Decay Properties
Near the Proton Drip Line

Scientific Contents

? **Introduction:**

- recent results concerning nuclear structure and their relation to fundamental physics, astrophysics and “applications”
- general remarks on decays of N ? Z

? **Experimental Techniques:**

- “radioactive beams” from ISOL versus those from in-flight method
- “isotope hunting” and mass measurement

? **Decay Spectroscopy 1: Direct Charged–Particle Emission**

- direct a, proton and two-proton emission decay
- direct a decay above ^{100}Sn
- direct proton and two-proton decay

? **Decay Spectroscopy 2: Beta Decay**

- Allowed **(**Fermi and Gamow–Teller) ß–decay
- 0^+ **?** 0^+ Fermi decay
- ß decay near ^{100}Sn
- ß-delayed charged-particle emission

? **Gamma-delayed Proton Emission, Isomer Spectroscopy**

? **Summary and Outlook:** from ISOLDE to REX ISOLDE and from GANIL to SPIRAL and on to EURISOL, from the UNILAC to SIS-ESR and on to the future GSI Project

Properties of N ? Z Nuclei

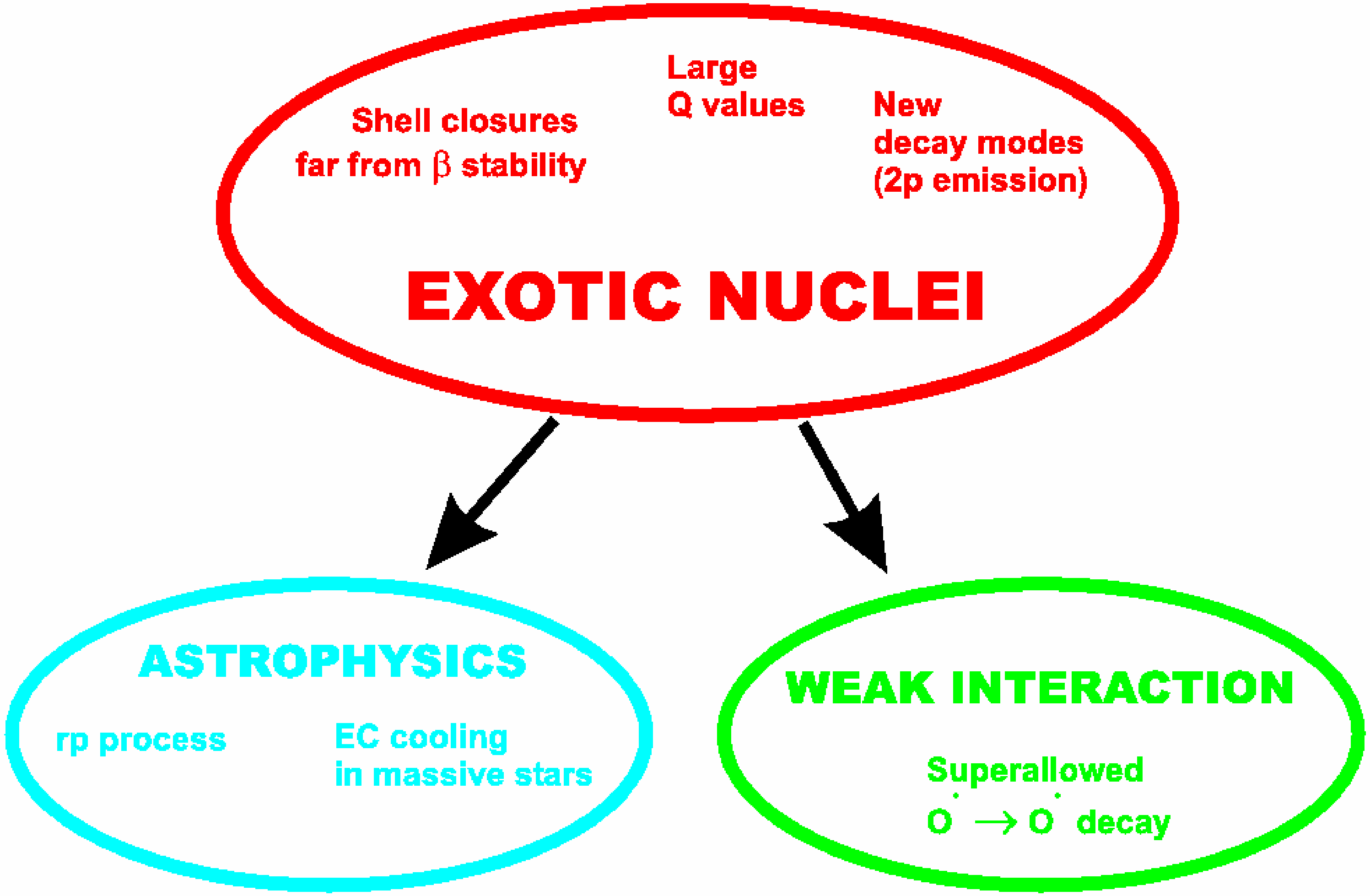
? **Nuclear--structure physics:** Particularly interesting phenomena, due to
- vicinity of the proton drip–line,
- occurrence of ls-open shell closures at ^{56}Ni and ^{100}Sn,
- occupation of identical orbits by neutrons and protons: T=1 versus T=0 pairing, enhanced binding for N=Z (Wigner t erm) etc.

? **Fundamental physics:** e.g. tests of the standard model of weak interaction by studying 0^+ **?** 0^+ Fermi decays

? **Astrophysics:**
- rp–process
- electron capture (EC) cooling of supernovae

? ? ? **Multidisciplinary scientific interest**

? ? ? **Experimental techniques leaning heavily on the use of “exotic” (radioactive) beams**


Shell closures
far from β stability
Large
Q values
New
decay modes
(2p emission)
EXOTIC NUCLEI
ASTROPHYSICS
rp process
EC cooling
in massive stars
WEAK INTERACTION
Superallowed
$0^+ \rightarrow 0^+$ decay

Experimental techniques

? Production by means of proton-induced spallation or heavy-ion induced fusion-evaporation or fragmentation reactions

? Separation of reaction residues from primary beam plus mass (and charge) separation required

? **I**sotope **S**eparation **O**n-**L**ine (ISOL):

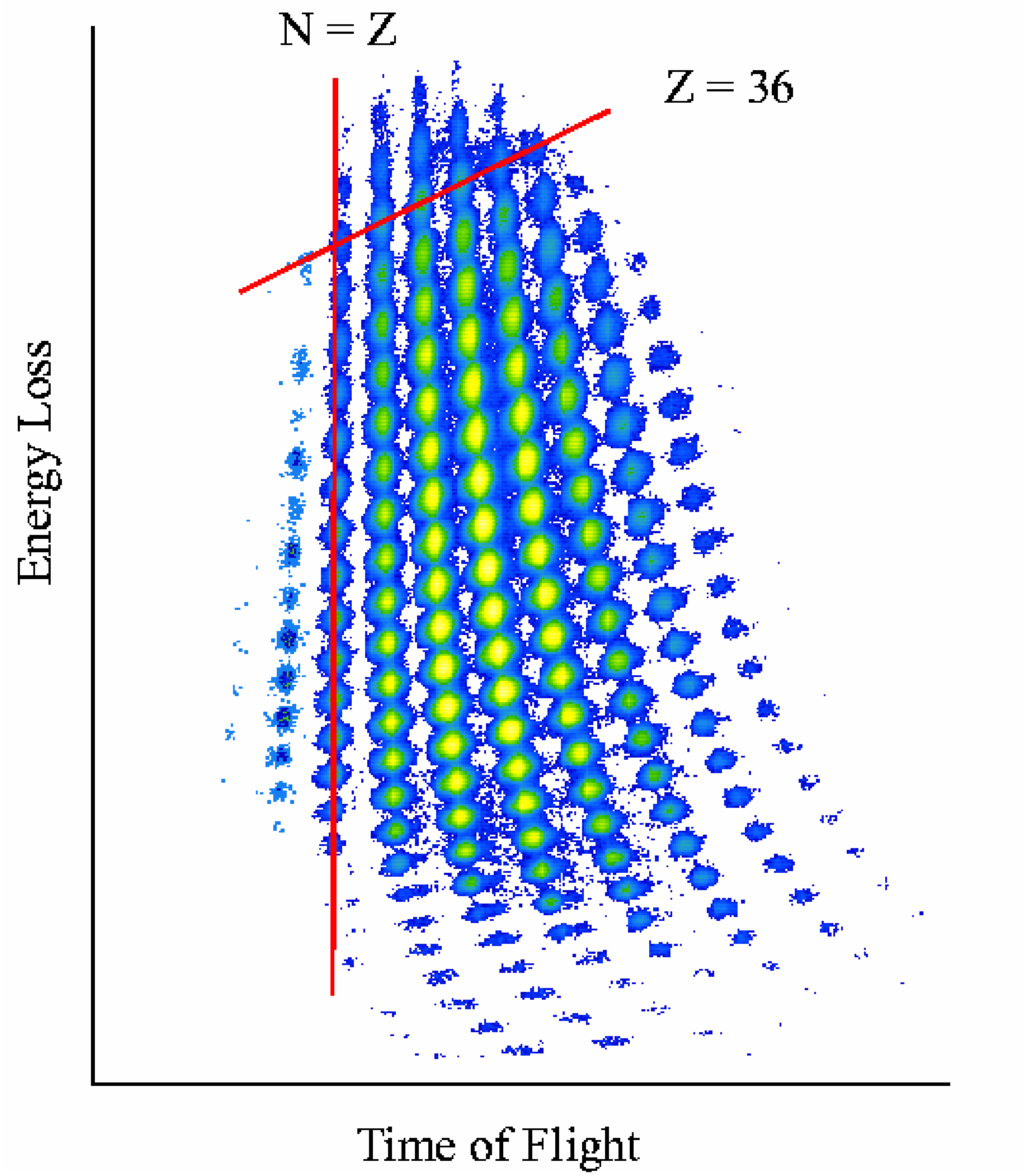
- „Ion sourcery“ (= ms); 50 keV secondary beam, point-like source
- Example: ISOL, Darmstadt

? In–Flight Separation:

- Separation time = µs, ˜ 1 MeV/u to 1 GeV/u secondary beam, implantation into, e.g., silicon detector
- Examples: **F**ragment **M**ass **A**nalyser (FMA), Argonne; **R**ecoil **M**ass **S**eparator (RMS), Oak Ridge; **L**igne d’**I**ons **S**uper-**É**pluchés (LISE-3), Caen; Projectile **FR**agment **S**eparator (FRS), Darmstadt; A 1200 Separator, East Lansing

