How well do we (need to) understand isospin symmetry breaking?

Some comparisons between theory and experiment

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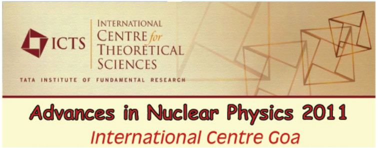
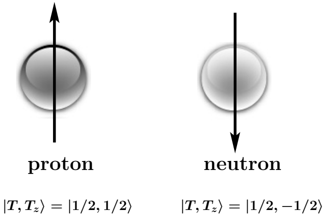
University of Delhi, India

November 8, 2011



Isospin: An Introduction

- Heisenberg (1932).



- Charge symmetry $V_{nn} \approx V_{pp}$
- Charge independence $V_{np} \approx V_{nn} \approx V_{pp}$
- Nearly equal $^3\mathrm{He}$ and $^3\mathrm{H}$ masses

G. Breit, E. U. Condon *et al.* (1936).

- Nuclear isospin $\Longleftrightarrow$ charge independence of nuclear forces $\Longrightarrow \mathrm{SU(2)}$ formalism analogous to spin.
- $[H, T] = 0 \Longrightarrow$ rotational invariance $\Longrightarrow$ broken by charge-dependent forces.

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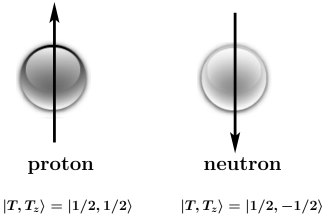

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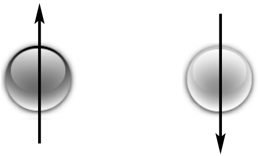

proton $|T, T_z\rangle = |1/2, 1/2\rangle$

neutron $|T, T_z\rangle = |1/2, -1/2\rangle$

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- $[H, T] \neq 0 \Longrightarrow$ ~~rotational invariance~~ $\Longrightarrow$ broken by charge-dependent forces.
- $Q_N|\psi_N\rangle = \sum_{i=1}^{A} Q_i|\psi_N\rangle = e(A/2 + T_z)|\psi_N\rangle = Ze|\psi_N\rangle$

Therefore, $[H, T_z] = 0$; $T_z = \left(\frac{Z-N}{2}\right)$

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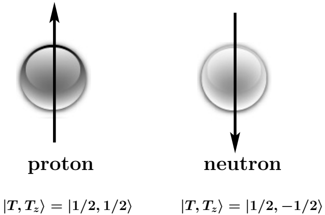

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Investigations

- Warburton and Weneser $\Longrightarrow$ isospin selection rules
- Advances in experimental techniques
  - Production of exotic nuclei about the $N = Z$ line
  - Large gamma-ray arrays (GAMMASPHERE, INGA, EUROBALL etc.)
- Theoretical techniques
  - Large-scale calculations (ANTOINE, Monte Carlo shell model, etc.)

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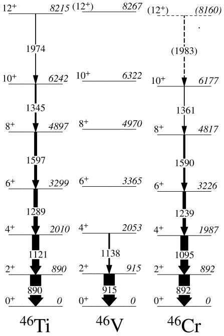

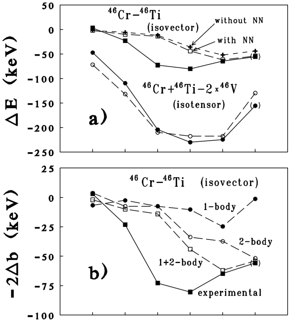

'Testing the IMME at high spin'

P. E. Garrett *et al.*, Phys. Rev. Lett **87**, 132502 (2001).

THE ISOBARIC MULTIPLET MASS EQUATION

- E. P. Wigner (1957).
- Introduce two-body charge-dependent forces of the generic form:

$$H_{\mathrm{EM}} = \sum_{i<j} (\alpha \tau_z(i) + \beta)(\alpha \tau_z(j) + \beta) f(r_{ij})$$

Such that,

$$H = H_{\mathrm{CI}} + H_{\mathrm{EM}}$$

- The masses of a multiplet are related by:

$$\boxed{\langle \alpha T T_z || H || \alpha T T_z \rangle = a + b T_z + c {T_z}^2} \,;\ T_z = \frac{(Z-N)}{2}$$

- Used to determine Q values when masses are not well known.

