

Exotic nuclei studied with the 8pi spectrometer at TRIUMF

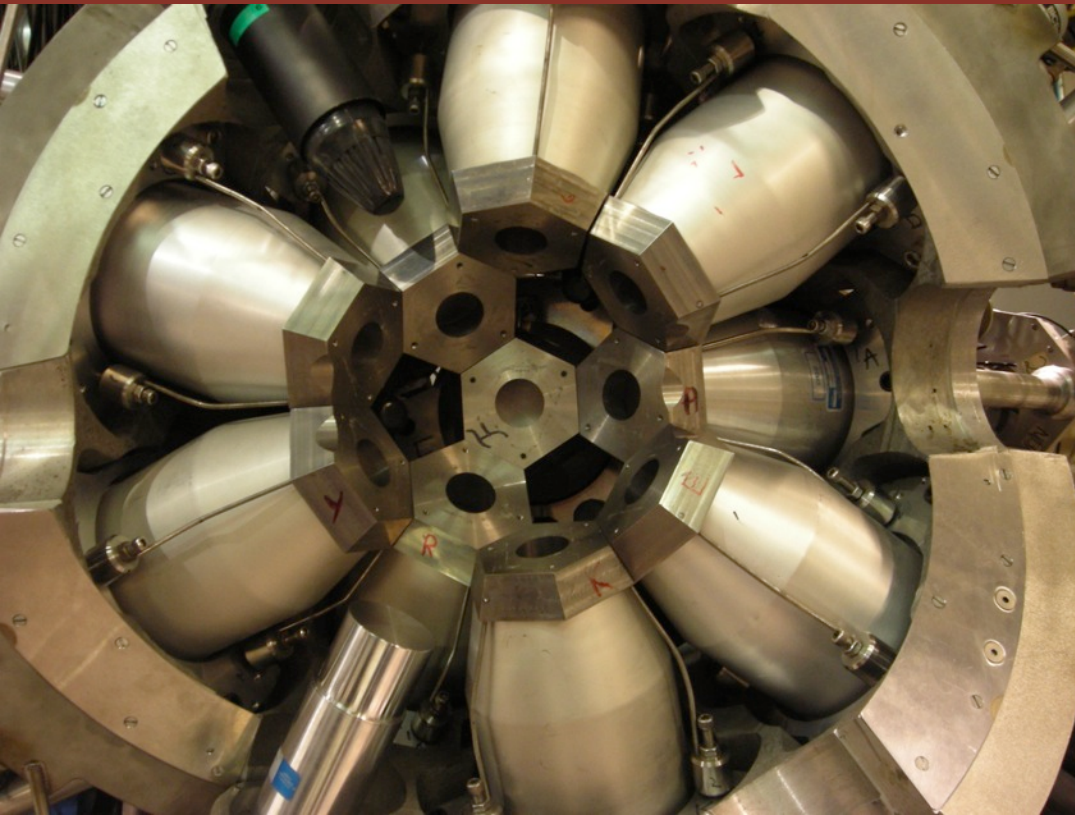
Adam Garnsworthy | Research Scientist | TRIUMF
On behalf of the 8pi collaboration

Accelerating Science for Canada
Un accélérateur de la démarche scientifique canadienne

Owned and operated as a joint venture by a consortium of Canadian universities via a contribution through the National Research Council Canada
Propriété d'un consortium d'universités canadiennes, géré en co-entreprise à partir d'une contribution administrée par le Conseil national de recherches Canada



