NUCLEAR LANDSCAPE EXPLORED WITH ELECTRIC MONOPOLE, E0 TRANSITIONS

Electric monopole, E0 transitions are unique to nuclei; they are not observed in any other manifestations of matter.

Tibor Kibédi
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Research School of Physics, Australian National university

Australian
National
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Electron spectroscopy and nuclei

We study nuclei by observing energy changes, notably by:

- ☐ Changes in particle energies — inelastic scattering of a monoenergetic beam by a target
- ☐ Emitted energies of radiations from radioactive decay or a reaction

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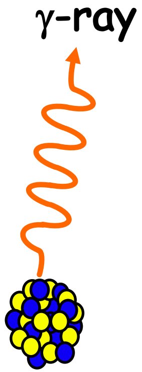

γ-rays — γ-ray spectroscopy

Talks by AJ Mitchell (MO), Martha Reece (TUE),

Andrew Stuchbery (FRI) and Ben Coombes FRI)

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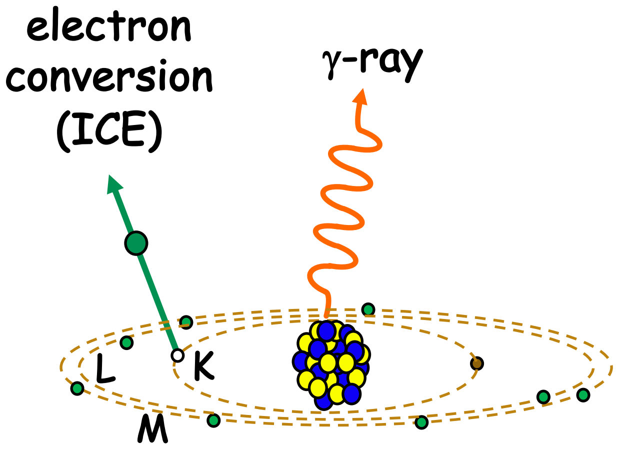

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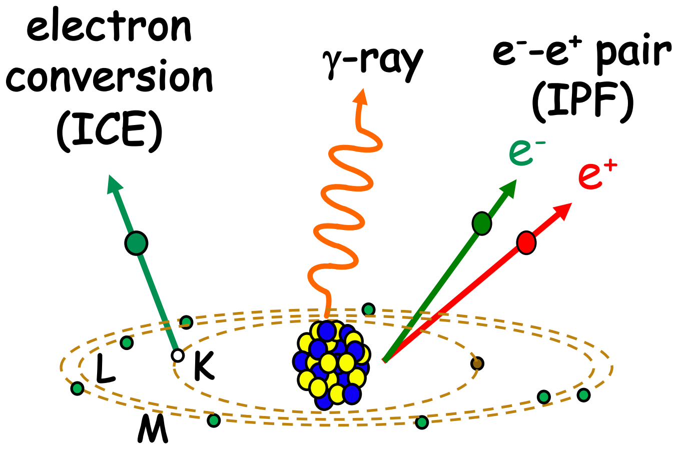

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Conversion electrons — ICE spectroscopy

e- e+ pair formation — IPF spectroscopy

Talk by Martin Sevior (TUE)

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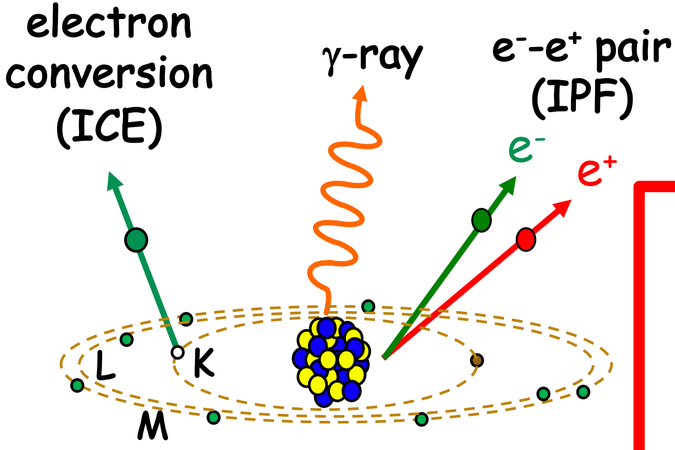

Relative ICE & IPF emission probabilities ~Z, Eγ

⇓

Conversion coefficient

⇓

Transition multipolarity
(electric or magnetic character & multipole order)

Electron spectroscopy and nuclei

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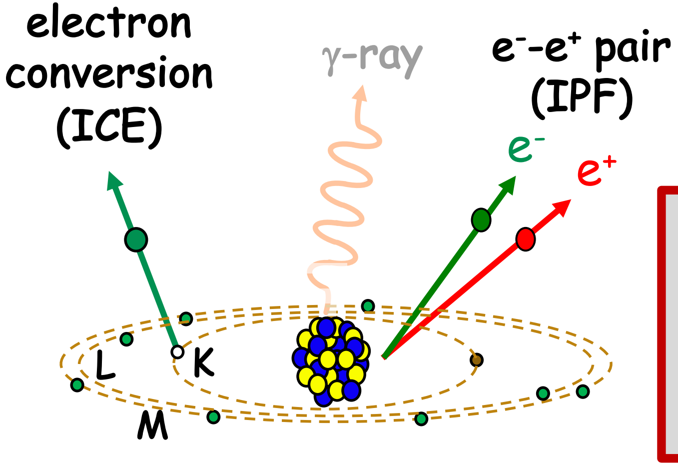
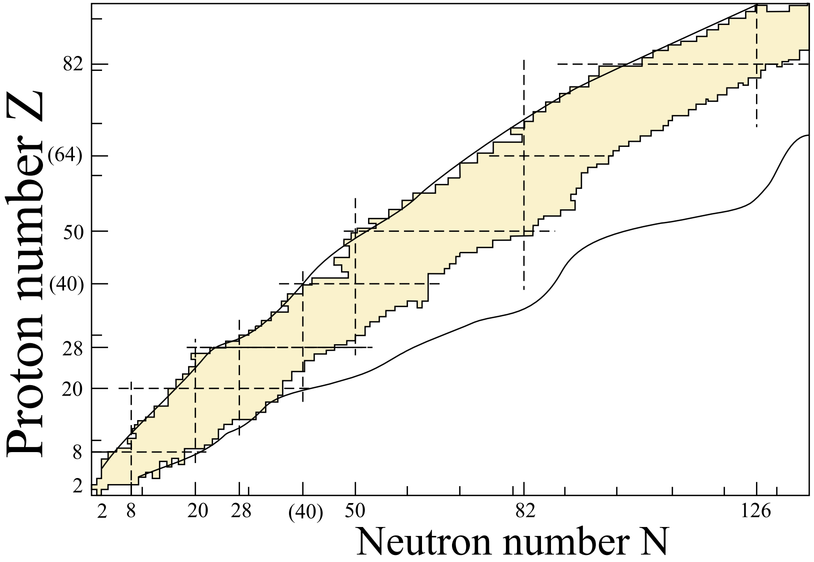


A fundamental limitation to γ-ray spectroscopy is γ-rays (photons) possess a spin of one ($1\,\hbar$):

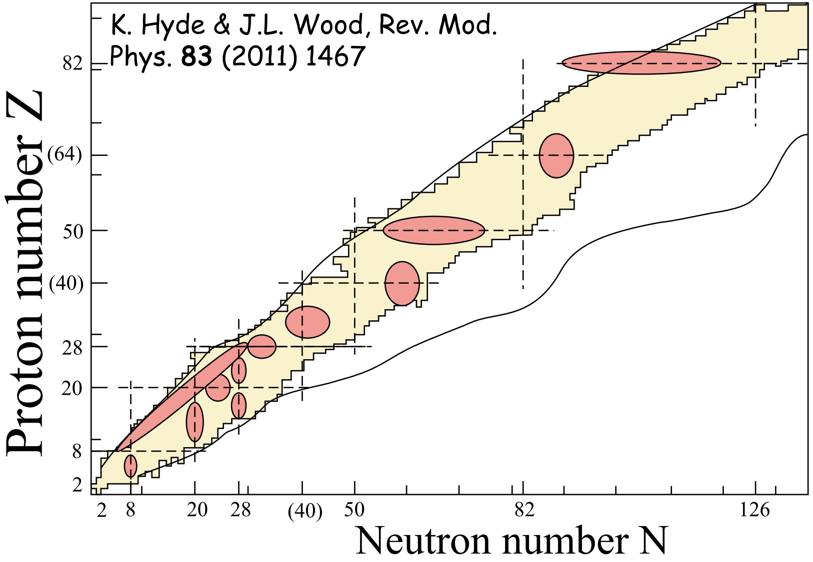
γ-ray spectroscopy cannot "see" spin-0 → spin-0 processes