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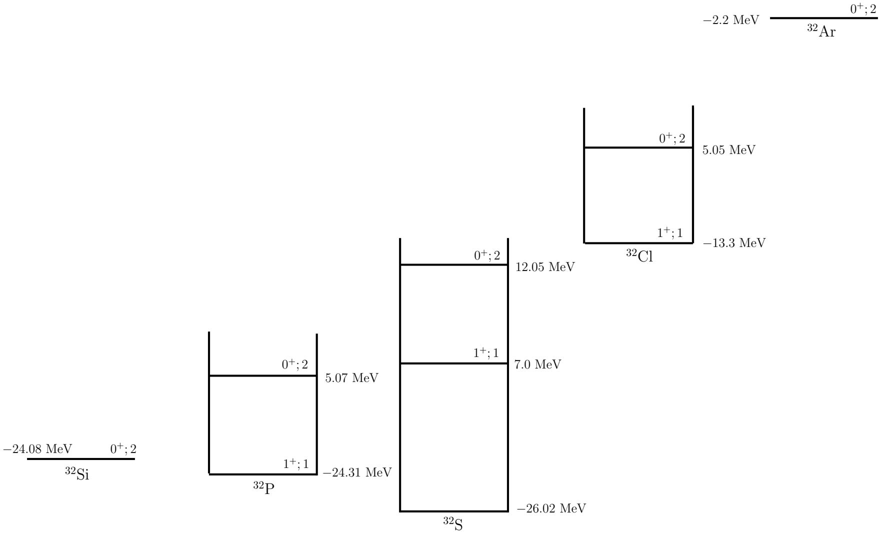
The $A = 32$ isobaric multiplet



A brief history

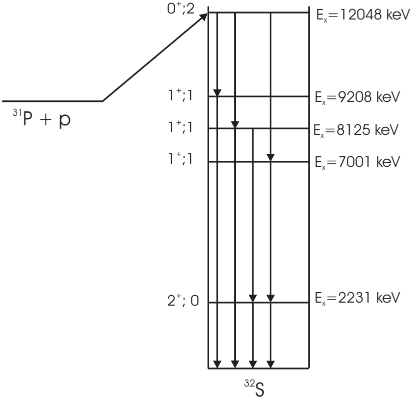
Isobar	T_z	$\mathrm{M_{Exp}}$ (keV) 1999	$\mathrm{M_{IMME}}$ (keV) 1999	$\mathrm{M_{Exp}}$ (keV) 2002	$\mathrm{M_{IMME}}$ (keV) 2002
$^{32}\mathrm{P}$	-1	-19232.88(20)	-19232.90(20)	-19232.88(20)	-19232.92(20)
$^{32}\mathrm{Si}$	-2	-24080.9(2.2)	-24081.9(1.4)	-24080.9(2.2)	-24079.5(1.0)
$^{32}\mathrm{S}$	0	-13970.98(41)	-13971.10(40)	-13970.98(41)[a]	-13970.80(38)
$^{32}\mathrm{Cl}$	$+1$	-8296.9(1.2)	-8296.6(1.1)	-8291.5(1.8)[b]	-8293.14(68)
$^{32}\mathrm{Ar}$	$+2$	-2180(50)	-2209.3(3.2)	-2200.2(1.8)[c]	-2200.0(1.6)

[a] M. S. Antony *et al.* in *Proceedings of the International Conference on Nuclear Physics, Berkeley, 1980* (Lawrence Berkeley Laboratory, Berkeley, CA, 1980), Vol. 1 ($E_X = 12045.0 \pm 0.4$ keV).

[b] M. C. Pyle *et al.*, Phys. Rev. Lett. **88**, 122501 (2002)

[c] K. Blaum *et al.*, Phys. Rev. Lett. **91**, 260801 (2003)

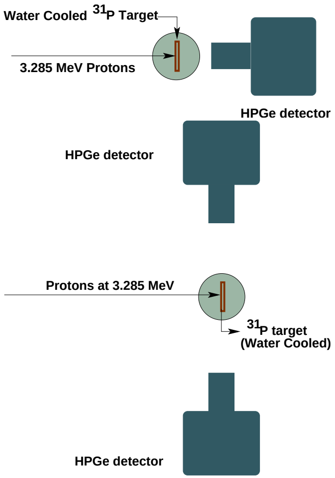
Mass of the lowest $T = 2$ state in $^{32}\mathrm{S}$ using $^{31}\mathrm{P}(p, \gamma)$

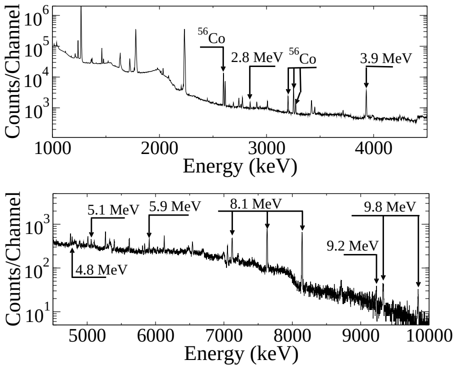


γ transitions: lowest $T = 2$ state in $^{32}\mathrm{S}$.