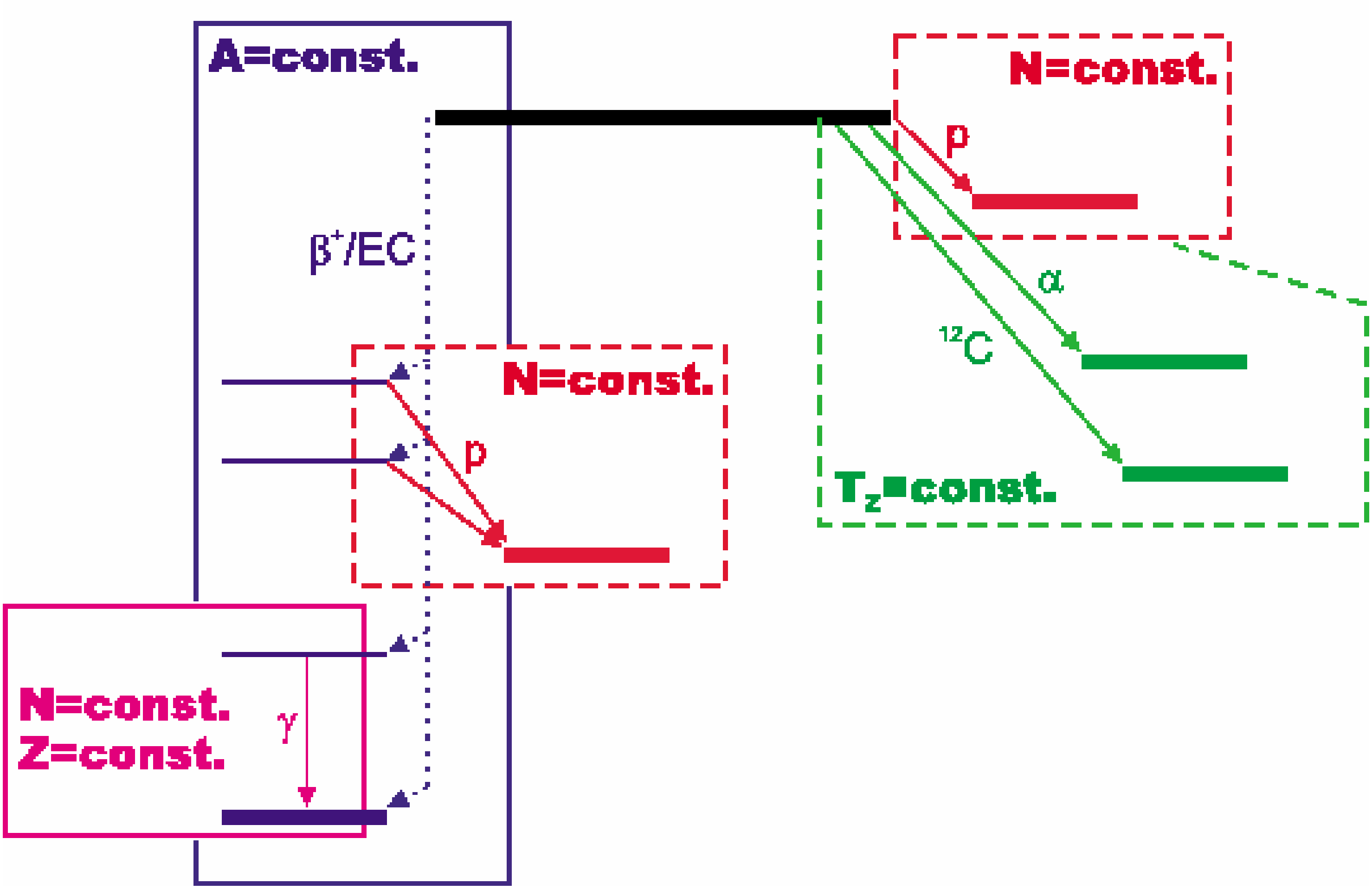
Energy Loss versus Time-of-Flight Plots from In-Flight Separators

70 MeV/u ^{78}Kr on ^{9}Be; R. Pfaff et al., Phys. Rev. C 53, 1753 (1996): data taken at the A 1200 Separator



Identification of new isotopes (“isotope hunting”) yields lower half-life limit. Shorter-lived resonances have to be studied by decay or reaction experiments.

Principle Sketch of Decay Modes of N ? Z Nuclei



Note: The charged-particle emitting states can be very broad resonances, e.g. ^{6}Be or ^{6}Be which decay by two-proton and two-a break-up, respectively.

Direct charged-particle decay

- Alpha decay: theory, definitions etc.
  Becquerel, Paris, **1895**
- Cluster (^{14}C, ^{12}C) decay
  Rose and Jones, Oxford, **1984**
- Proton decay
  Jackson et al., Oxford, **1970**: isomeric decay
  Hofmann et al., Klepper et al., Darmstadt, **1981**: ground-state decay
- Direct charged-particle decay yields a **line spectrum** (ground state to ground state, ground state to excited state(s) = **„fine structure“**), whereas ß-delayed particle decay of heavy nuclei generally yields a continuous spectrum

Experimental observables from ? decay

? Alpha-particle energy $E_?$? recoil corr. ? $Q_?$

? $Q_?$ values represent „mass links“:
$Q_? = ME(Z,N) – ME(Z-2,N-2) – ME(^4He)$

? **Total** half-life $T_{1/2}^{(tot.)}$

? Alpha-decay branching ratio $b_?$

? Alpha-decay constant $?_? = (b_? \times \ln 2)/T_{1/2}^{(tot.)}$
$= (\ln 2)/T_{1/2}^{(a,\ exp.)}$

Semi-empirical Gamow theory of ? decay

? $?_? = (v_?/2R_i)P = (\ln 2)/T_{1/2}^{(a,\ theor.)}$

- preformation probability = 1
- $v_? = \{2(U_0 + Q_? + ?E_{scr.})/M_?\}^{1/2}$
- P = barrier transmission

? $P = \exp\{-2_{Ri}?^{Ra}[2M_?/?(U(R) + Q_? + ?E_{scr.})]\}^{1/2}$
One-dimensional barrier for s-wave a particles,
plus *l*-dependent term for higher-*l* waves
(J.O. Rasmussen, Phys. Rev. 113, 1593 (1959))

Alpha-decay drip line:

defined by $Q_? > 0$ or $T_{1/2}^{(a)} < T_{1/2}^{(a,\ limit)}$

Alpha-decay parameters to be discussed

? „Spectroscopic factor“, defined as

$S^{(a)}_{exp.} = T_{1/2}^{(a, theor.)} / T_{1/2}^{(a, exp.)}$

- $S^{(a)}_{exp.} = 4 \times 10^{-3}$
- $S^{(cluster)}_{exp.}$ = small
- $S^{(p)}_{exp.} = 1$?

? „Reduced widths“, defined as

- W? **a** ?? **/**P, given relative to W? (^{212}Po), or
- d^2 = (?? x h)**/**P in MeV:

<u>Wide</u> variation of $Q_?^{(exp.)}$ and $T_{1/2}^{(a, exp.)}$ reduced to W? variations of a factor of **~ 60**!