Nuclear states of spin-0



One quarter of all nuclei (even-even) possess ground states with spin-0

Nuclear states of spin-0



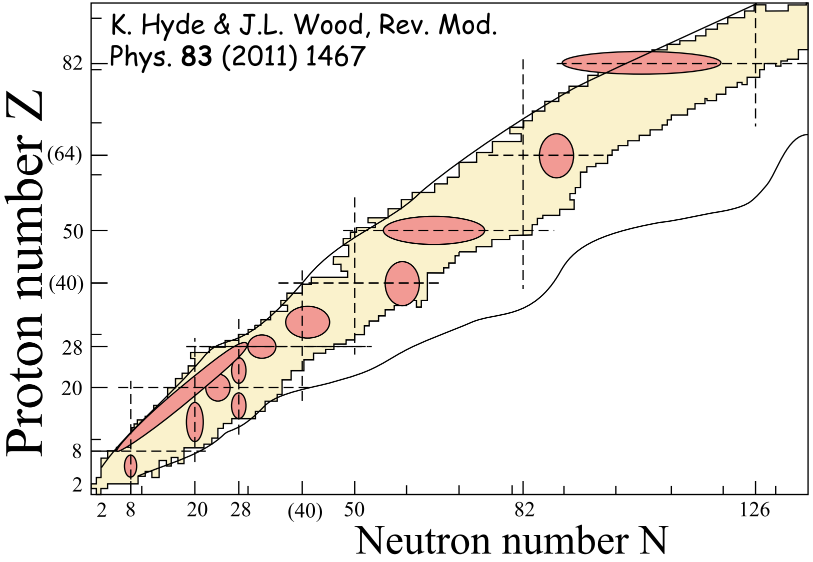
One quarter of all nuclei (even-even) possess ground states with spin-0

Spin-0 excited states occur widely, where nuclei can have different shapes (deformation) — shape coexistence

Shape coexistence:

- ❑ from an exotic rarity (1980')
- ❑ via a perception that is a phenomenon which exhibits "islands of occurrence" (1990')

Nuclear states of spin-0



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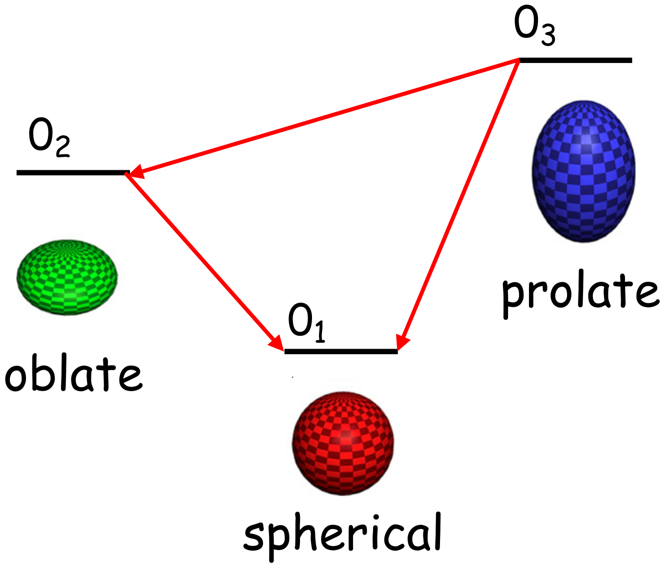
Shape coexistence:

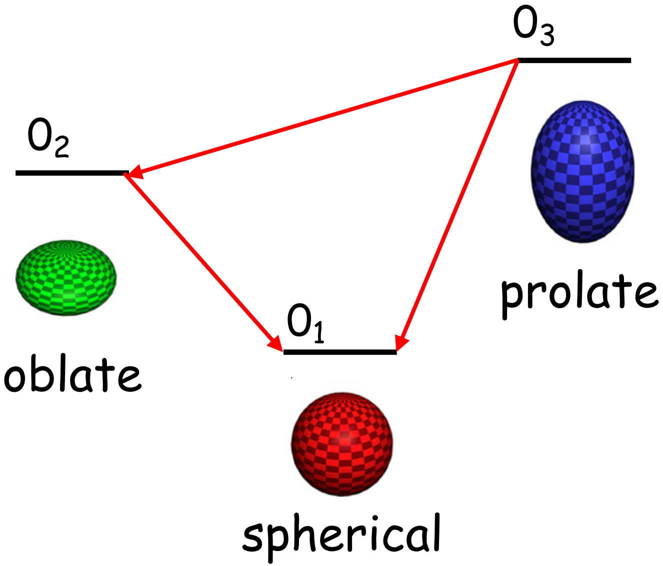
- ☐ from an exotic rarity (1980')
- ☐ via a perception that is a phenomenon which exhibits "islands of occurrence" (1990')
- ☐ to the current position in which it seems to occur in all nuclei (Z≥8)

E0 transitions – ideal probes of shape coexistence



Only E0 transitions allowed between spin-0 states

E0 transitions – ideal probes of shape coexistence

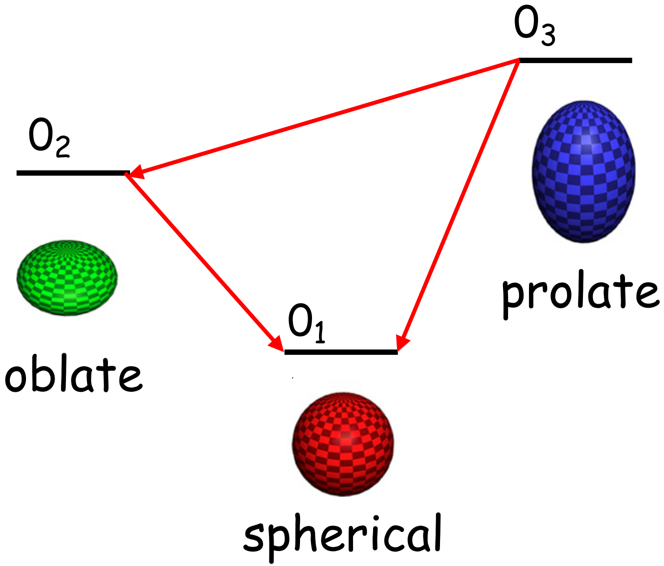


Only E0 transitions allowed between spin-0 states

E0 transitions in nuclei do not have an intrinsic origin:

- Monopole moments do not define rotation
- Monopole vibrations only exist at high energy (~15 MeV, nuclear matter is incompressible)
- Low energy E0 transitions in nuclei originate from quantum mechanical mixing

E0 transitions – ideal probes of shape coexistence



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Mixing origin of E0 strengths

- Strength generated by difference in mean-square radii of unmixed configurations
- Strength depends on mixing amplitudes
- Different deformations in nuclei = different mean-square charge radii

E0 transition strengths: a model-independent description

Monopole strength parameter

$$\rho_{if} = \frac{\langle f[\sum_j e_j r_j^2] i\rangle}{eR^2} \equiv \frac{\langle f|m(E0)|i\rangle}{eR^2} \equiv \frac{M_{if}(E0)}{eR^2}$$

Monopole strength from mixing of states with different <r²>

$|i\rangle = \alpha|1\rangle + \beta\,|2\rangle$, $\quad |f\rangle = -\beta|1\rangle + \alpha\,|2\rangle$

$$M_{if}(E0) = \alpha\beta\{\langle 2|m(E0)|2\rangle - \langle 1|m(E0)|1\rangle\} + (\alpha^2 - \beta^2)\langle 1|m(E0)|2\rangle$$

$$M_{if}(E0) \approx \alpha\beta\,\Delta\langle r^2\rangle$$

$$\Delta\langle r^2\rangle \equiv -\left\langle 1\left|\sum_j e_j r_j^2\right|1 + \left\langle 2\left|\sum_j e_j r_j^2\right|2\right\rangle\right\rangle$$

From David G Jenkins and John L Wood, Nuclear Data: A Primer, IOP, Bristol, UK, 2021

Observing E0 transitions

- Must be conversion electron (ICE) or electron-positron pair formation (IPF)
- Source/target and electron detector mast be in high vacuum
- γ-ray emission more probable; need magnetic separation
- High resolution; thin targets

