Isospin Symmetry of the A=46 T=1 triplet studied with AGATA

A Boso, S.A. Milne, M.A. Bentley, F. Recchia, S.M. Lenzi, M. Labiche et al.

(on behalf of AGATA, PRESPEC and LYCCA Collaborations)

- Introduction
- T=1 triplets and Isospin symmetry
- AGATA S434 experiment
- Coulex of $^{46}\text{Cr}$ and $^{46}\text{Ti}$ $2^+_1$ states
- Lifetimes of $^{46}\text{V}$ and $^{46}\text{Ti}$ $2^+_1$ states - stretched target method
- Test of one of the fundamental rules of isospin
Isospin Symmetry and T=1 Triplets

\[ T_z = \frac{(N - Z)}{2} \]

-5/2 -3/2 -1/2 1/2 3/2 5/2

-2 -1 0 1 2

even A
odd A

ground states
excited states

N=Z

forbidden states
proton rich
neutron rich

Isospin Symmetry for N=Z and T=1 Triplets

projection

The University of York
Isospin Symmetry and $T=1$ Triplets

\[ T_z = \frac{(N - Z)}{2} \]

- even $A$
- odd $A$

Ground states
Excited states
Forbidden states
Proton rich
Neutron rich

\[ N = Z \]

Isospin projection
In the current work, we seek to extract best-fit values of $V_B$, and do so modifi ed approach is necessary. We determine the theoretical MED for a given state, analogous to a state in the two mirror nuclei – using

$$MED_{th}(\alpha) = MED_{cr}(\alpha) + MED_{ll}(\alpha) + MED_{ls}(\alpha)$$

$$V_{(1),j} = V_{pp,j} + V_{nn,j}$$

$$TED_{th}(\alpha) = E_{J,T,T_z=0}^* + 2E_{J,T,T_z=0}^* - 2E_{J,T,T_z=+1}^*$$

$TED(\alpha) = E_{J,T,T_z=-1}^* + E_{J,T,T_z=+1}^* - 2E_{J,T,T_z=0}^*$

- **Isospin Symmetry-breaking corrections**
- **Strong $J$-dependent terms**
- Consistent with NN scattering data
- np interaction ~ 2-3% stronger than nn or pp.
Systematics of B(E2)s in Isobaric Triplets

Proton matrix element for isospin triplets:

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

Isoscalar + isovector

\[ J^\pi = 2^+ \rightarrow 0^+, \quad T = 1 \]

Prados Estavez et al., PRC75, 014309

2007 Compilation
Isospin symmetry in the A=46 Isobaric Triplet

AGATA-PRESPEC Experiment, April 2014 - analysis by: Scott Milne (York) and Alberto Boso (Padova)

Test linearity of E2 matrix element with $T_z$ - isospin selection rule

$M_p(T_z) = \frac{1}{2}[M_0 - T_z M_1^{T_z=1}]$
Isospin mixing in the $A=46$ Isobaric Triplet?

$^{46}\text{V}$ - good case for close $T=1$ and $T=0$ 2$^+$ state

- VERY close proximity of $T=0$ and $T=1$ in odd-odd $^{46}\text{V}$

Lifetime and Coulex Measurements performed across the T=1 A=46 Triplet of Nuclei
Scott Alexander Milne, sam519@york.ac.uk (and Alberto Boso, alberto.boso@pd.infn.it)

IOP Conference 2015

“Stretched Target” method

- GSI Fragment Separator + AGATA tracking array + LYCCA (Particle tracking)
- AGATA/PRESPEC Campaign in 2014

Primary → Secondary → Excited Secondary

$^{58}\text{Ni} \rightarrow \begin{array}{c} 46\text{Ti} \\ 46\text{Cr} \end{array} \rightarrow \begin{array}{c} 46\text{Ti}^* \\ 46\text{Cr}^* \end{array}$

Relativistic Coulomb excitation - measure relative to $^{46}\text{Ti}$

$^9\text{Be} (2.5\text{g/cm}^2)$  $^{197}\text{Au} (0.5\text{g/cm}^2)$

Primary → Secondary → Excited Secondary

$^{58}\text{Ni} \rightarrow \begin{array}{c} 46\text{Ti} \\ 46\text{V} \end{array} \rightarrow \begin{array}{c} 46\text{Ti}^* \\ 46\text{V}^* \end{array}$

Lifetimes by “stretched target” - measure relative to $^{46}\text{Ti}$

$^9\text{Be} (2.5\text{g/cm}^2)$  $^{197}\text{Au} ([0.75/0.5/0.5]\text{g/cm}^2)$
Using high velocity & target-thickness available in fragmentation reactions - FRIB/FAIR/RIBF technique!