? „Hindrance factor“, defined as

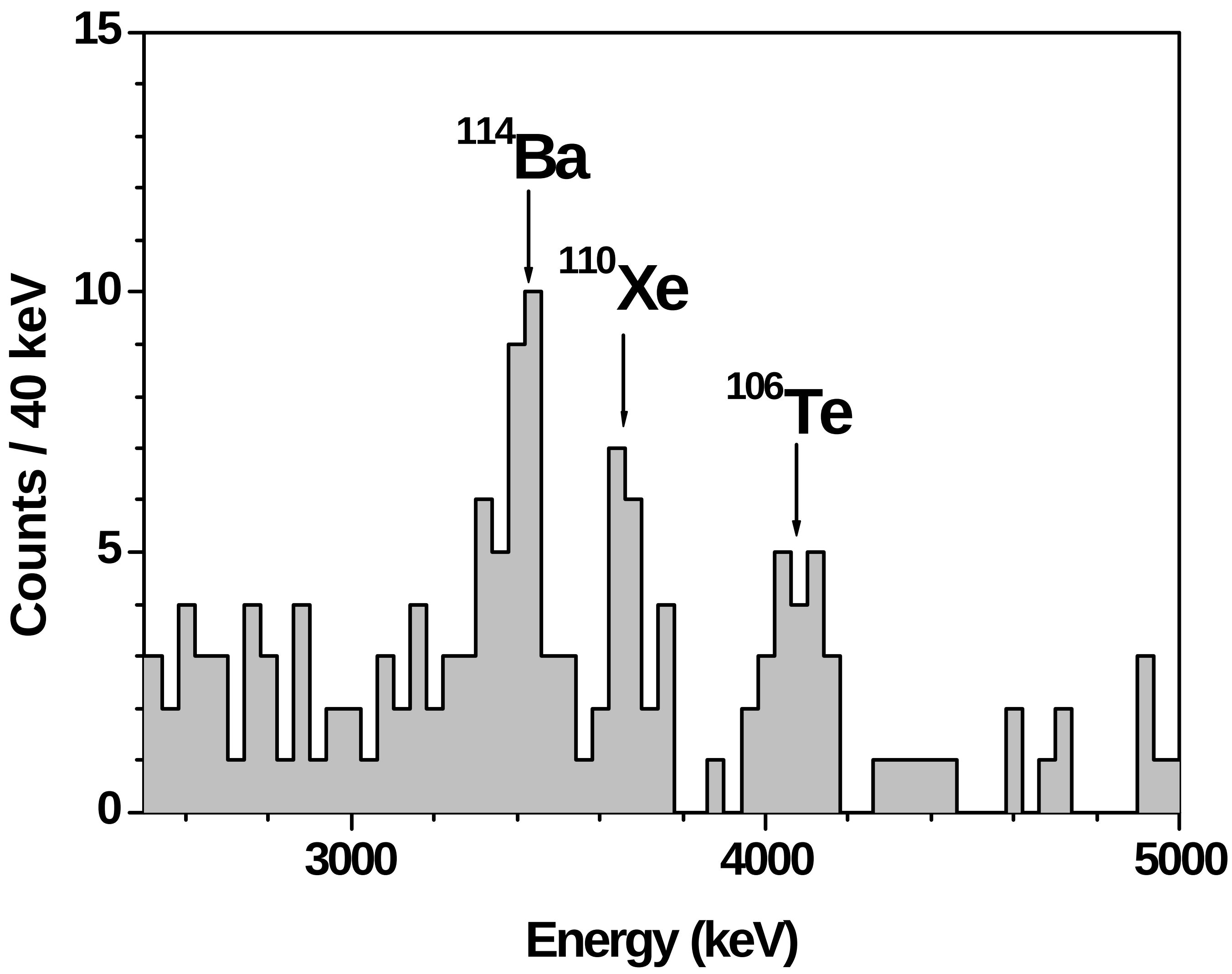
$HF = d^2_{g.st.} / d^2_{exc.st.}$

Alpha decay of ^{114}Ba

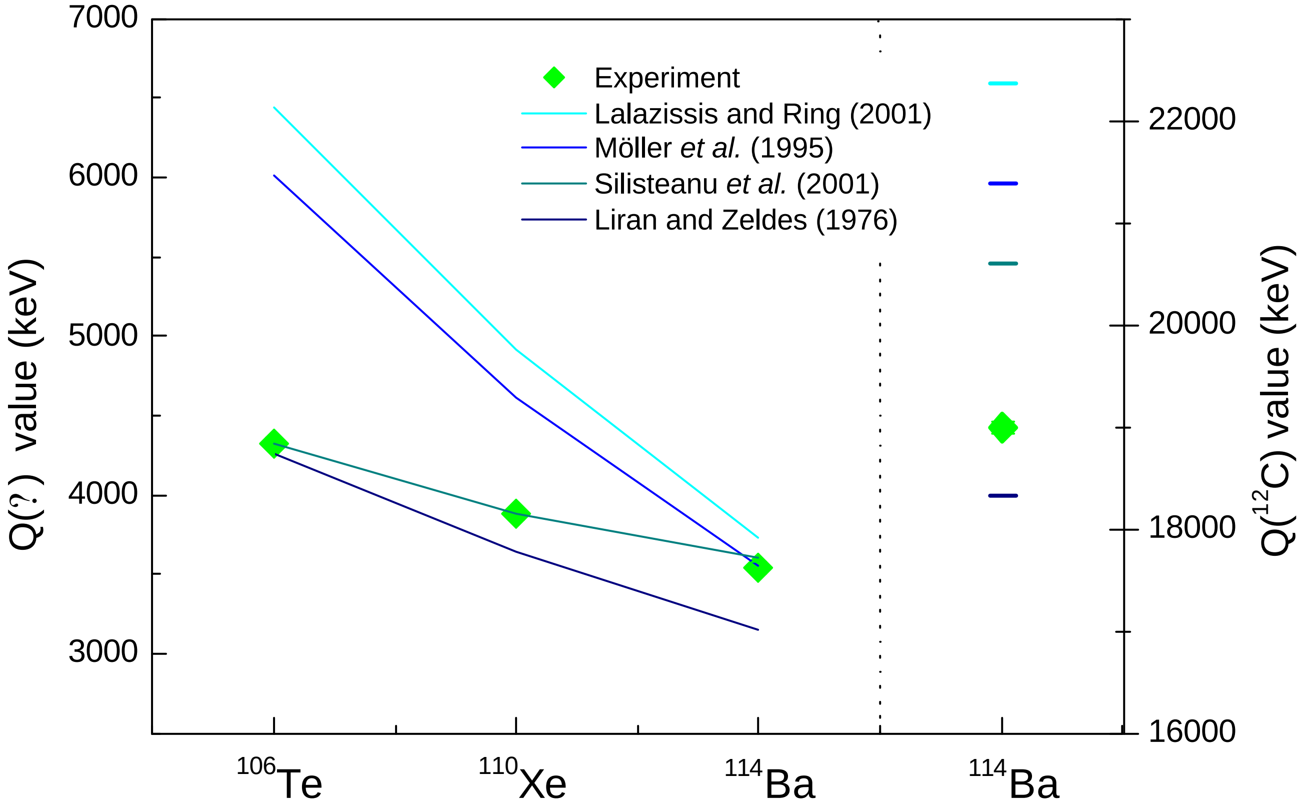
C. Mazzocchi et al., Phys. Lett. B 532 (2002) 29

$T_{1/2}$? 0.43 s, 4 ^{114}Ba^{19}F^{+} molecules/min

Technique: implantation of GSI–ISOL beam in foils viewed by silicon-silicon telecopes

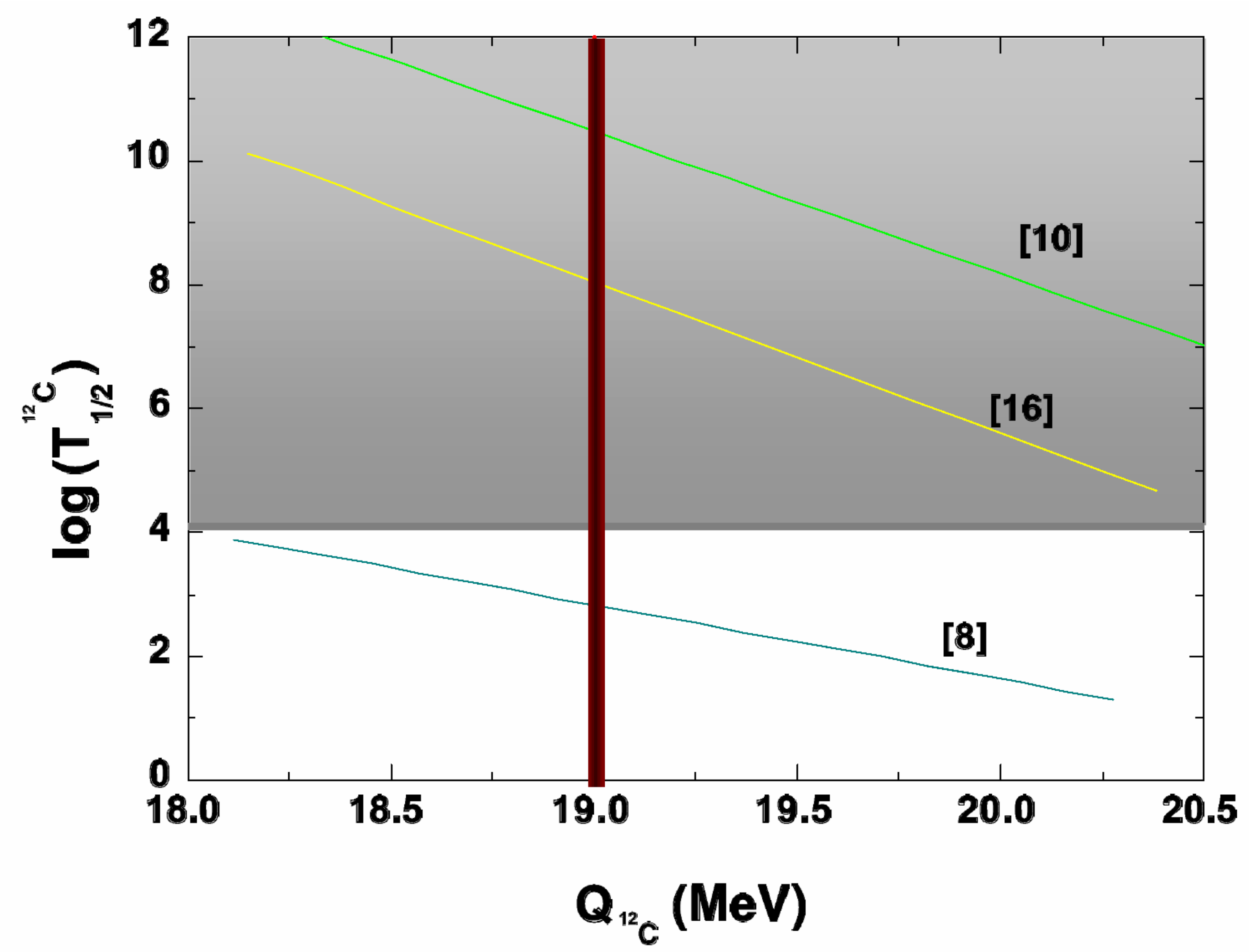


Alpha decay of ^{114}Ba (continued)



^{12}C decay of ^{114}Ba?