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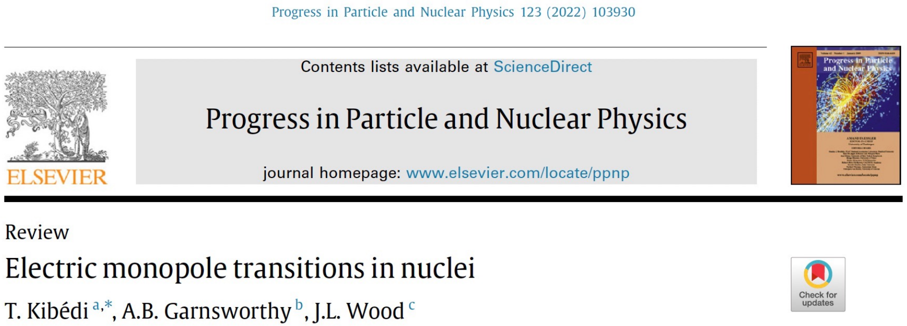

Progress in Particle and Nuclear Physics 123 (2022) 103930

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journal homepage: www.elsevier.com/locate/ppnp

Review

Electric monopole transitions in nuclei

T. Kibédi[a,*], A.B. Garnsworthy[b], J.L. Wood[c]

Characterizing E0 transitions

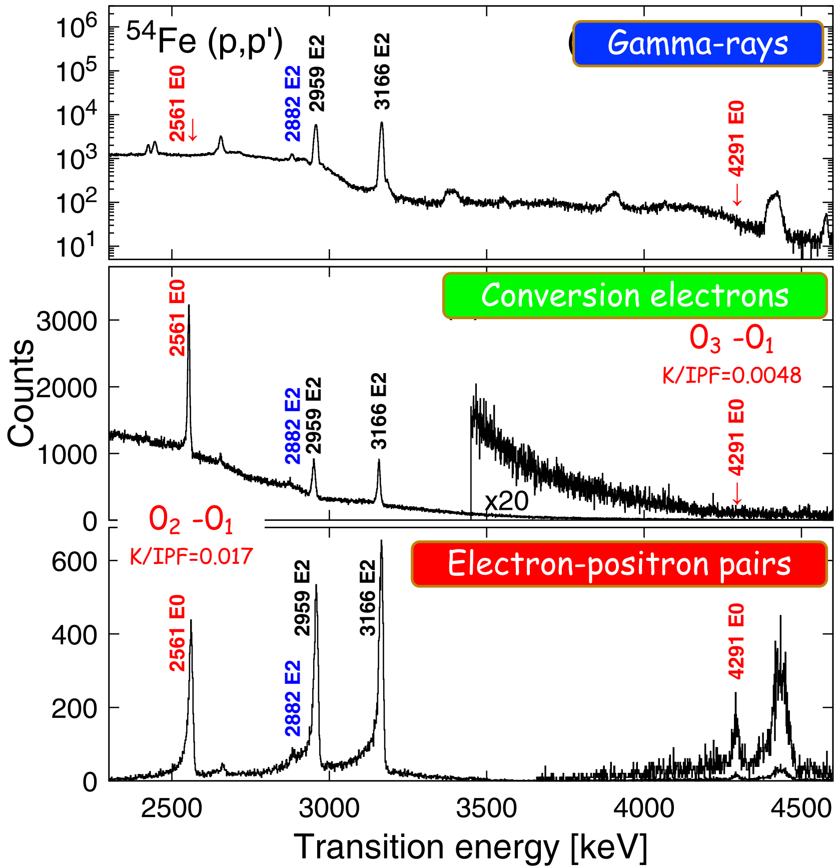
- Monopole strength parameter

$$\rho_{if} = \frac{M_{if}(E0)}{eR^2} = \frac{1}{\tau(E0)\times\Omega(E0)}$$

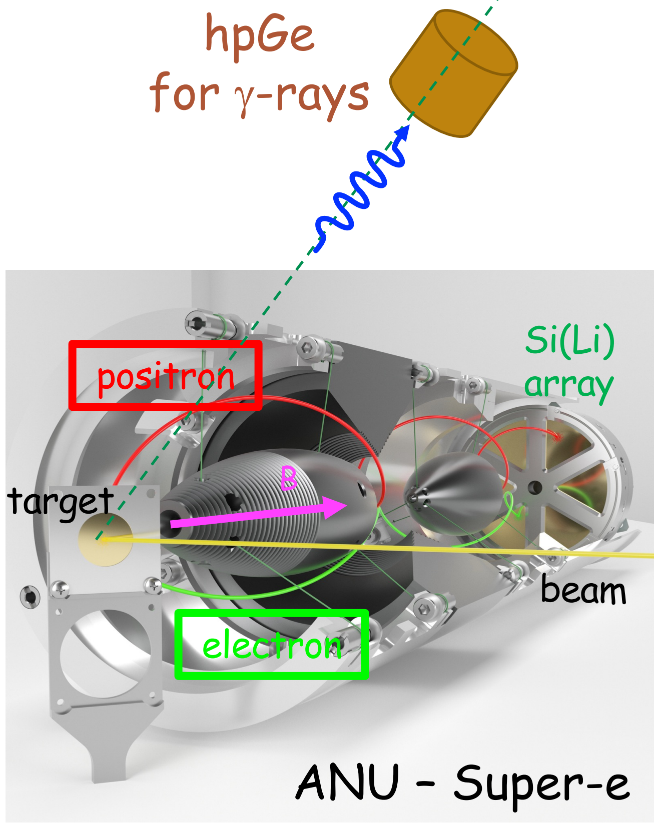
- γ-ray spectroscopy, branching ratios, conversion coefficients, E2/M1 mixing ratios for M1+E2+E0 transitions between J>0 states $(2^+ - 2^+)$
- Lifetime measurements

<u>ANU HIAF:</u> Has the flexibility to measure conversion electrons, e+e- pairs, γ-rays and lifetimes

Observing E0 transitions



T. Eriksen, PhD, ANU (2018)



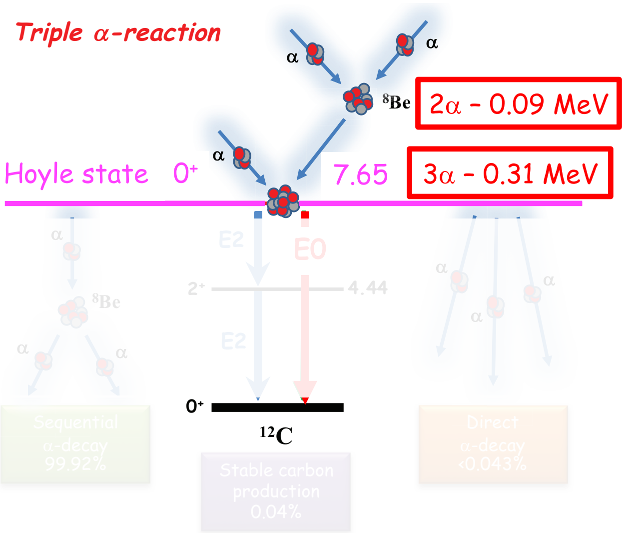
T. Kibédi, et al., NIM **A294** (1990) 223
T. Eriksen, et al., Phys. Rev. **C 102** (2020) 024320
J.T.H. Dowie, et al., Phys. Lett **B 811** (2021) 135855
E. Ideguchi, et al., Phys. Lett. **128** (2022) 252501

The Hoyle state

There are few nuclei that have captured the imagination more than carbon-12

Carbon production, the triple-α and the $^{12}C(a,\gamma)^{16}O$ reactions are the key to synthesis of all elements (except hydrogen and helium)

The production of the Hoyle state

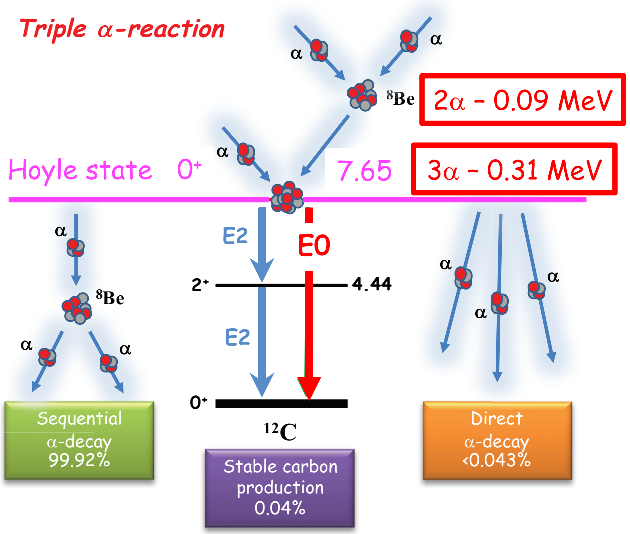


There are few nuclei that have captured the imagination more than carbon-12.

Carbon production, the triple-α and the $^{12}C(a,\gamma)^{16}O$ reactions are key to synthesis of all elements (except hydrogen and helium)

The gateway through which that synthesis proceeds is dominated by the presence of the second excited state at 7.65 MeV, $J^{\pi} = 0^{+}$ in ^{12}C; the Hoyle state.