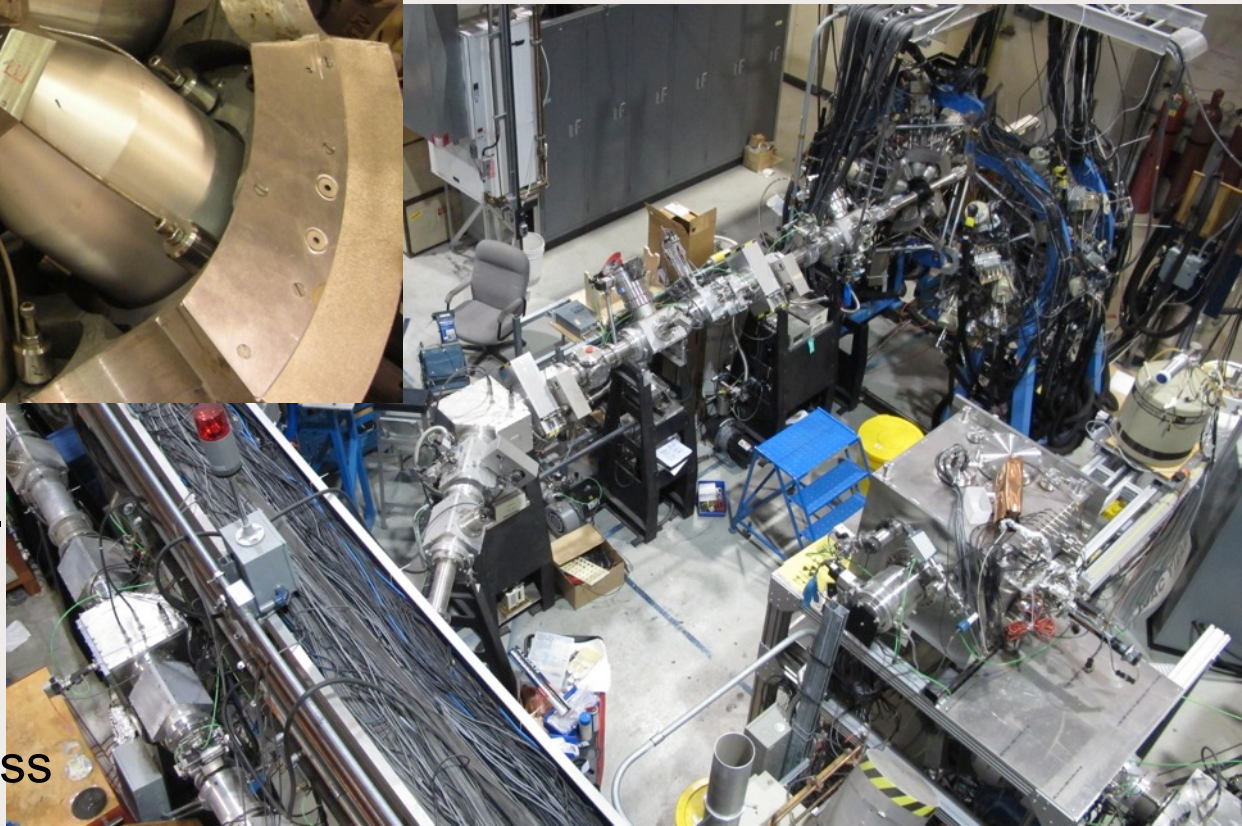
The 8π Spectrometer at TRIUMF-ISAC



Performed decay spectroscopy at TRIUMF-ISAC-I from Feb 2002 to Dec 2013

Researchers from 24 institutions from 8 countries.

>25 post-docs,
5 PhD, 12 MSc, 1 MPhys
12 Grad. Students in progress



The 8π Spectrometer at TRIUMF-ISAC

32 publications including 4 PRLs
19 on Nuclear Structure
13 on Superalowed beta decay

Superalowed Beta Decay

^{10}C , ^{14}O , ^{18}Ne , ^{19}Ne , ^{26}Al , ^{38}K , ^{62}Ga , ^{74}Rb

R. Dunlop et al., PRC 88, 045501 (2013)
G.F. Grinyer et al., PRC 87, 045502 (2013)
A.T. Laffoley et al., PRC 88, 015501 (2013)
P. Finlay et al., PRC 85, 055501 (2012)
S. Triambak et al., PRL 109, 042301 (2012)
P. Finlay et al., PRC 78, 025502 (2008)
K.G. Leach et al., PRL 100, 192504 (2008)
G.F. Grinyer et al., PRC 76, 025503 (2007)
E.F. Zganyar et al., Acta Phys.Pol. B38, 1179 (2007)
B. Hyland et al., PRL 97, 102501 (2006)
B. Hyland et al., AIP Conf.Proc. 819, 105 (2006)
G.F. Grinyer et al., PRC 71, 044309 (2005)
A. Piechaczek et al., PRC 67, 051305 (2003)