C. Mazzocchi et al., Phys. Lett. B 532 (2002) 29

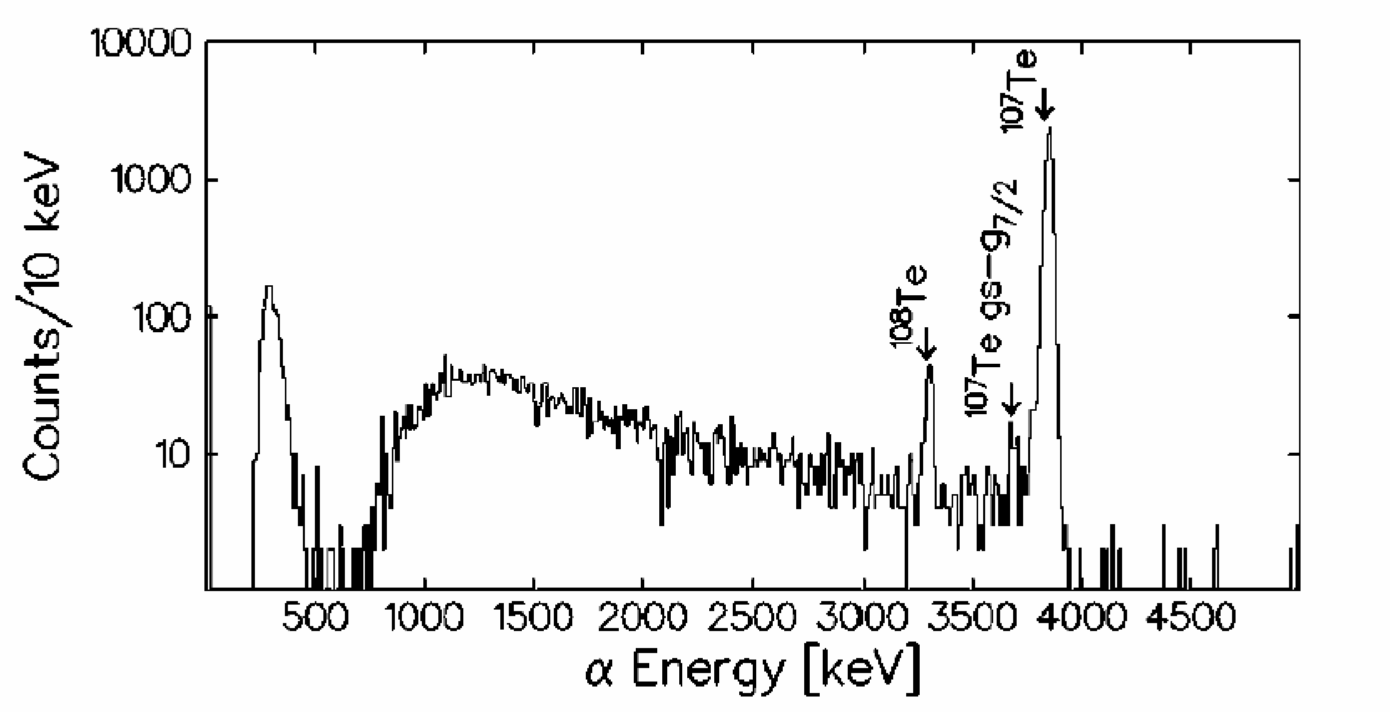


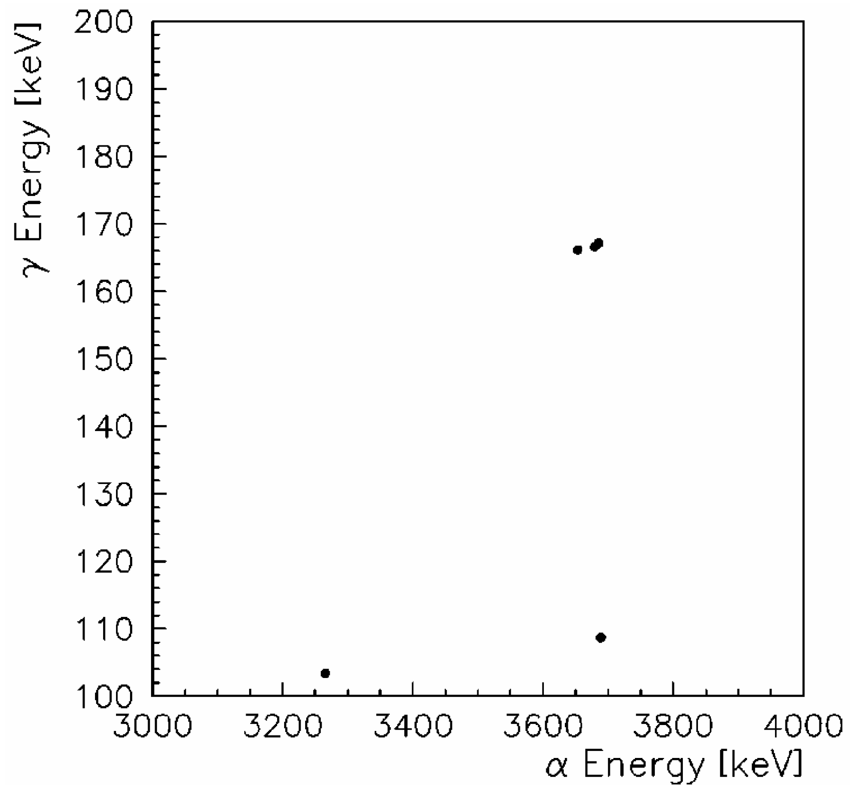
$Q^{(12C,\ exp.)}$ from this work

$T_{1/2}^{(12C,\ exp.)}$ limit from previous ISOL work (A. Guglielmetti et al., Phys. Rev. C **52**, 740 (1997))

[8] S.G. Kadmenski et al., Izv. Akad. Nauk. Rossii **57**, 12 (1993); [16] S. Kumar and R.K. Gupta, Phys. Rev. C **49,** 1922 (1994); [10] D.N. Poenaru et al., Phys. Rev. C **47**, 2030 (1993)

Fine structure in the a decay of ^{107}Te: Experimental data





D. Seweryniak et al., Phys. Rev. C **66**, 051307(R) (2002): data taken at the FMA of Argonne Nat. Lab.

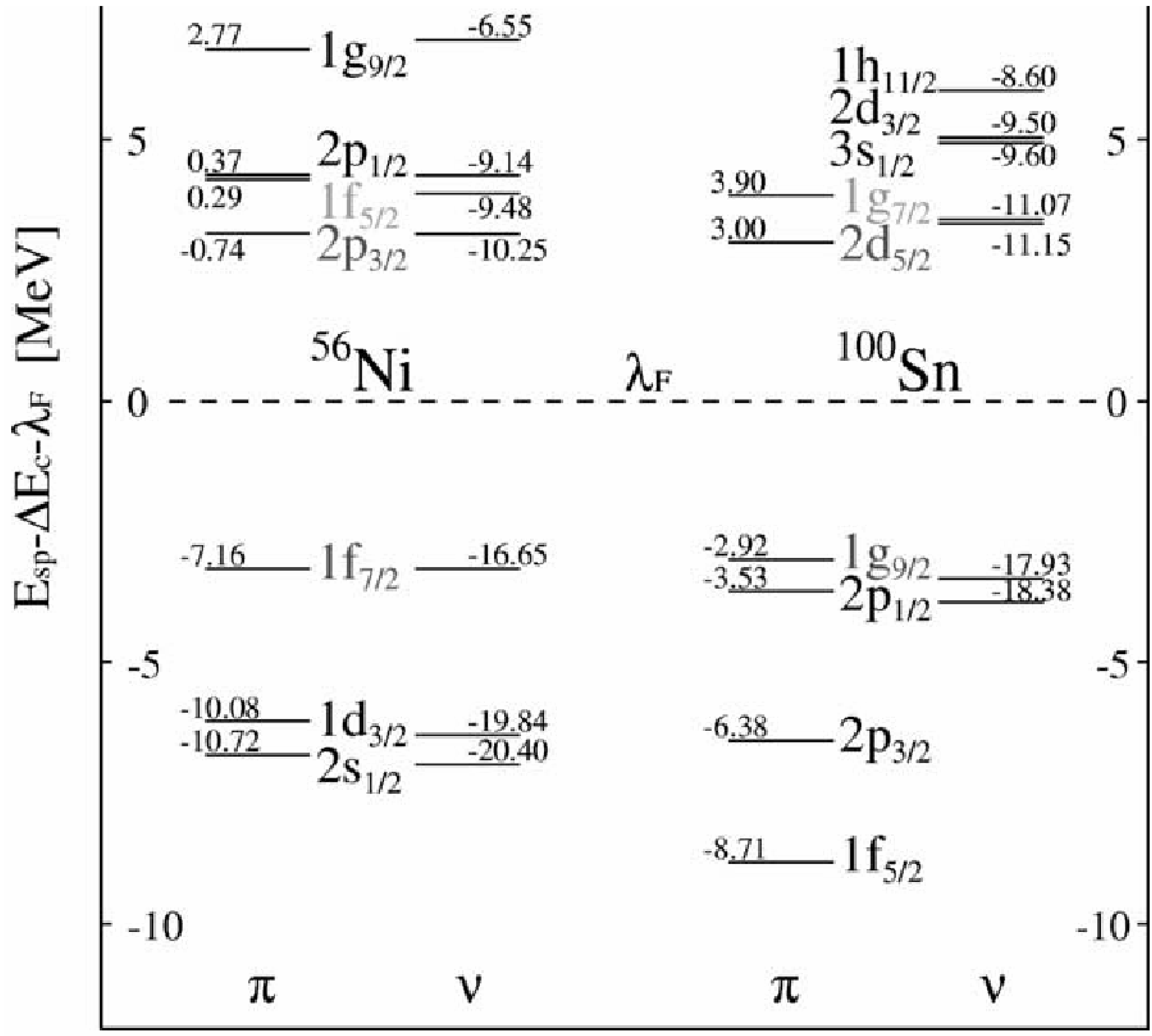
The nuclear shell model

Goeppert Mayer (1949); Haxel, Jensen & Suess (1949)

- ? (empirical…realistic) interaction
- ? model space
- ? number of particle-hole excitations
- ? computer code

Single particle (hole) energies in ^{56}Ni and ^{100}Sn

H. Grawe and M. Lewitowicz, Nucl. Phys. A **693**, 116 (2001))



Fine structure in the a decay of ^{107}Te: Identification of the first excited $g_{7/2}$ state at 168 keV in ^{103}Sn

Shell structure near ^{100}Sn (Z = N = 50)

Mother (^{107}Te) **? a ?** Daughter (^{103}Sn)

$g_{7/2}$ ———— ---------- $g_{7/2}$ ———— ----------

$d_{5/2}$ ———— ---------- $d_{5/2}$ ———— ----------

Z=50 **N=50** **Z=50** **N=50**

$g_{9/2}$ ———— --------- $g_{9/2}$ ———— ---------

p **?** **p** **?**

Experimental results (D. Seweryniak et al., Phys. Rev. C **66**, 051307(R) (2002)):

$b_?^{(exp.)}$ = 0.47(9) % for 168 keV state

($Q_?^{(exp.)}$ = 4012(10) keV, $T_{1/2}^{(a,\ exp.)}$ = 3.1(0.1) ms previously known)

? $W_?$ (g.st./?$d_{5/2}$ **?** g.st./?$d_{5/2}$) = 2.0

? $W_?$ (g.st./?$d_{5/2}$ **?** exc.st./?$g_{7/2}$) = 0.15

? HF = 6.5 ? „re-arrangement of single- particle structure“

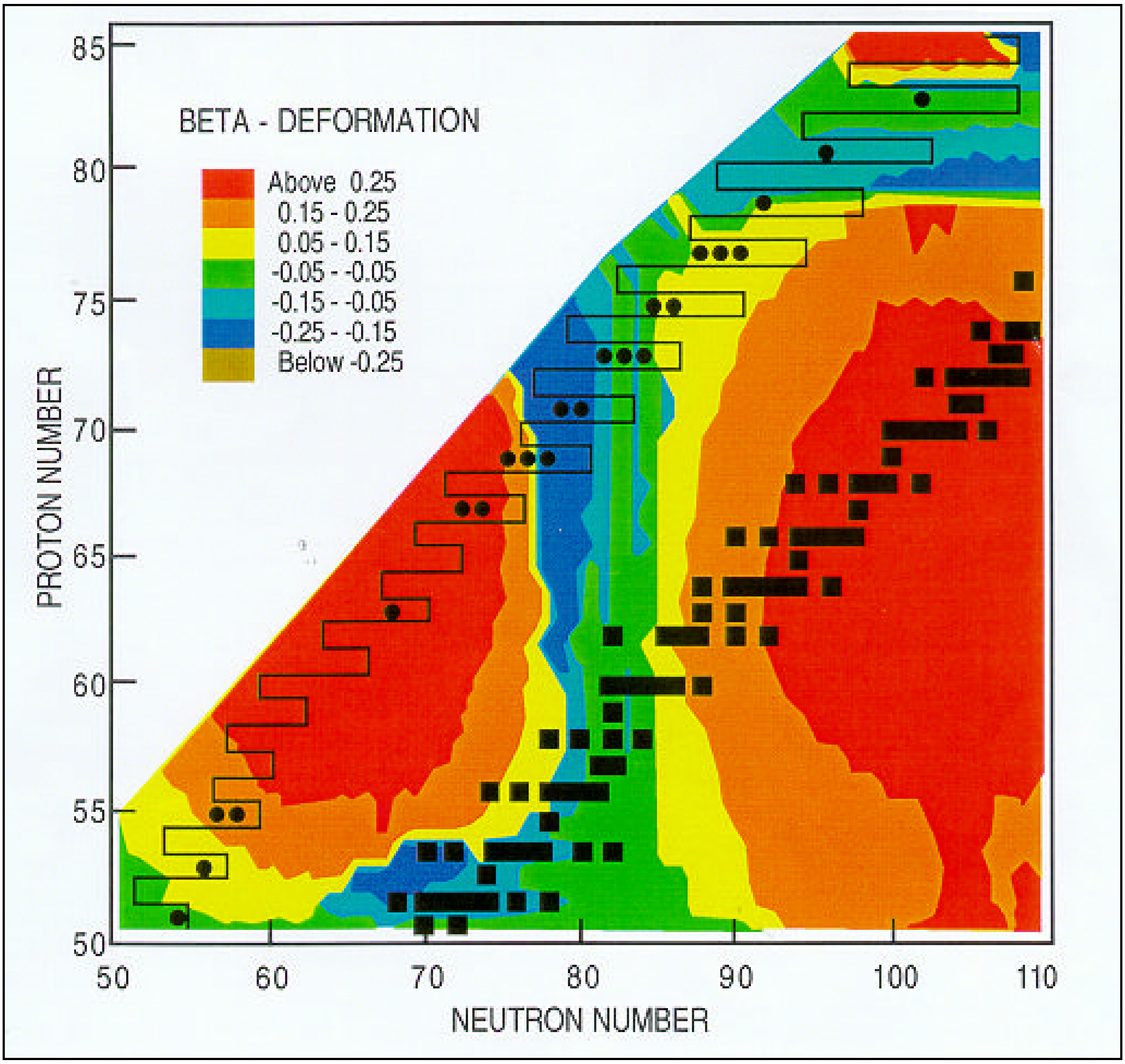
Conclusions from the experiment of Seweryniak et al.