The decay of the Hoyle state



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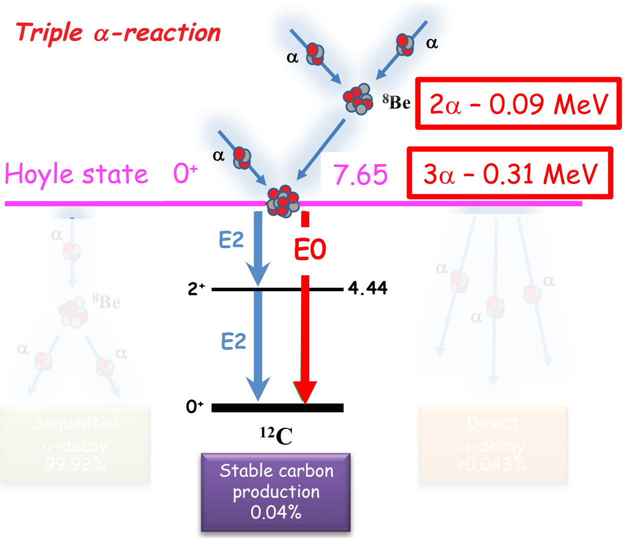
What we know about the radiative width of the Hoyle state (2014)



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The triple-α reaction rate:

$$r_{3\alpha} \sim \Gamma_{rad}$$

Γ_{rad} = 0.0037(4) eV; Γ=9.3 eV

1:2500 chance to make stable carbon!

Challenge: Can the accuracy improved?

$$\Gamma_{rad} = \left[\frac{\Gamma_{rad}}{\Gamma}\right]\times\left[\frac{\Gamma}{\Gamma_\pi(E0)}\right]\times[\Gamma_\pi(E0)]$$

- ☐ $\Gamma_\pi(E0)/\Gamma = 6.7(6)\times10^{-6}$
- ☐ $\Gamma_{rad}/\Gamma = 4.19(11)\times10^{-4}$
- ☐ $\Gamma_\pi(E0) = 62(2)\ \mu eV$

$\Gamma_\pi(E0)/\Gamma$ - Super-e (ANU)

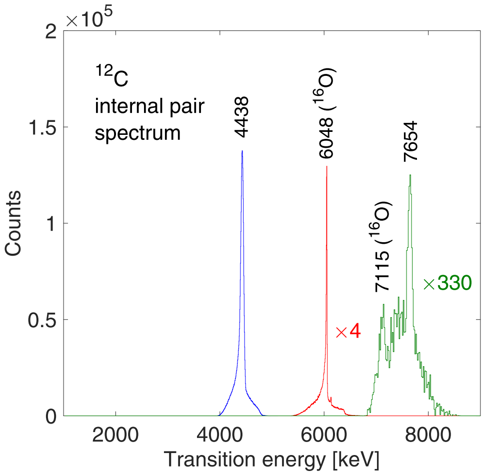
- ☐ $^{12}C(p,p')$ @ 10.5 MeV, ~1 μA, 1-2 mg/cm^2 nat C

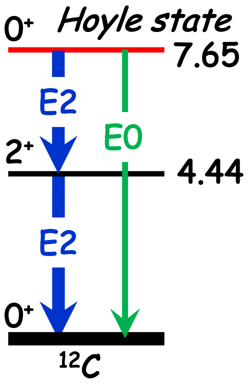
$$\boxed{\frac{\Gamma_\pi^{E0}}{\Gamma} = \frac{N_\pi^{E0}}{N_\pi^{E2}} \times \frac{N_p(4.44)}{N_p(7.65)} \times \frac{\epsilon_\pi^{E2}}{\epsilon_\pi^{E0}} \times \frac{\alpha_\pi}{1+\alpha_\pi}}$$

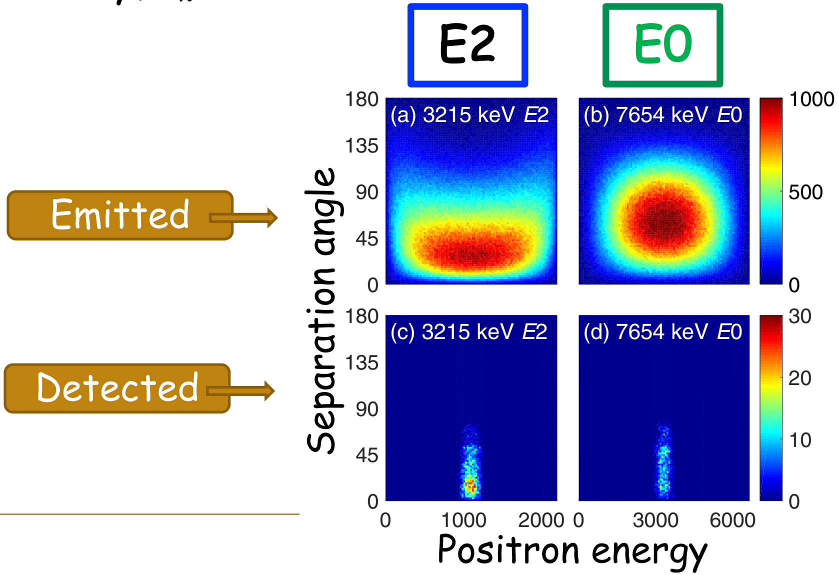
14% UP

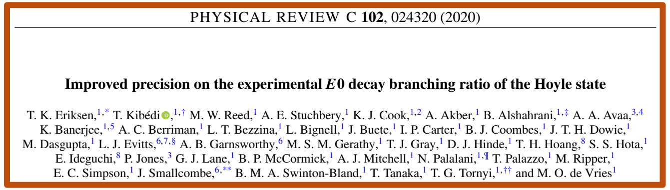
$$\boxed{\Gamma_{rad} = \left[\frac{\Gamma_{rad}}{\Gamma}\right] \times \left[\frac{\Gamma}{\Gamma_\pi(E0)}\right] \times [\Gamma_\pi(E0)]}$$

- ☐ 4.44 MeV E2 to normalise proton to e+e- pair ratio
- ☐ e+e- pair efficiency, ε_π from Monte Carlo





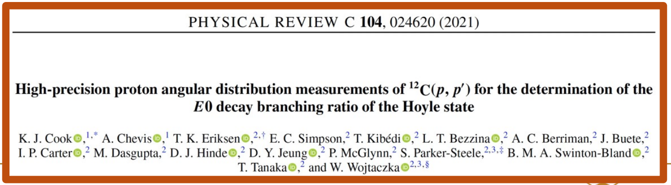




PHYSICAL REVIEW C **102**, 024320 (2020)

Improved precision on the experimental $E0$ decay branching ratio of the Hoyle state

T. K. Eriksen,[1,*] T. Kibédi,[1,†] M. W. Reed,[1] A. E. Stuchbery,[1] K. J. Cook,[1,2] A. Akber,[1] B. Alshahrani,[1,‡] A. A. Avaa,[3,4] K. Banerjee,[1,5] A. C. Berriman,[1] L. T. Bezzina,[1] L. Bignell,[1] J. Buete,[1] I. P. Carter,[1] B. J. Coombes,[1] J. T. H. Dowie,[1] M. Dasgupta,[1] L. J. Evitts,[6,7,§] A. B. Garnsworthy,[6] M. S. M. Gerathy,[1] T. J. Gray,[1] D. J. Hinde,[1] T. H. Hoang,[8] S. S. Hota,[1] E. Ideguchi,[8] P. Jones,[3] G. J. Lane,[1] B. P. McCormick,[1] A. J. Mitchell,[1] N. Palalani,[1,¶] T. Palazzo,[1] M. Ripper,[1] E. C. Simpson,[1] J. Smallcombe,[6,**] B. M. A. Swinton-Bland,[1] T. Tanaka,[1] T. G. Tornyi,[1,††] and M. O. de Vries[1]

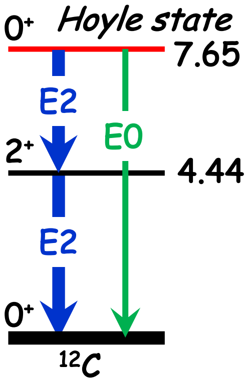


PHYSICAL REVIEW C **104**, 024620 (2021)