- implanted $^{31}\mathrm{P}$ target (55 $\mu\mathrm{Ah}$ of 90 keV ions).
- thickness $\approx$ 4 keV at $E_p =$ 3 MeV.
- resonance energy at $E_p \approx$ 3.285 MeV.
- precise Doppler correction of γ-ray energies.
- careful energy calibration and study of systematic effects.

Experimental setup

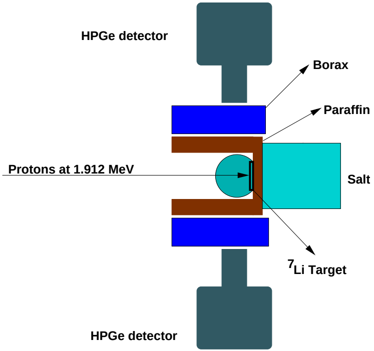




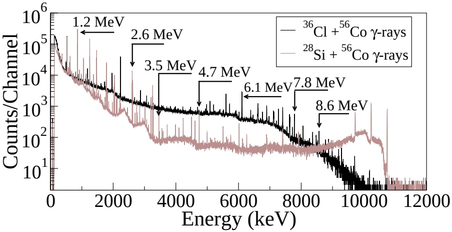
- Spectrum from the 0° expt.
- 9.8 MeV (direct capture)

Energy calibration

- $^{56}\mathrm{Co}$: $0 \leq E_\gamma \leq 3.5$ MeV
- $^{27}\mathrm{Al}(p,\gamma)$: $0 \leq E_\gamma \leq 8$ MeV
- $^{35}\mathrm{Cl}(n,\gamma)$: $0 \leq E_\gamma \leq 8$ MeV



- neutrons produced via $^{7}\mathrm{Li}(p,n)$
- Target: $\approx 500\ \mu\mathrm{g/cm}^2$ $\mathrm{Li_2O}$, $E_p \approx 1912$ keV
- For $^{27}\mathrm{Al}(p,\gamma)$: target thickness $\approx 20\ \mu\mathrm{g/cm}^2$, $E_p \approx 992$ keV



Systematic effects

- Gain drifts
- Line-shape variations
- ADC non-linearities
- Doppler effects
  - For $^{31}\mathrm{P}(p,\gamma)$ and $^{27}\mathrm{Al}(p,\gamma)$:
    - Detector size and possible mis-alignment
    - Recoil slowing
    - $\gamma - \gamma$ angular correlation
  - For $^{35}\mathrm{Cl}(n,\gamma)$:
    - Detector size and mis-alignment
    - Neutron angular distribution and scattering
    - Interaction of the γ rays with Ge (PENELOPE).
- field increment effect
- non-resonant background
- contact resistances

Results

J^π, T	E_x (keV) Previous Work	E_x (keV) This Work	E_γ (keV)†
2^+, 0	2230.57(15)	...	...
1^+, 1	7002.5(10)	7001.44(36)	4770.49(33)
1^+, 1	8125.40(20)	8125.32(24)	5894.32(28)
			8124.12(24)
1^+, 1	9207.5(7)	9207.55(71)	9206.13(71)
0^+, 2	12045.0(4)	12047.96(28)	2840.32(14)
			3922.37(15)
			5046.09(39)

† Obtained from a weighted mean of the 0° and the 90° data. The uncertainties are from the 0° data.

Our result is 7σ higher than the previously determined value.

A violation of the IMME

Isobar	T_z	$\mathrm{M_{Exp}}$ (keV)	$\mathrm{M_{IMME}}$ (keV)
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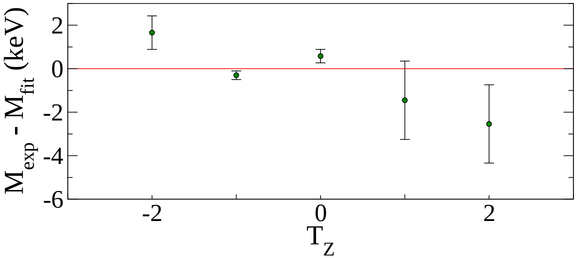
$^{32}\mathrm{P}$	-1	-19232.78 ± 0.20	-19232.48 ± 0.18
$^{32}\mathrm{S}$	0	-13967.74 ± 0.31	-13968.32 ± 0.26
$^{32}\mathrm{Cl}$	$+1$	-8291.5 ± 1.8	-8290.05 ± 0.63
$^{32}\mathrm{Ar}$	$+2$	-2200.2 ± 1.8	-2197.67 ± 1.50
		$Q(\chi^2 = 13.1, \nu = 2) = 0.001$	



S. Triambak, A. García, E. G. Adelberger *et al.*, Phys. Rev. C **73**, 054313 (2006).

What followed next?