? Alpha decay is an excellent tool for identifying single-particle states near ^{100}Sn (and to speculate about the configuration of the mother state)

? However, the first excited (168 keV) state was already known from in-beam spectroscopy

? … towards ^{105}Te **?** a **?** ^{101}Sn …

Direct Proton Radioactivity



Contour plot of the quadrupole deformation parameter ?$_2$ [1]. Filled circles mark known proton emitters, while the predicted is drawn as a solid line. Stable isotopes are indicated by full squares. The data concerning the proton drip-line [2] and the ?$_2$ data are taken from ref. [2].

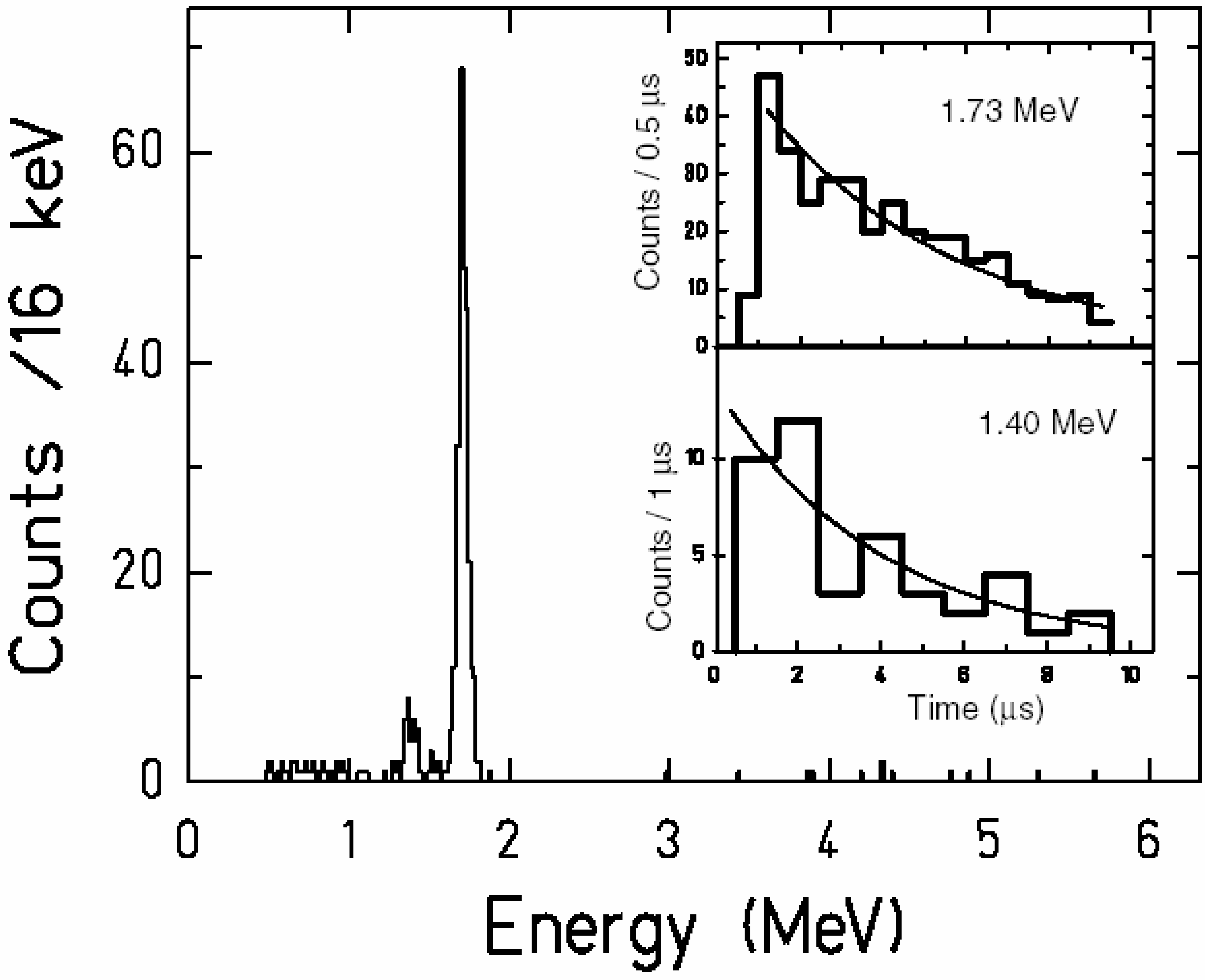
[1] P.J. Woods and C.N. Davids, Ann. Rev. Nucl. Part. Sci. **47** (1997) 541

[2] P. Möller *et al*., At. Data Nucl. Data Tab. **59** (1995) 189

Fine structure in direct proton emission

Example: ^{145}Tm

M. Karny et al., Phys. Rev. Lett. 90, 012502 (2003):
data taken at the FMA of Argonne Nat. Lab.



$T_{1/2}$ (1.73 MeV) = 3.1(3) µs

$T_{1/2}$ (1.40 MeV) = 2.7(10) µs

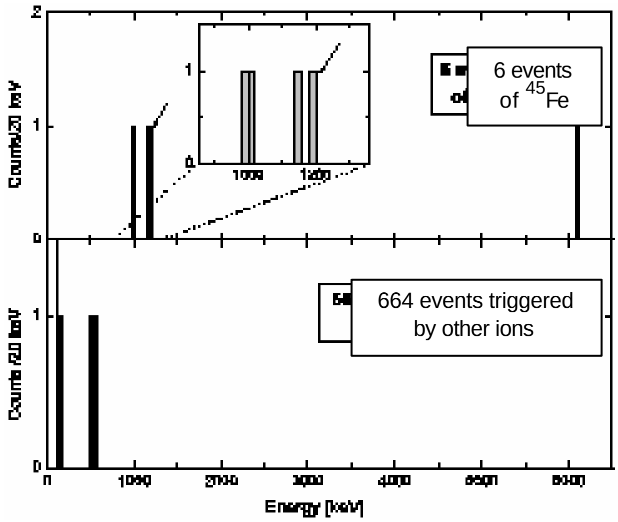
"…nuclear life beyond the limits…" (K. Rykaczewski)

Results obtained by Karny et al.

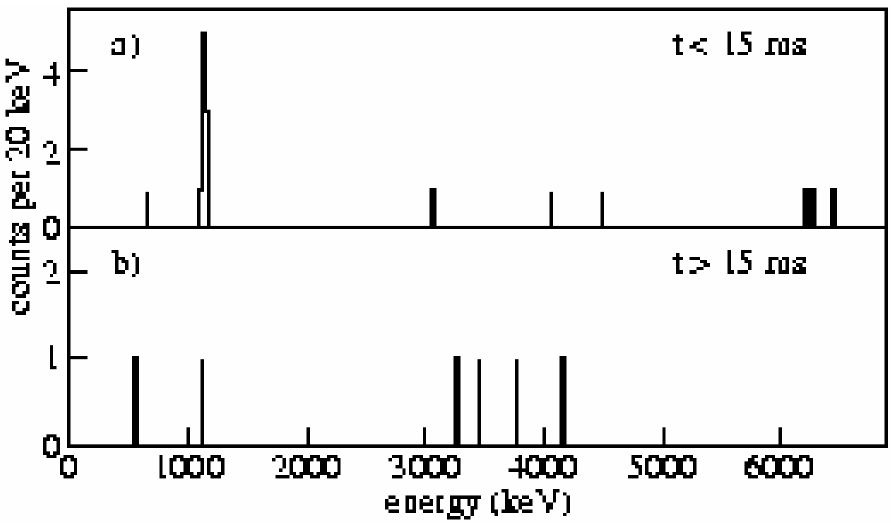
- ? Fine-structure decay of ^{145}Tm observed to have $T_{1/2}^{(a,\ exp.)}$ = 3.1(0.3) µs and $b_{?}^{(exp.)}$ = 9.6(1.5) % determined ($Q_{?}^{(g.st.,\ exp.)}$ previously known)
- ? First experimental evidence for first excited state (330(10) keV, 2^{+}) in ^{144}Er
- ? Conclusions drawn on the configuration of the ^{144}Er mother state

Two-Proton Decay of ^{45}Fe, Observed in ^{58}Ni–Fragmentation Reactions

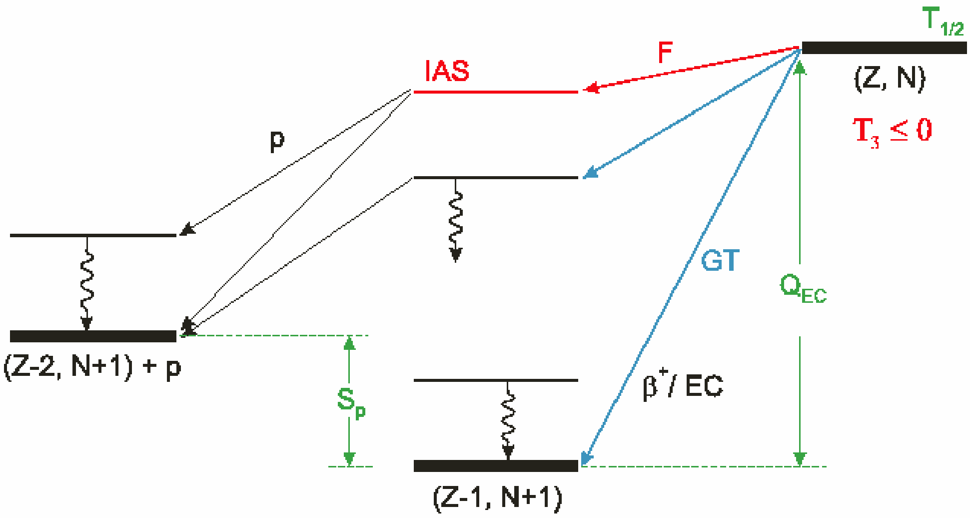
M. Pfützner et al., Eur. Phys. J. A 14, 279 (2002): data taken at the FRS