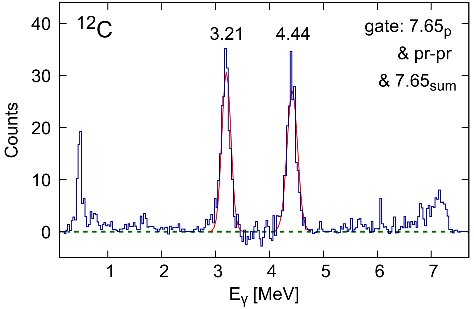
High-precision proton angular distribution measurements of $^{12}C(p,p')$ for the determination of the $E0$ decay branching ratio of the Hoyle state

K. J. Cook,[1,*] A. Chevis,[1] T. K. Eriksen,[2,†] E. C. Simpson,[2] T. Kibédi,[2] L. T. Bezzina,[2] A. C. Berriman,[2] J. Buete,[2] I. P. Carter,[2] M. Dasgupta,[2] D. J. Hinde,[2] D. Y. Jeung,[2] P. McGlynn,[2] S. Parker-Steele,[2,3,‡] B. M. A. Swinton-Bland,[2] T. Tanaka,[2] and W. Wojtaczka[2,3,§]

Γ_{rad}/Γ - CACTUS & SiRi (University of Oslo)



- ☐ ANU/Oslo experiment PRC 102, 024320 (2020)
- ☐ CACTUS (26 5"x5"NaI) & SiRi (64 ΔE-E)
- ☐ 12C(p,p`) @ 10.7 MeV, 180 μg/cm2 nat C
- ☐ $N_{020}^{7.65} = 217(21)$ p-γ-γ from $N_{sing}^{7.65} = 2.78(6)\times10^{8}$ singles proton events



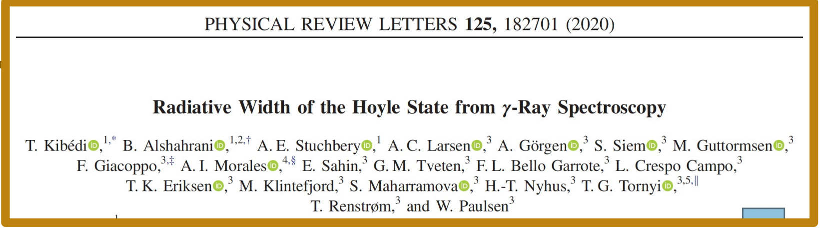
$$\frac{\Gamma_\gamma^{E2}}{\Gamma} = \frac{N_{020}^{7.65}}{N_{020}^{4.98}} \times \frac{N_{sing}^{4.98}}{N_{sing}^{7.65}} \times \frac{\epsilon_\gamma^{1.78}}{\epsilon_\gamma^{4.44}} \times \frac{\epsilon_\gamma^{3.20}}{\epsilon_\gamma^{3.21}} \times \frac{W_{020}^{4.98}}{W_{020}^{7.65}}$$

$$\frac{\Gamma_{rad}}{\Gamma} = \frac{\Gamma_\gamma^{E2}}{\Gamma}\times(1+\alpha_{tot}) + \frac{\Gamma_\pi^{E0}}{\Gamma} = 6.2(6)\times10^{-4}$$

50% UP

$$\Gamma_{rad} = \left[\frac{\Gamma_{rad}}{\Gamma}\right]\times\left[\frac{\Gamma}{\Gamma_\pi(E0)}\right]\times[\Gamma_\pi(E0)]$$

- ☐ 7.65 0+ (12C)
- ☐ 4.98 0+ (28Si) from 28Si(p,p`)
- ☐ ε_γ - gamma efficiency from MC
- ☐ W_{020} - correction for γ–γ angular correlation; 0+ - 2+ -0+



PHYSICAL REVIEW LETTERS **125,** 182701 (2020)

Radiative Width of the Hoyle State from γ-Ray Spectroscopy

T. Kibédi,[1,*] B. Alshahrani,[1,2,†] A. E. Stuchbery,[1] A. C. Larsen,[3] A. Görgen,[3] S. Siem,[3] M. Guttormsen,[3] F. Giacoppo,[3,‡] A. I. Morales,[4,§] E. Sahin,[3] G. M. Tveten,[3] F. L. Bello Garrote,[3] L. Crespo Campo,[3] T. K. Eriksen,[3] M. Klintefjord,[3] S. Maharramova,[3] H.-T. Nyhus,[3] T. G. Tornyi,[3,5,||] T. Renstrøm,[3] and W. Paulsen[3]

Recommended decay properties of the Hoyle state (2022)

$$\Gamma_{rad} = \left[\frac{\Gamma_{rad}}{\Gamma}\right] \times \left[\frac{\Gamma}{\Gamma_{\pi}(E0)}\right] \times [\Gamma_{\pi}(E0)]$$

The only absolute transition rate, from (e,e') scattering
M. Chernykh, et al.,
PRL 105 (2010) 022501

→

Property	Freer & Fynbo (2014)	Present study	Change
Γ_{rad}/Γ [x 10^{-4}]	4.19(11)	6.2(6)	+50(16)%
$\Gamma_{\pi}(E0)/\Gamma$ [x 10^{-6}]	6.7(6)	7.6(4)	+14(12)%
$\Gamma_{\pi}(E0)$ [μeV]	6.23(20)	adopted	N/A
Radiative width [eV]	0.0037(4)	0.0052(6)	+38(22)%
Total width [eV]	9.3(9)	8.2(5)	-10(11)%

New Radiative width – impact on nuclear astrophysics

☐ $^{12}C(\alpha,g)^{16}O$ rate: down by 15% (DeBoer, et al., Rev. Mod. Phys. 89 2017) 035007

> The **reliability of nucleosynthesis predictions** depends on the quality of the **stellar models** and the **nuclear reaction input parameters**

☐ Triple alpha rate: up by 38% (Kibédi, et al., PRL, 125 (2020) 182701

☐ Woosley & Heger, APJ 912 (2021) L31, "*The Pair-instability Mass Gap for Black Holes*":

> Using this large value of 3α and a reduced value for $^{12}C(\alpha,\gamma)^{16}O$ **may lead to difficulties in stellar nucleosynthesis** that have yet to be fully explored; Increased 3α rate considered as the upper error limit

☐ First results that the increased 3α rate could not be ruled out:

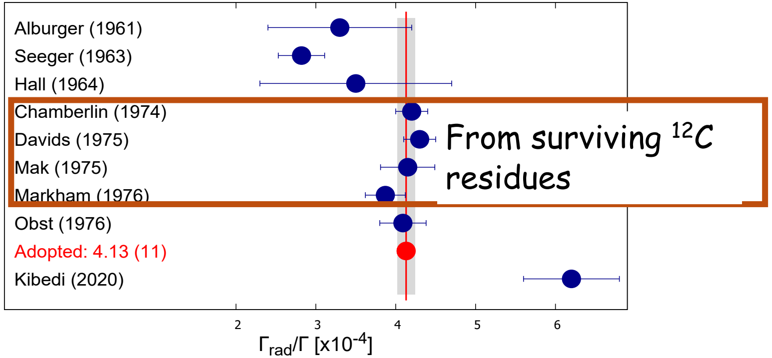
Farag, et al., APJ 937(2022) 112 (Black Hole Mass Spectrum);

Romano, Astron AstroPhys. Rev. 30 (2022) 7 (CNO nucleosynthesis)

Summary & Outlook

- ☐ ^{12}C: Γ_{rad} is determined from 3 independent measurements

$$\Gamma_{rad} = \left[\frac{\Gamma_{rad}}{\Gamma}\right] \times \left[\frac{\Gamma}{\Gamma_{\pi}(E0)}\right] \times [\Gamma_{\pi}(E0)]$$



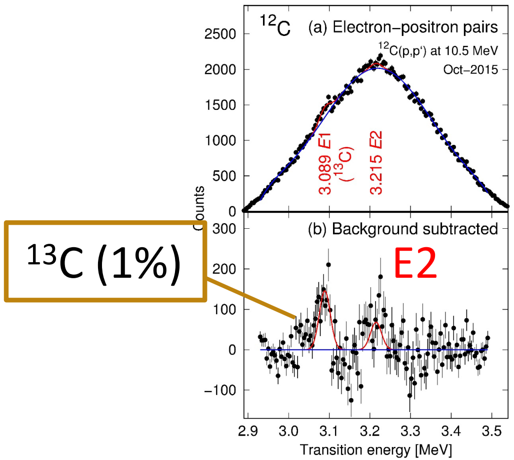
From surviving ^{12}C residues

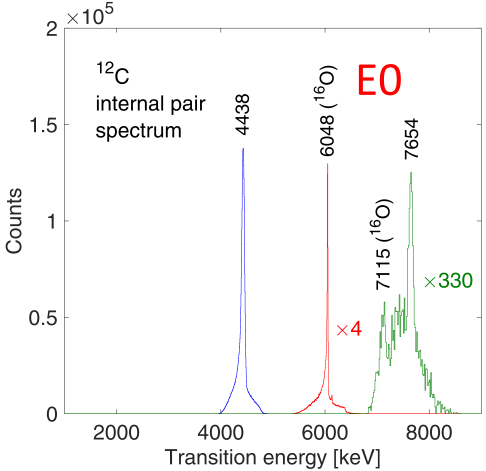
G. Cardella, et al., PRC 104, 064315 (2021)
CHIMERA 1192 Si-CsI(Tl) telescopes