- Mass of $^{32}\mathrm{Si}$ remeasured. $\sim$ 3 keV shift reported

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- Mass of $^{32}\mathrm{Cl}$ indirectly measured using Q3D spectrograph. 2 keV shift

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- Predicted admixed state at 70 keV lower in energy possibly observed in β-delayed proton spectrum

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- More calculations ongoing

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Require a $d{T_z}^3$ term with $d \sim 1$ keV.

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CKM unitarity.

A test of the $SU(2)_L$ structure of the Standard Model

- Cabibbo's hypothesis: Mass eigenstates $\neq$ weak eigenstates.

$$|d'\rangle = \cos\theta_C |d\rangle + \sin\theta_C |s\rangle$$
$$|s'\rangle = -\sin\theta_C |d\rangle + \cos\theta_C |s\rangle$$

- Kobayashi and Maskawa: Generalized to three quark families. (Nobel Prize, 2008)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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CKM unitarity tests from superallowed Fermi decays

- Is the CKM matrix unitary?

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - \delta$$

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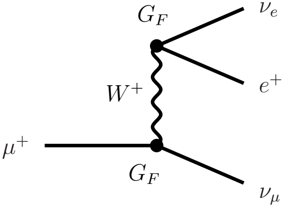
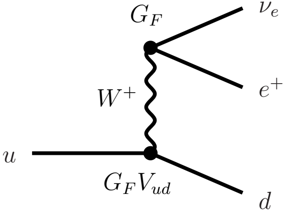
Compare to the coupling constant for a purely leptonic process (muon decay); $G_V = G_F V_{ud} C_V$

purely leptonic



semi-leptonic



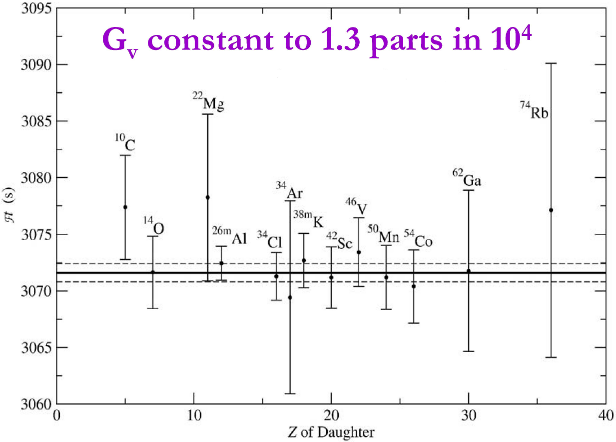
A $0^+ \to 0^+$ β-decay between IAS proceeds via a purely vector interaction.

The CVC hypothesis: $ft = \dfrac{K}{{G_V}^2 |M_F|^2}$.

Testing the CVC hypothesis and CKM unitarity:

- Corrected ft value

$$\mathcal{F}t \equiv ft(1+\delta_R)(1-\delta_C) = \frac{K}{|M_F|^2 G_V^2 (1+\Delta_R^V)}$$



From Towner & Hardy

Testing the CVC hypothesis and CKM unitarity:

$$V_{ud} = 0.97424(22), V_{us} = 0.22534(93), V_{ub} = 3.39 \times 10^{-3}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99990 \pm 0.00060$$