J. Giovinazzo et al., Phys. Rev. Lett. 89, 102501 (2002): data taken at LISE-3

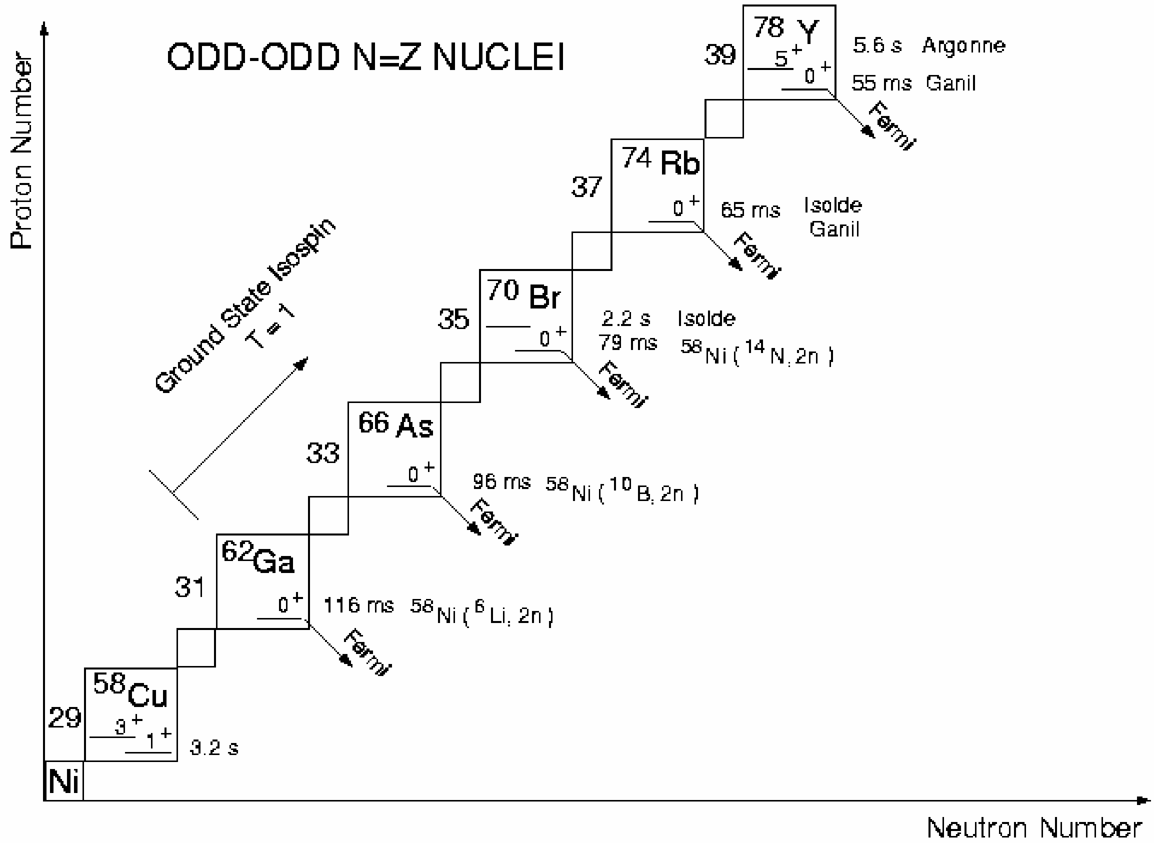


? *Experimental results agree (Q_p ? 1.14 MeV, $T_{1/2}$? 3.8 ms) but decay process – ^{2}He “radioactvity” or three-body break-up – remains to be clarified!*



T1/2
IAS
F
(Z, N)
T3 ≤ 0
p
GT
QEC
(Z-2, N+1) + p
Sp
β+/ EC
(Z-1, N+1)

Odd-odd N = Z Nuclei: Ground–States Versus Isomers, F Versus GT Decay



See also occurrence of $I^{p} = 7^{+}$ and I = 17 isomers in ^{94}Ag, discussed later

Precision measurements of superallowed $0^+ ? \ 0^+$ ß-decay (between T=1 states)

Definition of Ft as the “corrected” ft value:

$$Ft = ft(1 + d_R)(1 - d_C) = K\{2G_V^2(1 + ?_R^{(V)})\}$$

f = statistical rate function = f(Z,Q_{EC}),

Z = charge of daughter nucleus,

t = partial half-life = $T_{1/2}/b(0^+ ? \ 0^+)$,

$b(0^+ ? \ 0^+)$ = branching ratio for $0^+ ? \ 0^+$ decay,

d_C = isospin-symmetry-breaking correction
(nuclear-structure dependent)

d_R = transition-dependent part of radiative correctio
(contains nuclear-structure independent part
(Z,Q_{EC}) and nuclear-structure dependent part)

K = fundamental constant,

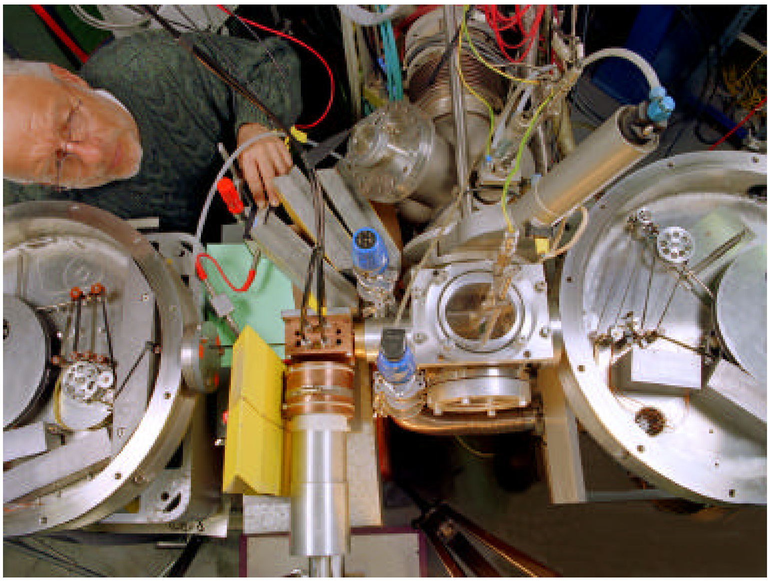
G_V = vector-coupling constant

$?_R^{(V)}$ = transition-independent part of radiative
correction

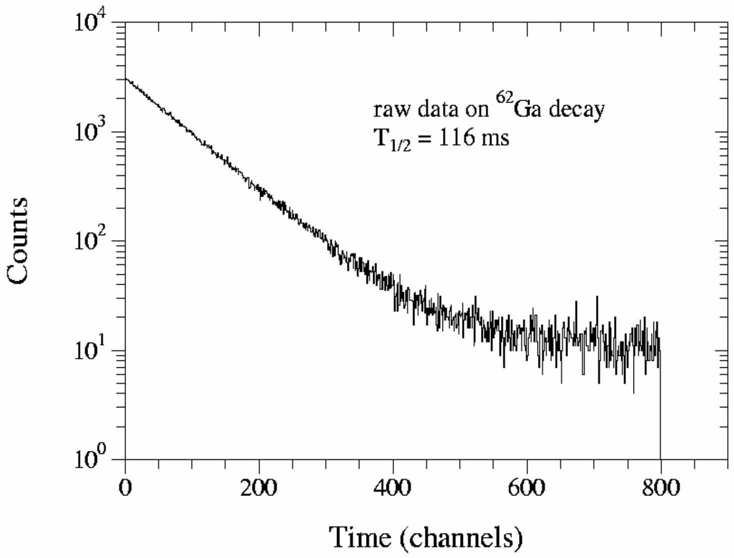
Precision measurement of the half-life of ^{62}Ga

^{62}Ga ($T_{1/2}$ = 116.12(23) ms, 1.7x10^3 ^{62}Ga atoms/s)

Technique: detection of positrons by proportional counter (Argonne); GSI-IOSL experiment: 1.2x10^5 cycles of 0.35 s collection, 0.1 s transport, 1.6 s counting



Part of raw data from 1800 cycles



Physics: Precision half-life data (116.19(4) ms, i.e. 3 parts in 10^4) for a superallowed 0^+? 0^+ ? - transition

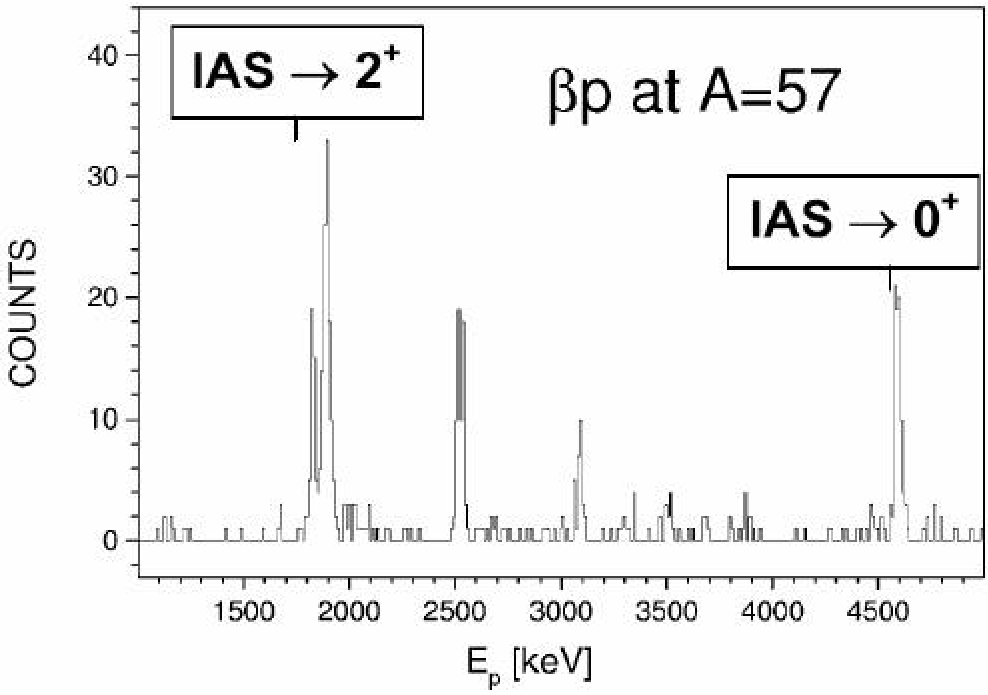
B. Blank et al., submitted to Phys. Rev. C (July 2003)