Γ_{rad}/Γ=1.8(6) x10^{-3}

Can Γ_{rad} improved from pair conversion

$$\Gamma_{rad} = \left(\boxed{\frac{\Gamma_{\pi}(E2)}{\Gamma_{\pi}(E0)}} \times \left(1+\frac{1}{[\alpha_{\pi}(E2)]}\right)+1\right) \times [\Gamma_{\pi}(E0)]$$

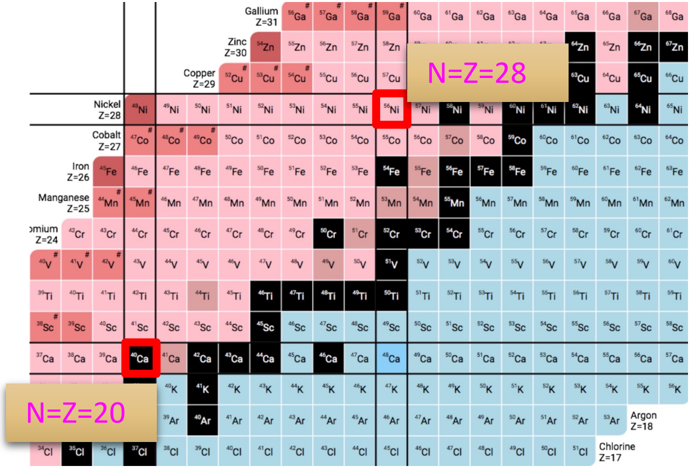




Super-e: background need to be reduced!

(α,α) could be a better reaction?

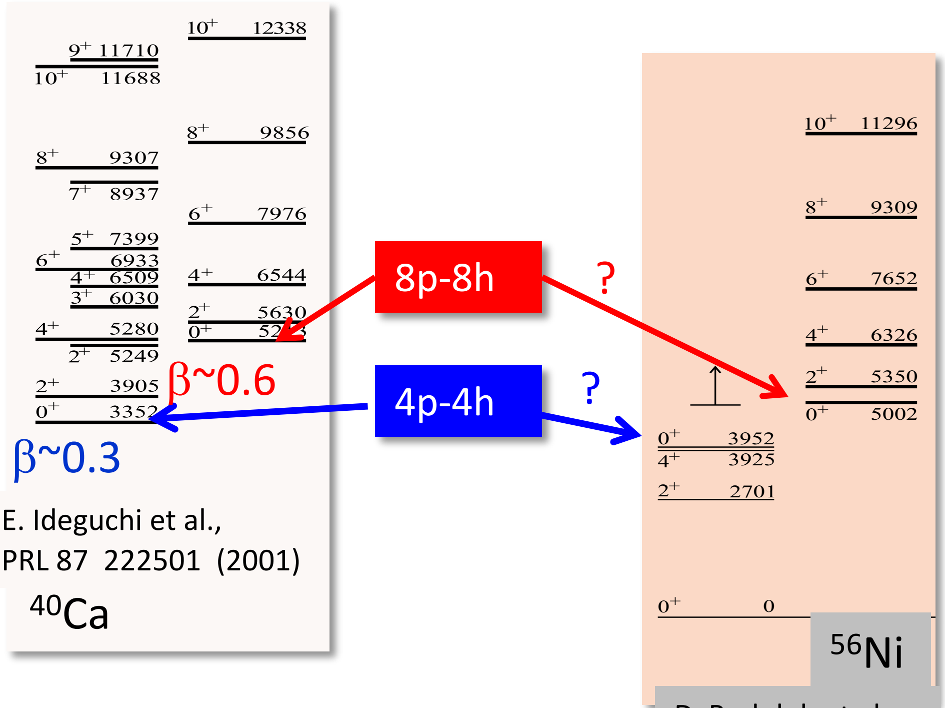
Shape coexistence in the double-closed shell nuclei ^{40}Ca and ^{56}Ni



- <u>Shape coexistence:</u>

  ^{40}Ca: ^{36,38,40}Ar, ^{42,44}Ca, ^{44}Ti; possible around N=28: ^{52,54,56}Fe, ^{50,52}Cr, ^{50}Ti(?)

- <u>Superdeformation:</u> ^{40}Ca, ^{58,60}Ni, ^{60}Zn
- <u>Limited number of nucleons</u> – relatively small model space in SM, and other models



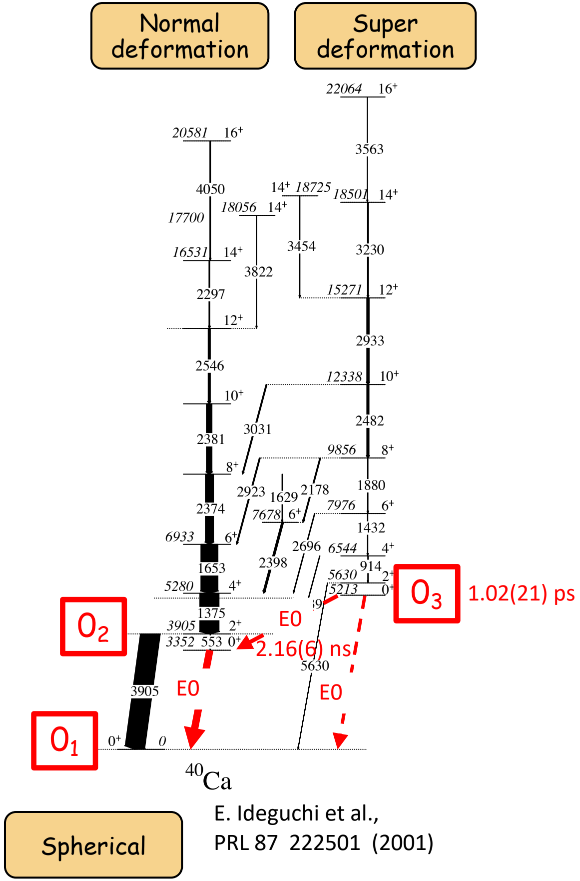
E. Ideguchi et al., PRL 87 222501 (2001)

D. Rudolph et al., PRL 82 3763 (1999)

Figure from K. Heyde & J.L. Wood

E0 transitions in ^{40}Ca

with Eiji Ideguchi (Osaka)

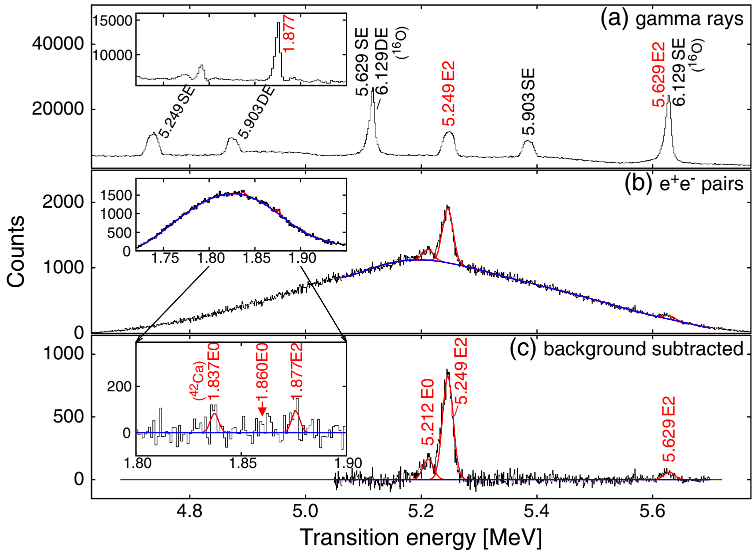


E. Ideguchi et al.,
PRL 87 222501 (2001)

Most γ-lines from 1st (FE) & 2nd (DE) escape peaks

Magnetic field optimmised for E0`s from 0_3 state

ANU Super-e ^{40}Ca(p,p`) at 8.6 MeV

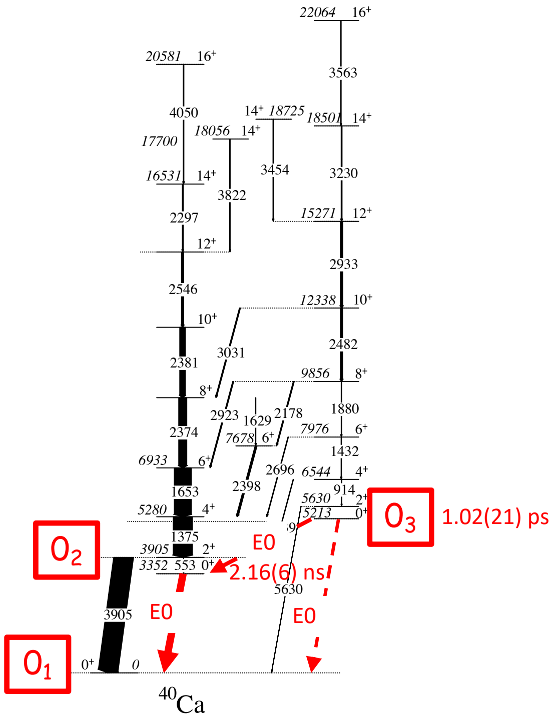


E0 transitions in ^{40}Ca

with Eiji Ideguchi (Osaka)

