin symmetry

Isospin-symmetry-breaking probes include:

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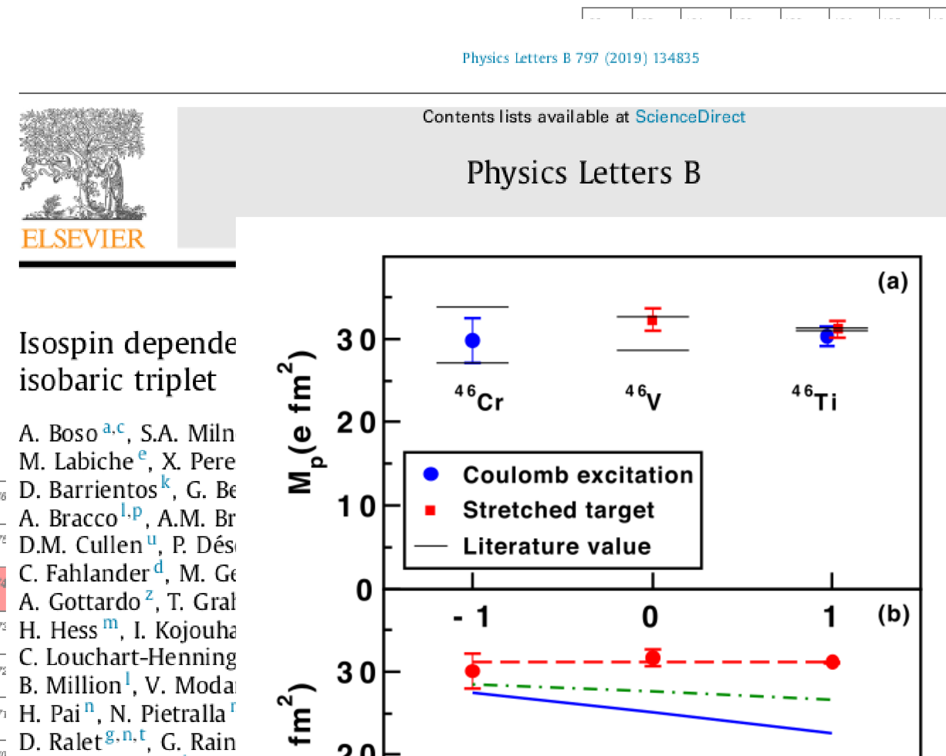
- Coulomb energy differences (CED)

$$M_p(T_z) = \frac{1}{2}[M_0 - T_z M_1^{T_z=1}]$$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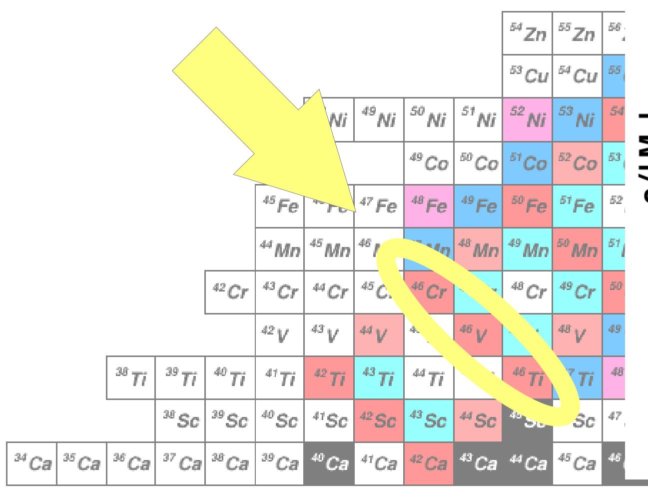

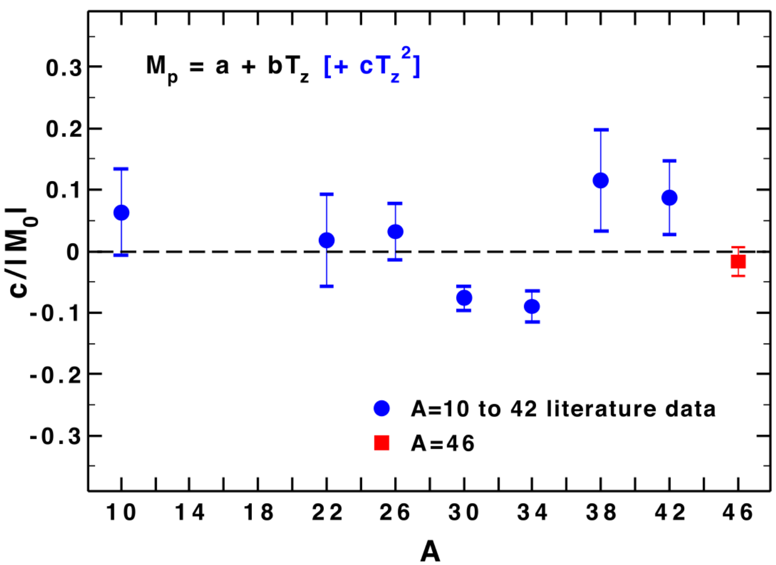

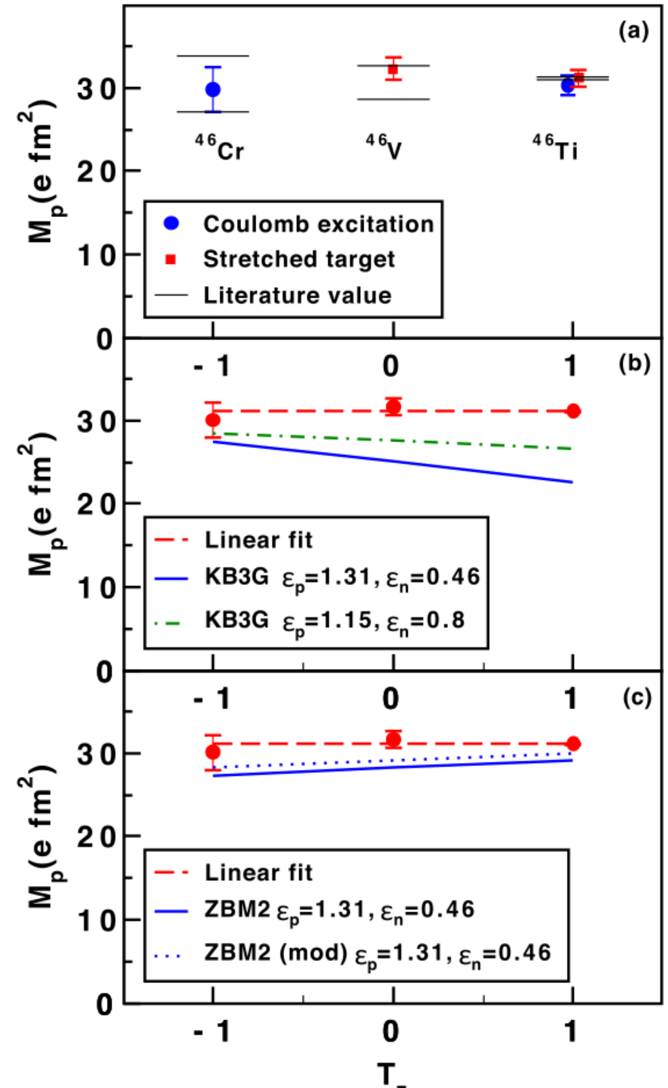

Collaborators

In-beam spectroscopy of excited states of ^{94}Ag

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