- Isospin breaking corrections
  - Towner and Hardy: Phys. Rev. C, 77, 025501 (2008) ($\delta_C = \delta_{C1} + \delta_{C2}$)
    - Shell model with Woods-Saxon and Hartree-Fock radial functions
  - Miller and Schewnk: Phys. Rev. C, 78, 035501 (2008)
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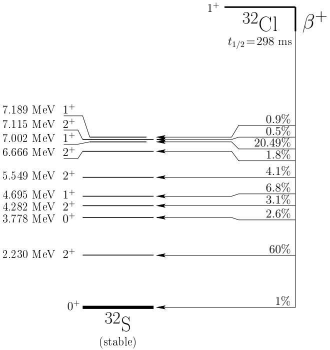
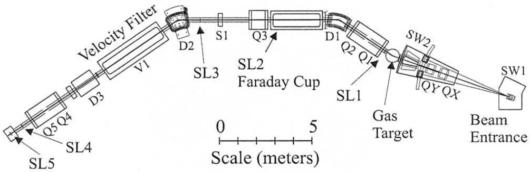
    "Standard Model isospin commutation relations are violated if one uses the isospin operators of Towner and Hardy"
    "The neglected radial contributions are significant at leading (second) order in ISB interactions"
  - Auerbach: Phys. Rev. C, **79**, 035502 (2009)
    - Isovector monopole resonance model (IVMR)
  - Liang, Van Giai, and Meng: Phys. Rev. C, **79**, 064316 (2009)
    - Relativistic Hartree-Fock with the random phase approximation (RPA) + density-dependent interactions.
  - Satula, Dobaczewski, Nazarewicz, and Rafalski: Phys. Rev. Lett, **106**, 132502 (2011)
    - Self-consistent isospin-and angular-momentum-projected nuclear density functional theory

^{32}Cl decay as a means to test the calculations

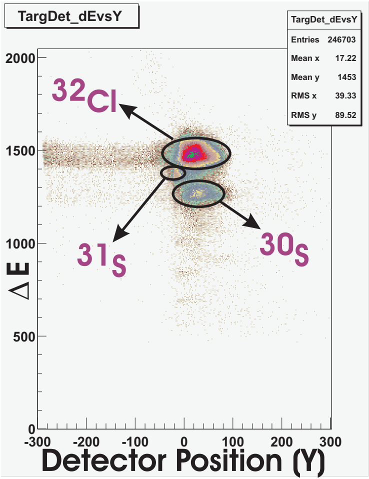


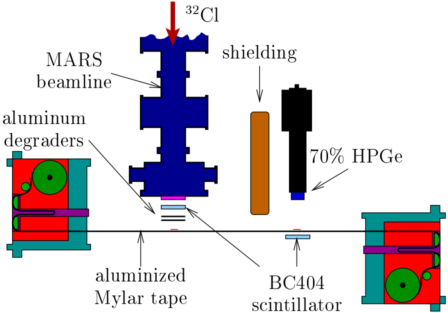


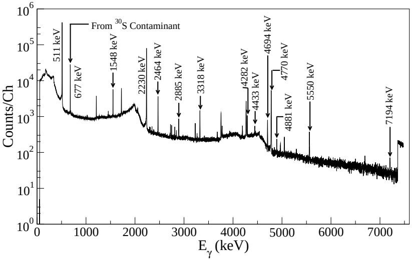
MARS at TAMU

- Check in cases where δ_C is large ($A = 4n$ nuclei)
- ^{32}Cl decay seems to be a close-to-ideal case for such tests (A shell model calculation yields $\delta_C = 4.8 \pm 0.5\%$)