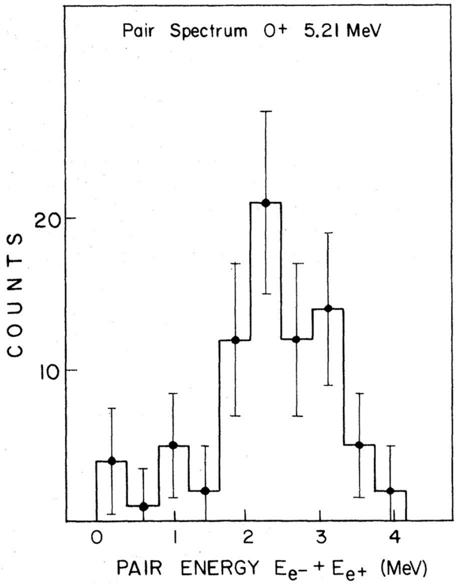
Normal deformation

Super deformation



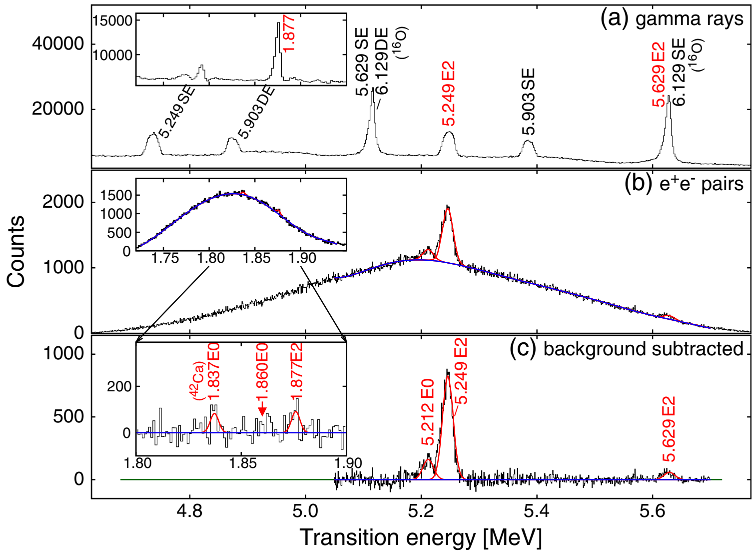
Spherical

E. Ideguchi et al.,
PRL 87 222501 (2001)



M. Ulrickson, et al., PRC15 (1977) 186
Two ΔE-E scintillator telescopes

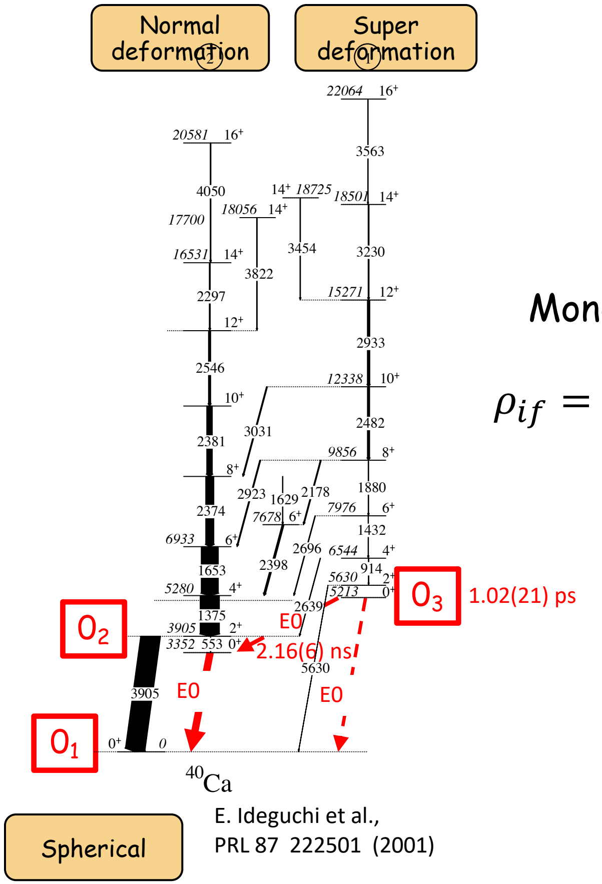
ANU Super-e ^{40}Ca(p,p`) at 8.6 MeV



FWHM~20 keV

E0 transitions in ^{40}Ca

with Eiji Ideguchi (Osaka)



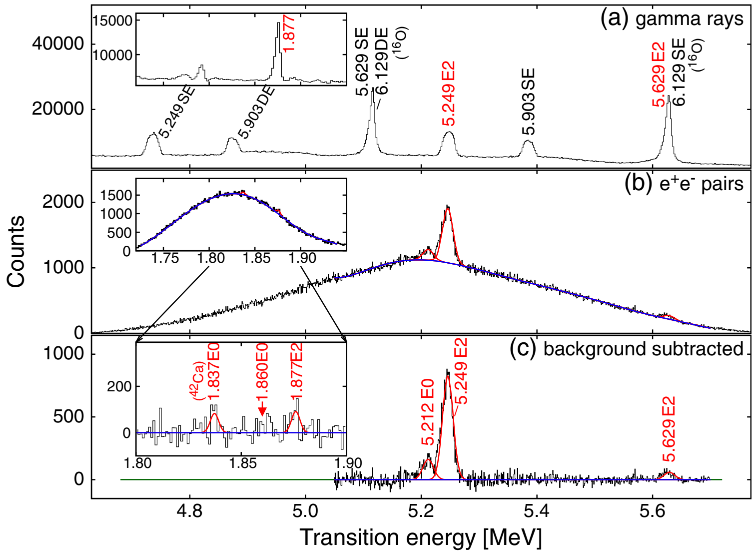
E. Ideguchi et al.,
PRL 87 222501 (2001)

Monopole strength parameter

$$\rho_{if} = \frac{M_{if}(E0)}{eR^2} = \frac{1}{\tau(E0)\times\Omega(E0)}$$

	$10^3\,\rho^2$
$0_2 \rightarrow 0_1$	25.9(16)
$0_3 \rightarrow 0_1$	2.3(5)
$0_3 \rightarrow 0_2$	< 45

ANU Super-e ^{40}Ca(p,p`) at 8.6 MeV

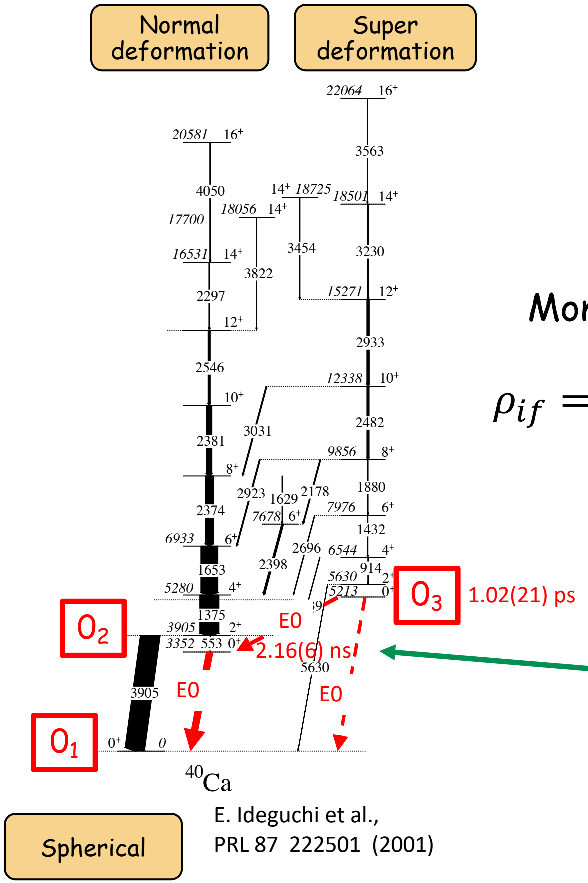


Calculated Ω(E0) electronic factors from

J. Dowie, ADNDT 131 (2020) 101283

E0 transitions in ^{40}Ca

with Eiji Ideguchi (Osaka)