Lifetime measurement: Idea from P. Bednarczyck

3 Fe foils (both target and degrader)

\[ ^{37}\text{Ca} -1p \rightarrow ^{36}\text{K} \]

Isospin mixing in the A=46 Isobaric Triplet

Lifetime and Coulex Measurements performed across the T=1 A=46 Triplet of Nuclei

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(and Alberto Boso, alberto.boso@pd.infn.it)

IOP Conference 2015

The Experiment @GSI

Primary Beam from SIS: $^{58}\text{Ni}$ 600MeV/u

Primary Target: (2.5g/cm$^2$ Be)

S1 Degrader: All: (2g/cm$^2$ Al)

S2 Degrader (Achromatic): $^{46}\text{Ti}$: (8.0g/cm$^2$ Al) $^{46}\text{V}$: (6.8g/cm$^2$ Al) $^{46}\text{Cr}$: (5.7g/cm$^2$ Al)

S2 Slits

S2 TPCs

S2 Finger

FRS ToF: S2 Sci → S4 Sci ($\beta\gamma$)

$A = B \rho e$

$Q = c \rho \beta \gamma$

FRS Id: Z vs A/Q

LYCCA Id: DSSSD dE vs CsI E

TARGET DSSD

LYCCA DSSD

LYCCA CsI

AGATA + HECTOR

FRS

S1 Slits

S2 Slits

S2 TPCs

S3 Slits

B$\rho_1$

B$\rho_2$

B$\rho_3$

S4 Slits

S4 TPCs

S4 Scintillator

Target DSSD

Secondary Target: (0.5g/cm$^2$ Au) OR ([0.75/0.5/0.5]g/cm$^2$ Au)

TOF Start

TOF Stop

S4 MUSIC (ΔE)

S4 TPCs

FRS

ToF:

S2 Sci → S4 Sci ($\beta\gamma$)

$A = B \rho e$

$Q = c \rho \beta \gamma$

FRS Id: Z vs A/Q

LYCCA Id: DSSSD dE vs CsI E

Primary Beam from SIS: $^{58}\text{Ni}$ 600MeV/u
Isospin symmetry in the A=46 Isobaric Triplet

Analysis from Alberto Boso, Padova

Efficiency Corrections for:
- Dead time
- Angular distributions

$^{46}$Ti Coulex

Counts / 4 keV

Energy [keV]

$^{46}$Cr Coulex

Counts / 8 keV

Energy [keV]

1087(88) counts
$B(E2) = 918(74)$ e$^2$fm$^4$

117(21) counts
$B(E2)^\uparrow = 886(158)$ e$^2$fm$^4$
46-Ti Lifetime Simulation [Peak 3, 5.25 ps]

β for peak 3
30±5°

Full AGATA Simulation + stretched-target event generator
Marc Labiche + Scott Milne

Stretched Target Lifetime Measurement
angle limit \( \theta_{\text{max}} = 50^\circ \)

**46V:**  
*Simulation 4.2 ps*  
*Lit:*  
4.7(6) ps  

**46Ti:**  
*Simulation 5.3 ps*  
*Lit:*  
5.28(5) ps  

Statistical error \( \sim 0.3 \) ps  
Systematic error estimate \( \sim 0.2 \) ps
Isospin symmetry in the A=46 Isobaric Triplet

E2 matrix element as a function of $T_z$

Lifetime and Coulex Measurements performed across the $T=1$ $A=46$ Triplet of Nuclei

Scott Alexander Milne, sam519@york.ac.uk (and Alberto Boso, alberto.boso@pd.infn.it)