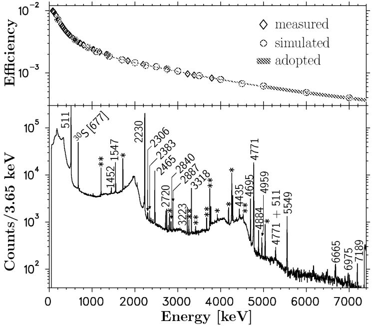
Experimental setup

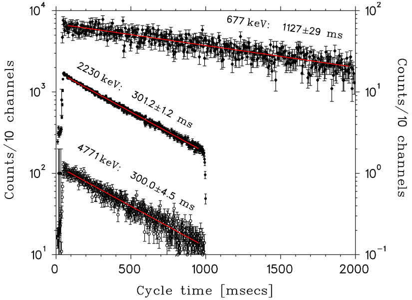


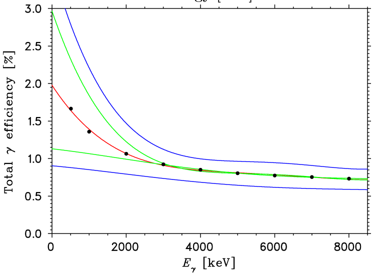


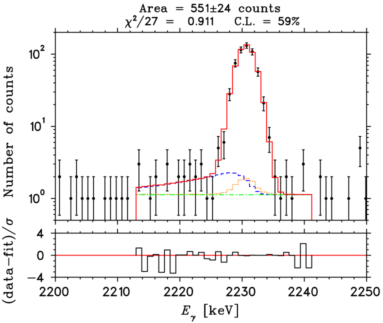


Understanding our systematic effects

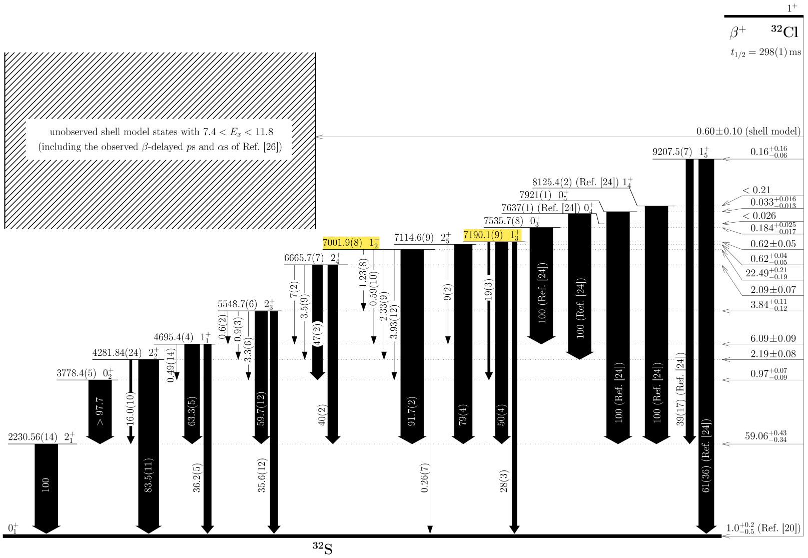




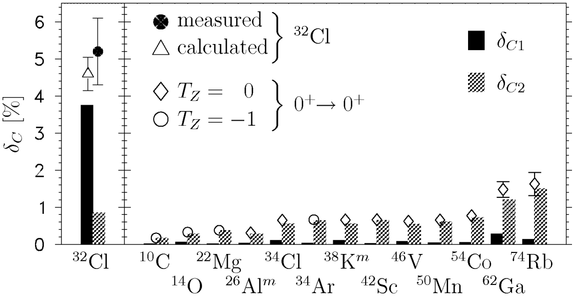




Detailed decay scheme (include pandemonium effects)



Results



$$(\delta_C - \delta_{NS})_{\text{exp}} = 1 - \frac{2\mathcal{F}t^{0^+\to 0^+}}{ft^{\text{IAS}}(1+\delta_{R'})\,[B(F)+B(GT)]} = 5.4 \pm 0.9\%$$

$\mathrm{B(GT)} = 0.002 \pm 0.002$; B.R $= 22.49 \pm 0.13^{+0.16}_{-0.14}$

Shell model: $\delta_{C1} = 3.75 \pm 0.45\%$, $\delta_{C2} = 0.85 \pm 0.03\%$

A sensitive benchmark for the methods used to calculate δ_C

Another stringent test of isospin symmetry breaking

Phys. Rev. Lett. 107, 182301 (2011) [5 pages]

Experimental Validation of the Largest Calculated Isospin-Symmetry-Breaking Effect in a Superallowed Fermi Decay

D. Melconian[1,2,3,*], S. Triambak[3,4], C. Bordeanu[3,†], A. García[3], J. C. Hardy[1,2], V. E. Iacob[2], N. Nica[2], H. I. Park[1,2], G. Tabacaru[2], L. Trache[2], I. S. Towner[1,2], R. E. Tribble[1,2,‡], and Y. Zhai[1,2]

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[2]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843-3366, USA*

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See accompanying *Physics* Synopsis

Conclusions

- Completed a set of high-precision measurements in the $A = 32$ system.
- Observe a large violation of the IMME.
- Observe large isospin symmetry breaking for $^{32}\mathrm{Cl}$ decay.
- Shell model calculations of isospin symmetry breaking agree with experimental extractions.

Collaborators:

- University of Washington: A. García and E. G. Adelberger
- TAMU: J.C. Hardy, D. Melconian, I. S. Towner, V.E. Iacob, and R. E. Tribble,

Thank you for your attention!

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Thank you for your attention!

Data analysis procedure

- Line-shape function used to fit γ peaks was of the form:

$$L(E;E') = \sum_{i=1}^{2} \frac{\alpha_i}{2\lambda_i} \exp\left[\frac{(E-E')}{\lambda_i} + \frac{1}{2}\left(\frac{\sigma}{\lambda_i}\right)^2\right] \times$$
$$\mathrm{erfc}\left[\frac{1}{\sqrt{2}}\left(\frac{(E-E')}{\sigma} + \frac{\sigma}{\lambda_i}\right)\right] + G(E;E')\ ,$$

- Peak centroids and areas were obtained using the fitting function:

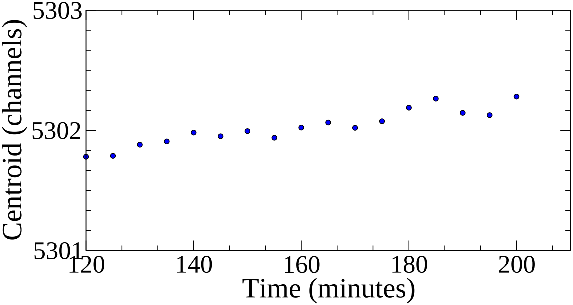
$$F(E;E') = \frac{A}{1+\alpha_1+\alpha_2} L(E;E') + B$$

- Minimize sensitivity to line-shape variations:

$$E_{\gamma i} = a + bx_i; \qquad E_{\gamma i}(^{32}\mathrm{S}) = E_{\gamma i}(\textsf{cal}) + b \times [x_i(^{32}\mathrm{S}) - x_i(\textsf{cal})]$$

Systematic effects

- Gain drifts



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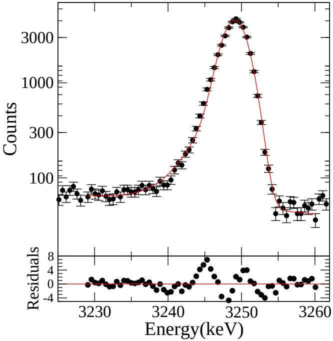
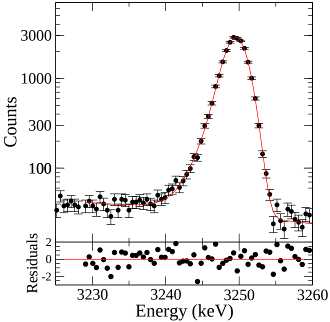


$$\chi^2/\nu = 3.99$$



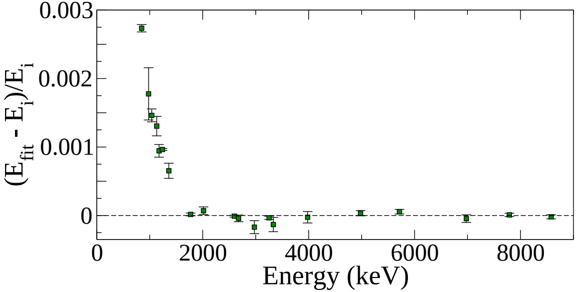
$$\chi^2/\nu = 1.09$$

Systematic effects

- Doppler effects
  - For $^{31}\mathrm{P}(p,\gamma)$ and $^{27}\mathrm{Al}(p,\gamma)$:
    - Detector size and possible mis-alignment
    - Recoil slowing
    - $\gamma - \gamma$ angular correlation
  - For $^{35}\mathrm{Cl}(n,\gamma)$:
    - Detector size and mis-alignment
    - Neutron angular distribution and scattering
    - Interaction of the γ rays with Ge (PENELOPE).

Systematic effects

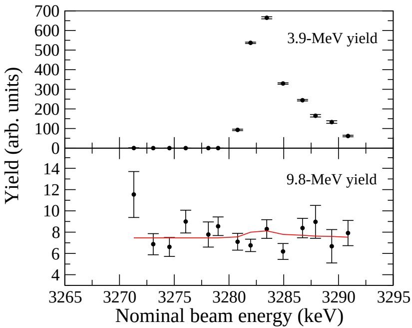
- ADC non-linearities

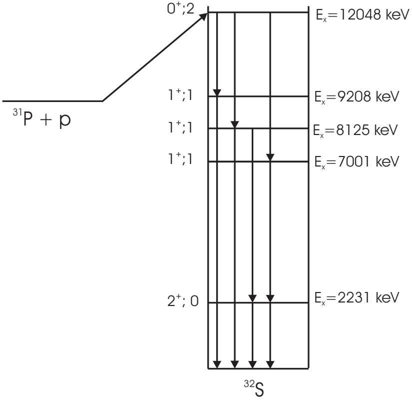


- Field increment effect
- non-resonant background

Isospin mixing?