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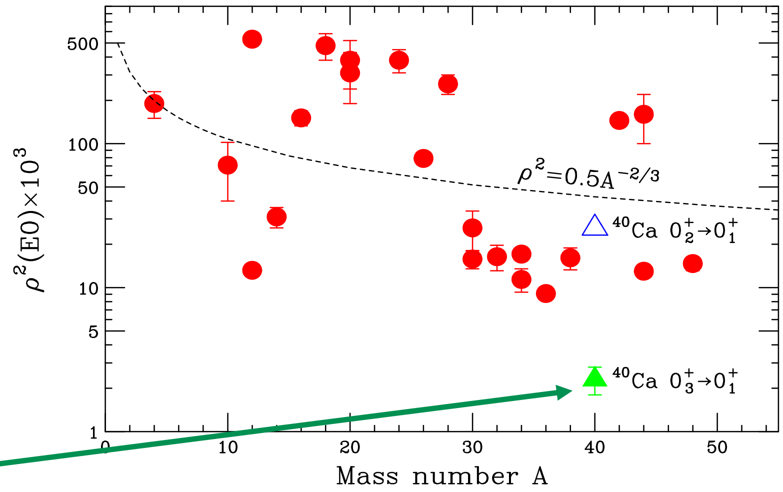
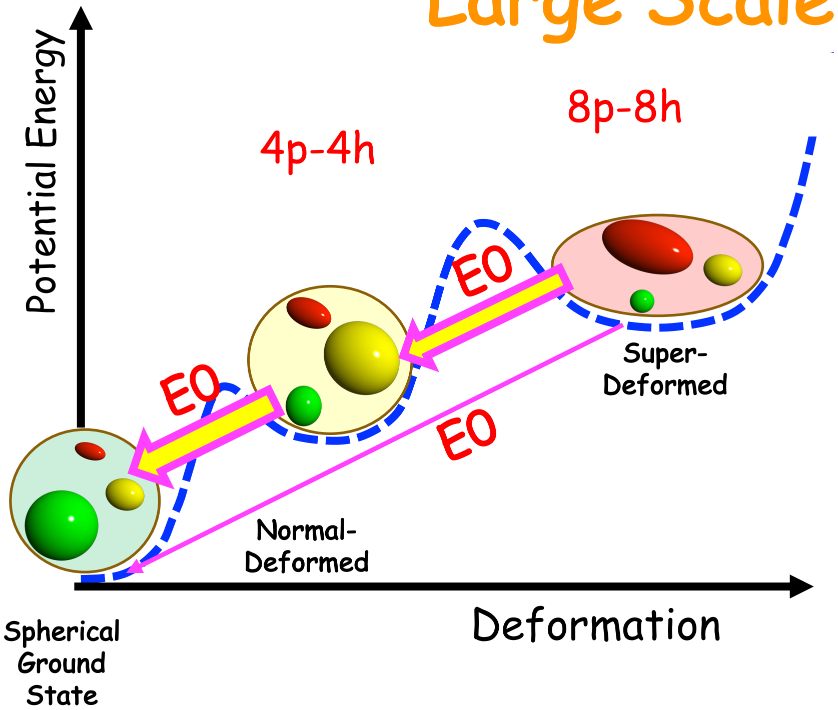


Strong E0 expected from SD to spherical GS

Smallest value in A<60 system!

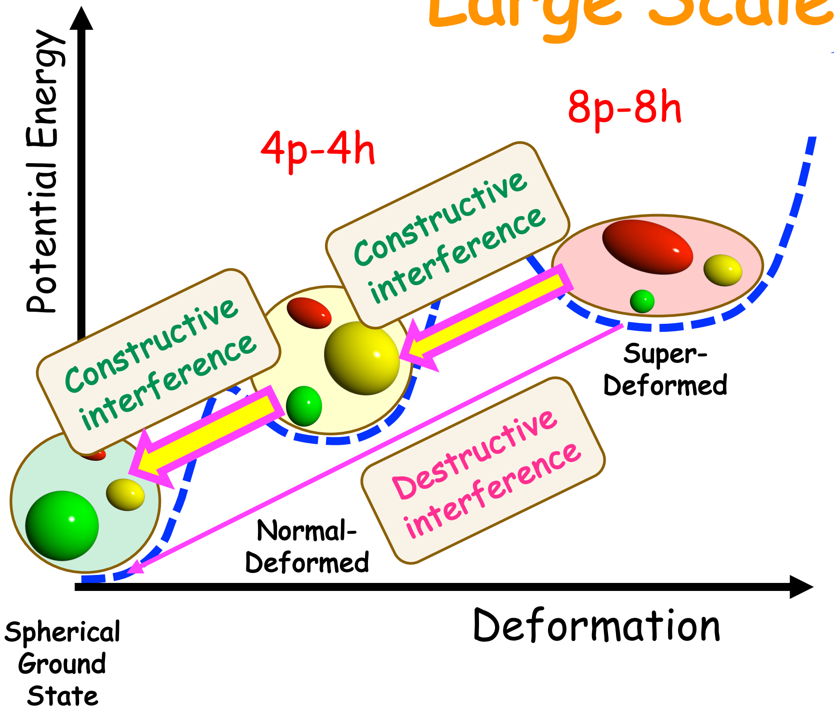
Large Scale Shell Model calculations ^{40}Ca

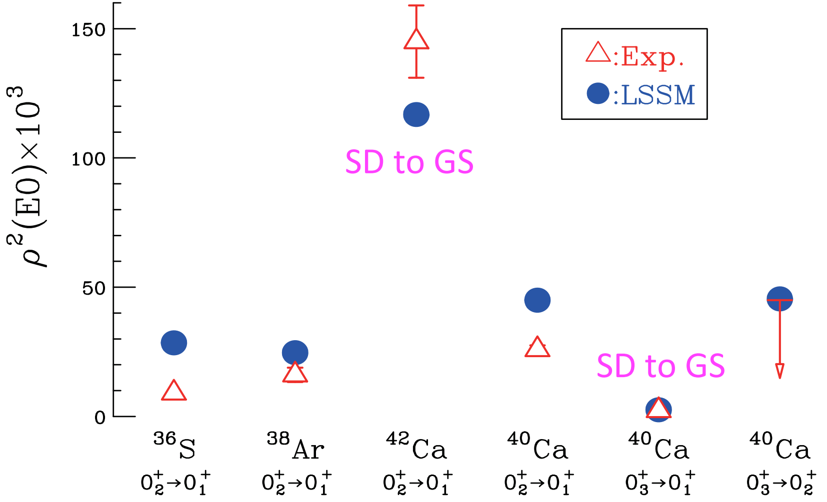
N. Shimizu (CNS, UTK) and Y. Utsuno (JAEA)



- ☐ Main configurations: gs: spherical, 0_2: 4p4h , 0_3: 8p8h
- ☐ ^{16}O core, full *sd* + $f_{7/2}$ + $p_{3/2}$ space
- ☐ <u>Significant configuration mixing</u> between 0^+ states

Large Scale Shell Model calculations ^{40}Ca





- Main configurations: gs: spherical, 0_2: 4p4h , 0_3: 8p8h
- ^{16}O core, full *sd* + $f_{7/2}$ + $p_{3/2}$ space
- Significant configuration mixing between 0^+ states
- Good agreement between experiment and prediction

PHYSICAL REVIEW LETTERS **128,** 252501 (2022)

Electric Monopole Transition from the Superdeformed Band in ^{40}Ca

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Summary & Outlook

❑ ^{40}Ca: Do we understand the relation of E0`s and shape coexistence?

- Z=N=20 double magic nucleus
- Alpha conjugate nucleus: ^{40}Ca = 10 x ^{4}He
- Accessible for Large Scale SM
- Is it an isolated case?

We want to understand how nuclear shape of a reasonable simple proton-neutron quantum system is evolving

Essential experimental and theoretical tools are available to do it!

Potential candidate Si isotopes:

- Deformed & superdeformed 0^+ candidates, no E0 observed,
- Alpha conjugate nucleus: ^{28}Si = 7 x ^{4}He
- Sudden changes in nuclear structure across Si isotopes

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ANU Major Equipment Grans 2011
ARC Discovery DP140102986, DP170101673

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