IOP Conference 2015

Current: absolute values

$\frac{M_p}{M_p^{(46\text{Ti})}}$ as a function of $T_z$

Relative values: $^{46}\text{Cr}/^{46}\text{Ti}$ Coulex
$^{46}\text{V}/^{46}\text{Ti}$ Stretched target

statistical errors only
Isospin symmetry in the A=46 Isobaric Triplet

Lifetime and Coulex Measurements performed across the T=1 A=46 Triplet of Nuclei
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IOP Conference 2015

KB3G interaction in $f_{7/2}p_{3/2}/f_{5/2}p_{1/2}$ space

Dufour and Zuker, PRC 54, 1641 (1996)

du Rietz et al., PRL 93, 222501 (2004) (from A=51 mirrors)

ZBM2 interaction in $s_{1/2}d_{3/2}/f_{7/2}p_{3/2}$ space

A. Boso, S.A. Milne, M.A. Bentley, F. Recchia et al. submitted PLB 2019
A. Boso, S. A. Milne, M. A. Bentley, F. Recchia

et al. submitted PLB 2019

\[ M_p(T_z) = \frac{1}{2}[M_0 - T_z M_{1T_z=1}] \]

**Linearity of proton M.E with**\( T_z \)**

\[ M_p = a + b T_z \] \( + c T_z^2 \]

- A=10 to 42 literature data
- A=46

**e-e Data from** Pritychencko et al., At.Nuc.Dat.Tab. 107, 1139 (2016) + recent results

**o-o Data from** Nuclear Data Sheets + recent results
A. Boso, S. A. Milne, M. A. Bentley, F. Recchia et al. *submitted PLB 2019*

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

**Linearity of proton M.E with \( T_z \)**

\[ M_p = a + bT_z [ + cT_z^2 ] \]

**10B** Kuvin et al., *PRC96, 041301(R) (2017)*

**A=22**, Henderson et al., *PLB782, 468 (2018)*

**30S**, Petkov et al., *PRC96, 034326 (2017)*

**42Ca**, K. Hadynska-Klek et al., *PRL96, 117, 062502 (2016)*

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e-e Data from *Prytchencko et al., At.Nuc.Dat.Tab. 107, 1139 (2016) + recent results*

o-o Data from *Nuclear Data Sheets + recent results*
A. Boso, S. A. Milne, M. A. Bentley, F. Recchia

*et al. submitted PLB 2019*

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

**Linearity of proton M.E with \(T_z\)**

- **Figure 1:** Gamma-ray spectra for \(A=46\) and \(\text{Cr}^{38}\) using relativistic Coulomb excitation. Incoming and outgoing energies and scattering angles are cut – see text for details.

- e-e Data from *Pritychencko et al., At. Nuc. Dat. Tab. 107, 1139 (2016)* + recent results
- o-o Data from *Nuclear Data Sheets* + recent results

\[M_p = a + bT_z [+ cT_z^2]\]
• High precision measurement of B(E2)s in T=1 triplet
• Heaviest triplet for which this has been done (so far!)
• No evidence for non-linear behaviour with $T_z$
• $A=30$ and $34$ may deviate from the selection rule…
• Stretched target technique - **excellent technique for FAIR & FRIB**
Scott Milne (York)
Alberto Boso (Padova)
Marc Labiche (Daresbury)
Francesco Recchia and Silvia Lenzi (Padova)


AGATA Team
GSI/PRESPEC team
The most recent data are included.

It can also be seen that data on one of the most precise tests of the rule to zero, and it is clear that the ear fit to the same data—see Eq. 1). As expected the isoscalar matrix element, varies significantly in this mass range, we have plotted in Fig. 3(b). Since the total matrix element data used for model calculation if the line. The dotted line (mod) shows the result of the shell calculation using the KB3G interaction are shown by the solid and dotted lines. (c): Data as (b). Shell-model calculations using the KB3G interaction are shown by the red dashed line is a linear fit to the data. Shell-model

\[
M_p / M_p^{(46\text{Ti})} = 0.46
\]

The above analysis clearly points towards the in-stability of the experimental values for near equality of the experimental values for

\[
A \epsilon = 0.5
\]

The near equality of the experimental values for

\[
\frac{M_p}{M_p^{(46\text{Ti})}} = 0.46
\]

The above analysis clearly points towards the inadequacy of the overall agreement, however, remains poor.