High-statistics studies of Cd, Sn, Xe

P.E. Garrett et al., PRC 86, 044304 (2012)
P.E. Garrett et al., Acta Phys.Pol. B42, 799 (2011)
P.E. Garrett et al., AIP Conf.Proc. 1377, 211 (2011)
K.L. Green et al., PRC 80, 032502 (2009)

Half Life of geochronometer, ^{176}Lu

G.F. Grinyer et al., PRC 67, 014302 (2003)

Structure of $^{219-223}\text{Rn}$ towards a RnEDM search

Isomer decay in ^{174}Tm , ^{178}Hf , ^{179}Lu

R.S. Chakrawarthy et al., PRC 73, 024306 (2006)
R.S. Chakrawarthy et al., EPJ. A 25, S1, 125 (2005)
M.B. Smith et al., NPA746, 617c (2004)
M.B. Smith et al., PRC 68, 031302 (2003)

Shape coexistence in neutron-rich Sr, Zr

A. Chakraborty et al., PRL 110, 022504 (2013)

Island of inversion, ^{32}Mg

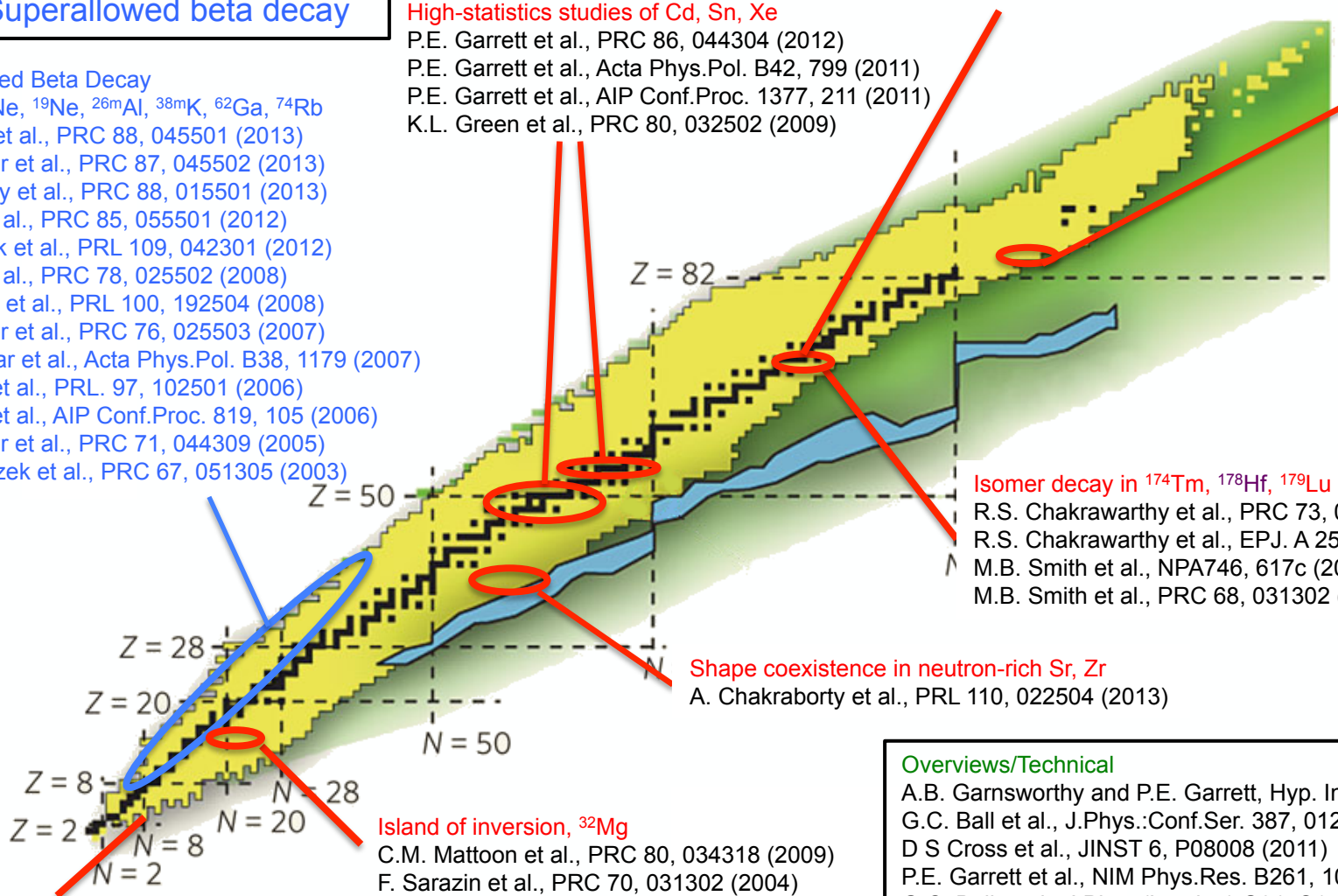
C.M. Mattoon et al., PRC 80, 034318 (2009)
F. Sarazin et al., PRC 70, 031302 (2004)