- isospin violating branch (upper limit)
- two 0^+ states nearby (potential candidates)





Superallowed Fermi decays & the Standard Model

β-decay rate given by Fermi's golden rule: $\frac{1}{t} = \frac{2\pi}{\hbar}|M_{fi}|^2 f(E)$

The transition matrix element can be decomposed into two components: $|M_{fi}|^2 = {G_V}^2|M_F|^2 + {G_A}^2|M_{GT}|^2$

$|M_F|^2 = \frac{1}{2J_i+1}\sum_{f,i}|\langle f||\sum_k \tau^{\pm}(k)||i\rangle|^2$: Fermi (vector) from (γ^μ)

$|M_{GT}|^2 = \frac{1}{2J_i+1}\sum_{f,i}|\langle f||\sum_k \tau^{\pm}(k)\vec{\sigma}(k)||i\rangle|^2$: Gamow-Teller (axial vector) from $(\gamma^\mu\gamma_5)$

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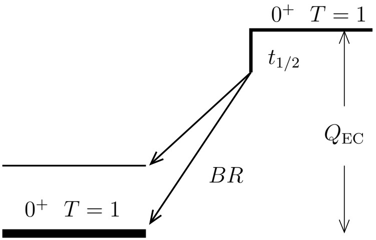
$|M_F|^2 = \dfrac{1}{2J_i+1} \sum_{f,i} |\langle f|| \sum_k \tau^{\pm}(k)||i\rangle|^2$: Fermi (vector) from (γ^μ)

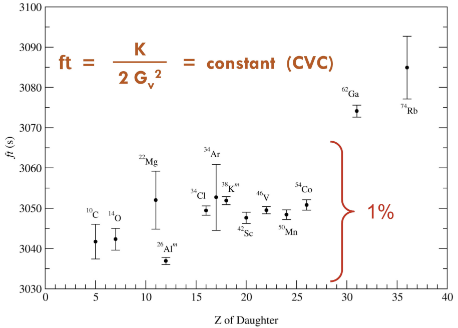
- A $0^+ \to 0^+$ transition between IAS proceeds via a purely vector interaction.
- Axial-vector coupling strength vanishes to lowest order
- The CVC hypothesis: $ft = \dfrac{K}{{G_V}^2 |M_F|^2}$.

CVC and CKM unitarity tests using superallowed decays

- Procedure: measure the ft values for many $0^+ \to 0^+$ transitions

Required experimental data:

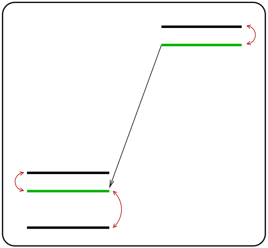




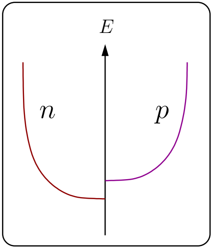
J.C. Hardy and I.S. Towner, Physical Review C **79**, 055502 (2009)

Nuclear structure and radiative effects

- Isospin symmetry breaking

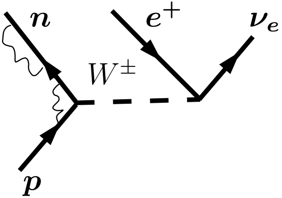
1) 

Configuration mixing

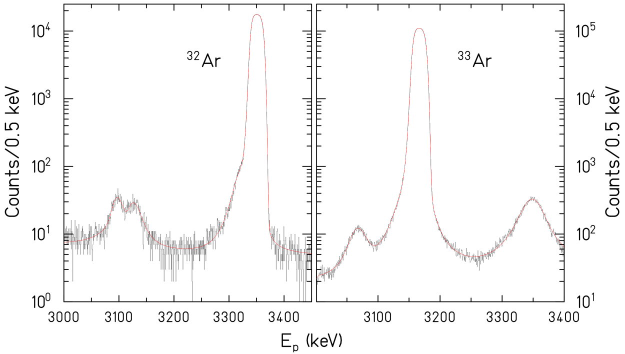
2) 

Radial overlap

- Radiative corrections

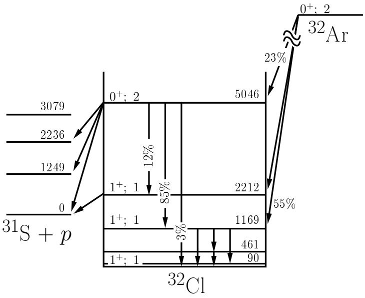


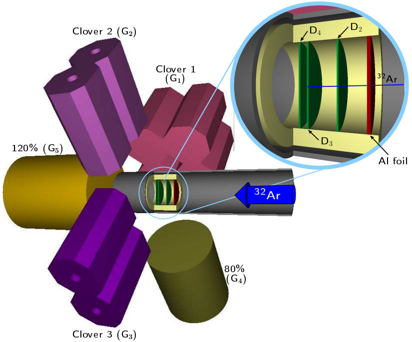
^{32}Ar proton spectrum



ft value for the decay of ^{32}Ar

- NSCL at Michigan State University
- cocktail ^{32}Ar beam





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