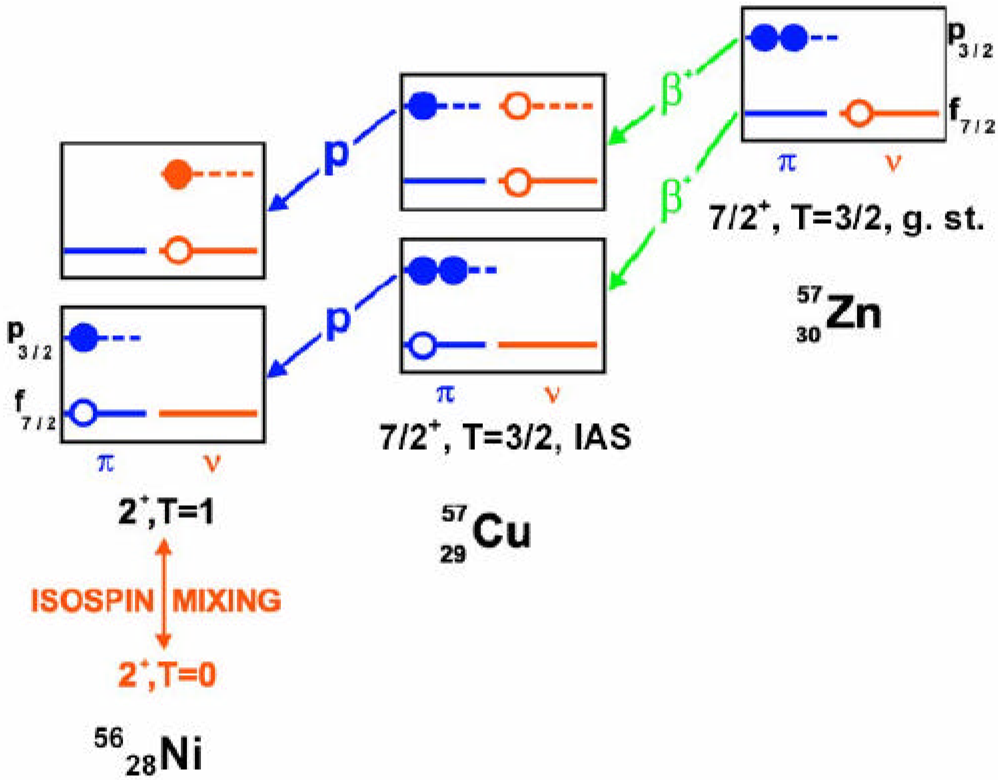
Fermi and Gamow-Teller β decay

^{57}Zn ($T_{1/2}$ = 38(4) ms, 2 atoms/min)

A. Jokinen et al., EPJdirect **4**, A3 (2002) 1

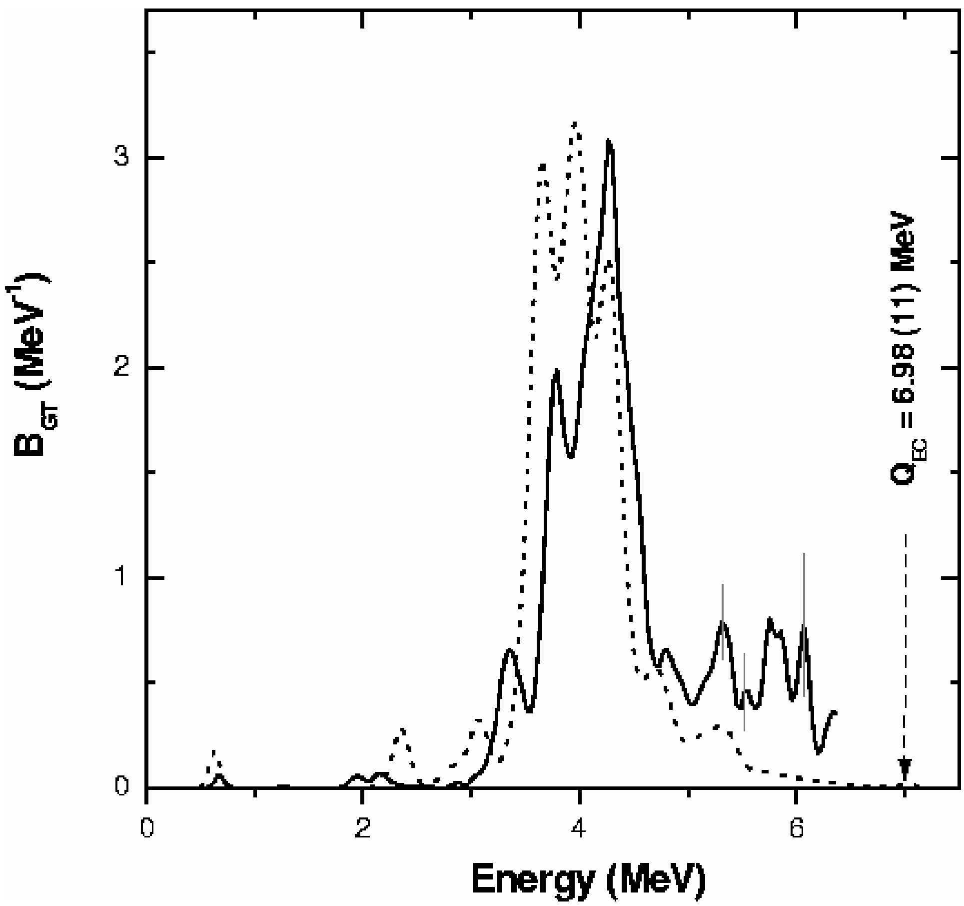
Fermi decay → isospin mixing, comparison of exp. Gamow-Teller strength with shell-model predictions





Beta–Decay Studies in the ^{100}Sn Region

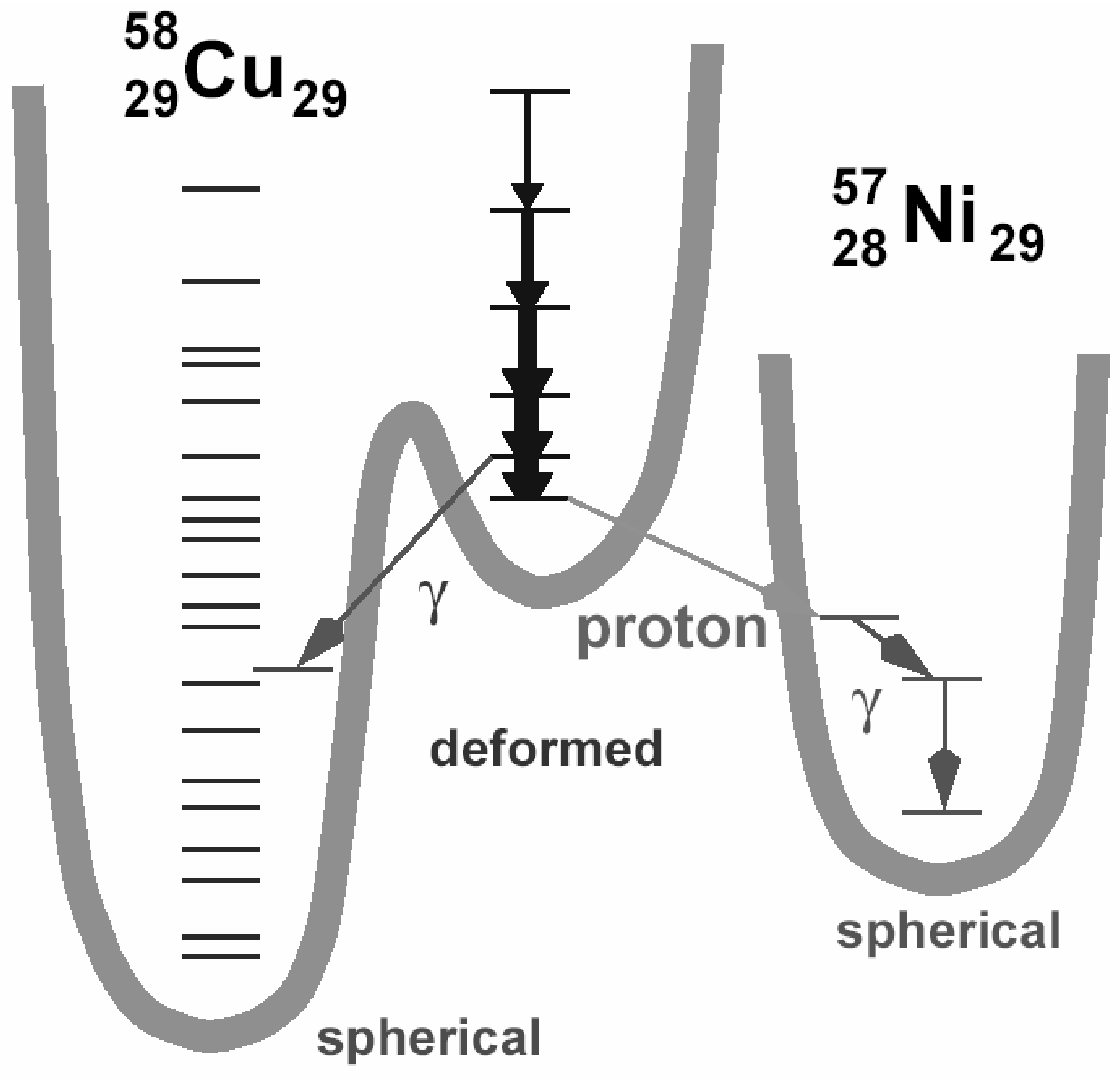
- **Motivation:** tests of nuclear models based on (i) the “Super GT Resonance” of ^{100}Sn, (ii) the GT resonance of neighbouring nuclei, (iii) single-particle states near ^{100}Sn
- **^{100}Sn identified** by experiments at the FRS (R. Schneider et al., Z. Phys. A **348**, 241 (1994)) and LISE-3 (M. Lewitowicz et al., Phys. Lett. B **332**, 20 (1994)), but information insufficient concerning Super GT Resonance
- **GSI–ISOL Experiments:**
  - Unambigious identification of GT resonance for ^{97}Ag: experiment (? –) versus SNB shell–model prediction (----), the latter being reduced by factor 4.3.