The near equality of the experimental values for

\[
\frac{M_p}{M_p^{(46\text{Ti})}} = 0.46
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The above analysis clearly points towards the inadequacy of the overall agreement, however, remains poor.
UK-HISPEC

LYSCCA - an operational HISPEC device

Lund York Cologne CALorimeter

incoming relativistic radioactive ion beam
LYCCA ToF Start
LYCCA Target secondary reaction
circulars
LYCCA ToF Stop
LYCCA Wall DSSSD
LYCCA Wall CsI

ΔE−E_{res}

ToF_{in}, d_{in}

ToF_{out}, d_{out}

(x, y)

ToF_{tot}, d_{tot}

(x, y)

Printed circuit board
Mounting parts
Brass frame
Connector for DSSD signal cables
Photodiodes
CsI scintillators

P. Golubev et al. NIMA. 723, 55-66 (2013)
LYCCA - an operational HISPEC device

UK-HISPEC

UK contribution of LYCCA:

Large-area time-of-flight detectors

ASIC-based signal-processing and DAQ
Isospin mixing in the A=46 Isobaric Triplet

Triple Gold Foil (stretched target)

Doppler Shift: \( E_{exp} = E_{cor} \sqrt{\frac{1-\beta^2}{1-\beta \cos(\theta_{dop})}} \)

Gold Foils:
- 750mg/cm\(^2\)
- 500mg/cm\(^2\)
- 500mg/cm\(^2\)

Secondary Beam

~170MeV/u Secondary Beam
LYCCCA - an operational HISPEC device

P. Golubev et al. NIMA. 723, 55-66 (2013)

Particle tracking

Z-measurement

A-measurement

Doppler correction
In the absence of Coulomb interactions between the protons, a perfectly charge-symmetric and charge-independent nuclear force would result in the binding energies of all these isobaric analogue nuclei being identical; that is, they would be structurally identical.

<table>
<thead>
<tr>
<th>Isobaric Spin (Isospin)</th>
<th>( T_z = \frac{(N - Z)}{2} ) projection</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5/2</td>
<td>-2</td>
</tr>
<tr>
<td>-3/2</td>
<td>-1</td>
</tr>
<tr>
<td>-1/2</td>
<td>0</td>
</tr>
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<td>1/2</td>
<td>1</td>
</tr>
<tr>
<td>3/2</td>
<td>2</td>
</tr>
<tr>
<td>5/2</td>
<td></td>
</tr>
</tbody>
</table>

\( N/Z \) even \( A \)

\( N/Z \) odd \( A \)

Even states

Odd states

Proton rich

Neutron rich

Excited states

Forbidden states

Ground states

Isospin
Isospin Symmetry and Isospin Breaking

**Charge symmetry**

\[ V^{J}_{pp} = V^{J}_{nn} \]

Isospin invariance

**Isovector** interaction

Probed in mirror nuclei (MED)

**Charge independence**

\[ (\frac{V^{J}_{pp} + V^{J}_{nn}}{2}) = V^{J}_{np} \]

Isospin non-conserving interactions (INC)

**Isotensor** interaction

Probed in \( T=1 \) triplets (TED)

\[ V^{(1),J} = V^{J}_{pp} - V^{J}_{nn} \]

\[ V^{(2),J} = V^{J}_{pp} + V^{J}_{nn} - 2V^{J}_{np} \]
“safe” impact parameter

\[ b_{\text{min}} = r_0 \left( A_P^{1/3} + A_T^{1/3} \right) + 5\text{fm} \]

Efficiency Corrections for:
- Dead time
- angular distributions
- working detectors

**46**Ti Coulex

![Graph showing measured cross section as a function of the cut on the scattering angle for the nuclei of interest.](image)

The only statistical error to be considered is the one due to the parameters of the relative efficiency curve, which is related to several terms:

- The dominant sources of systematic errors are the uncertainties on the E2 cross sections and the E2/E1 branching ratios.

The uncertainties on the cross section and B(E2) have been estimated by using the subtraction method. The only statistical error to be considered is the one due to the parameters of the relative efficiency curve, which is related to several terms:

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