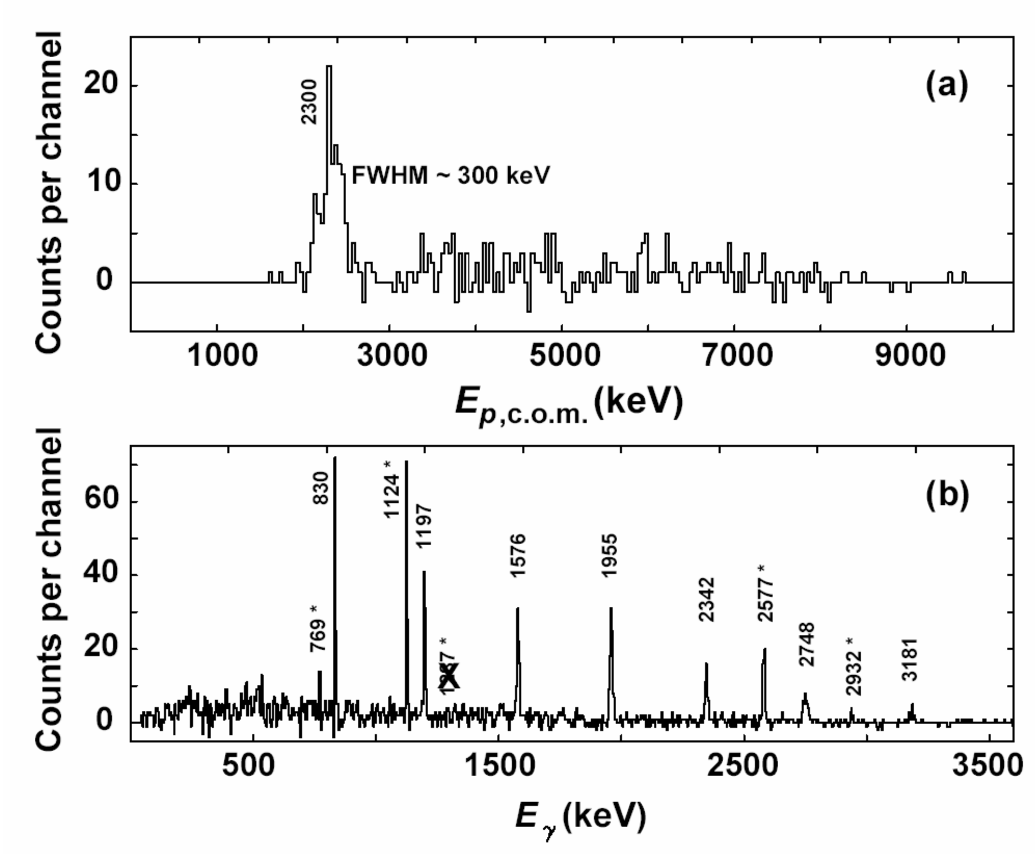


  - Recent development of SnS technique: ß–decay studies of light tin isotopes down to ^{101}Sn and maybe even ^{101}Sn (?)

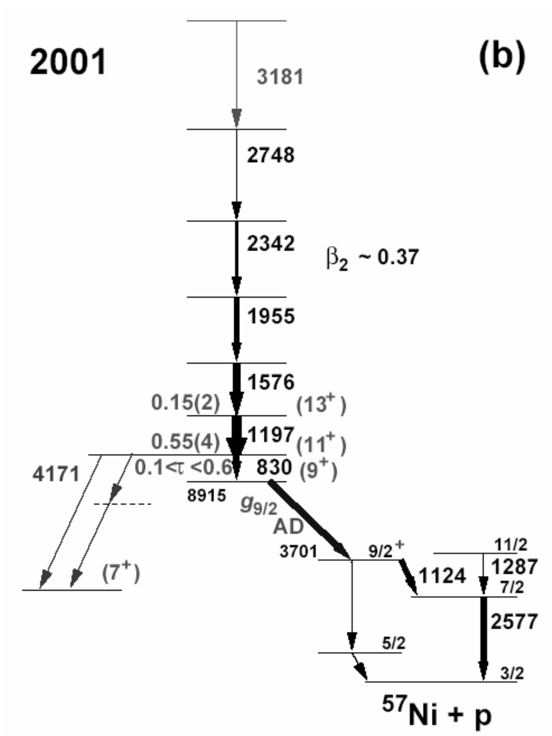
“Gamma-delayed” proton emission

D. Rudolph, Eur. Phys. J. A **15**, 281 (2002)



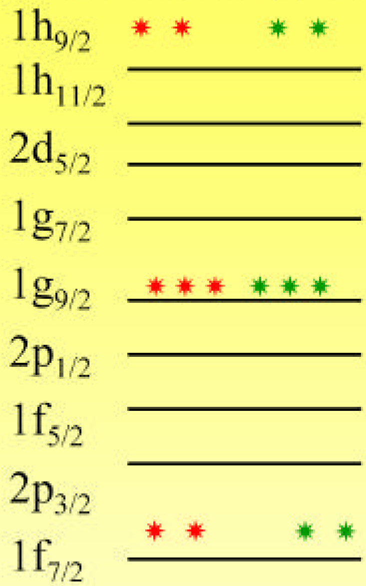


(a) proton spectrum, (b) ?-? coincidence spectrum (“sum gate”)



Spin-gap isomers (foil prepared by C.Plettner)

- Where were they observed? What is the mechanism behind?



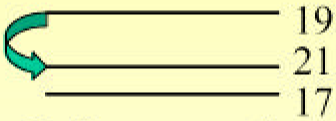
^{212}Po $J = 18$ $T_{1/2} = 46$ s

^{95}Pd $J = 21/2^{+}$ $T_{1/2} = 14$ s

^{94}Ag $J = 21$? $J_{max} = j_p + j_n$ $2(9/2+7/2+5/2)=21$

^{52}Fe $J = 12^{+}$ $T_{1/2} = 46$ s

At maximum spin, the residual interaction is more attractive:

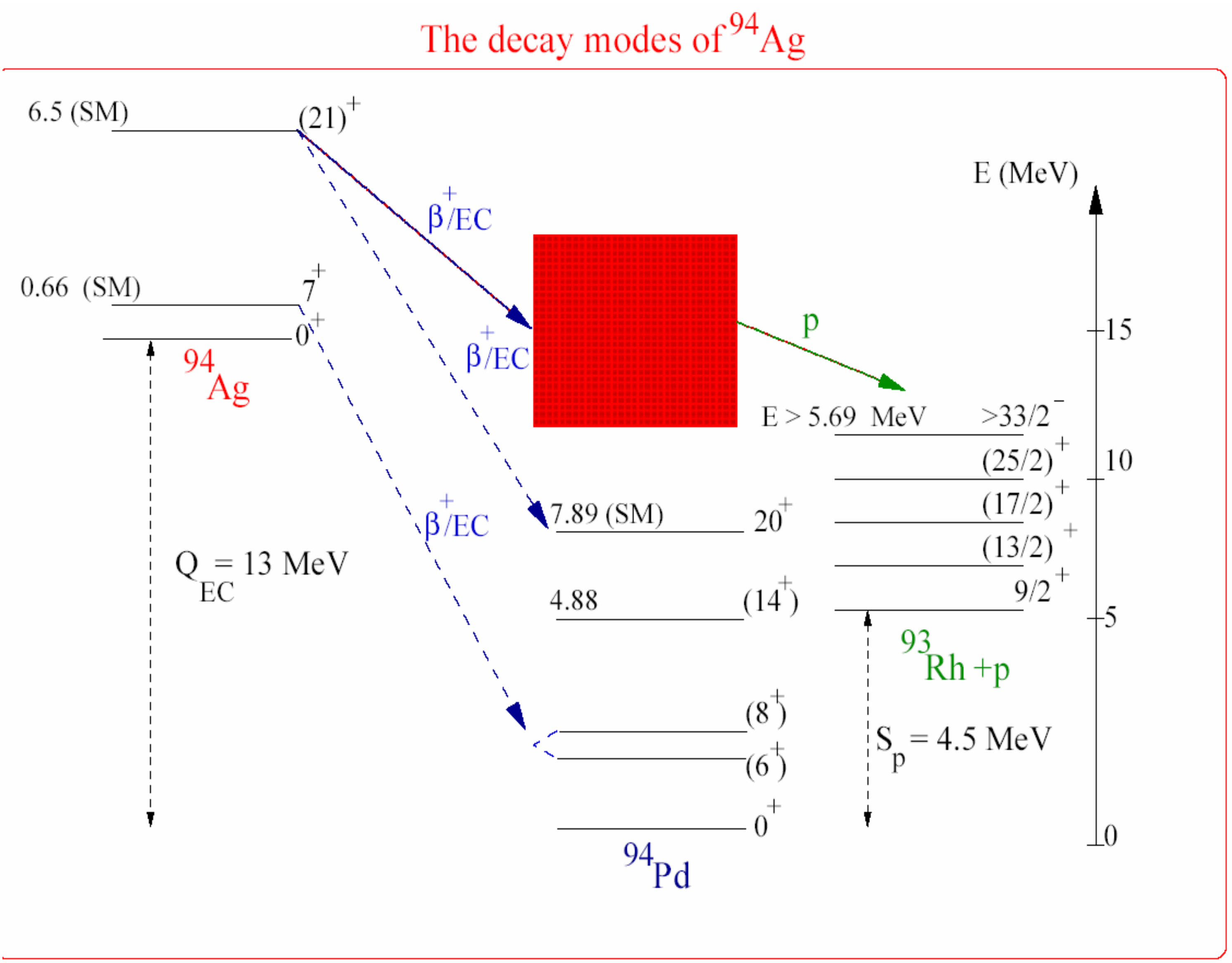


K. Ogawa predicted using shell-model calculations with ^{100}Sn as core: ^{96}Cd, ^{95}Ag, ^{97}Cd, ^{95}Pd. So far, no predictions concerning ^{94}Ag

crucial shell-model test

Beta decay of the (I>17) isomer of ^{94}Ag

- The highest spin ever observed for a ß-decaying nucleus
- **High-spin proton spectroscopy!!**
- **GSI-SOL:** M. La Commara et al., Nucl. Phys. A **708**, 167 (2002); C. Plettner et al., contr. to Hirschegg Workshop (2003); I. Mukha et al., Contr. to PROCON Conf.



Summary

? Triple ?–chain ^{114}Ba ? ^{102}Sn

? Fine structure of a decay of ^{107}Te and for proton decay of ^{145}Tm

? Direct two-proton decay of ^{45}Fe

? Precision measurements of 0^{+} **?** 0^{+} Fermi decays: New physics beyond the Standard Model!?

? Gamow-Teller resonance below ^{100}Sn

? **etc.**

Outlook

(even more biased by my personal judgement
than the rest of the lecture)

✍ **Exciting new results have been obtained on N ? Z nuclei recently**

✍ New (European) facilities on the horizon: from ISOLDE to REX ISOLDE and from GANIL to SPIRAL and on to EURISOL, from the UNILAC to SIS-ESR and on to the future GSI Project