Overviews/Technical

A.B. Garnsworthy and P.E. Garrett, Hyp. Int. 225, 121 (2014)
G.C. Ball et al., J.Phys.:Conf.Ser. 387, 012014 (2012)
D S Cross et al., JINST 6, P08008 (2011)
P.E. Garrett et al., NIM Phys.Res. B261, 1084 (2007)
G.C. Ball et al., J.Phys.(London) G31, S1491 (2005)
S.J. Williams et al., J.Phys.(London) G31, S1979 (2005)

^{11}Li beta-delayed neutron emission

C.M. Mattoon et al., PRC 75, 017302 (2007)



8 π : Results with long-lived sources

The Half-Life of ^{176}Lu by a $\gamma - \gamma$ Coincidence Technique:

$$T_{1/2} = 40.8 \pm 0.3 \text{ billion years}$$

Used as a geochronometer with Lu/Hf abundance ratios.

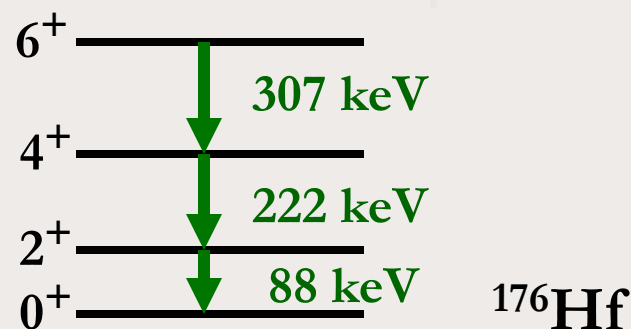
Experiment: February 2002

Published: *G.F. Grinyer et al.,
Phys. Rev. C 67, 014302 (2003)*

$$7^- \quad T_{1/2} \sim 4 \times 10^{10} \text{ y}$$

β

^{176}Lu



8 π : Results with long-lived sources

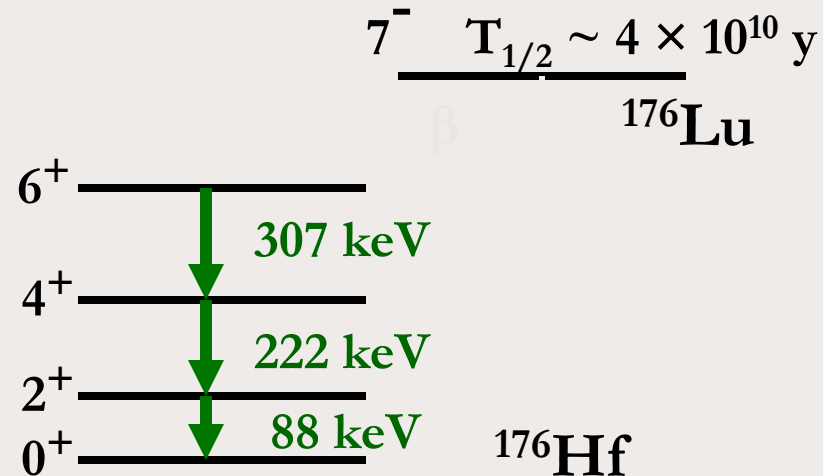
The Half-Life of ^{176}Lu by a $\gamma - \gamma$ Coincidence Technique:

$$T_{1/2} = 40.8 \pm 0.3 \text{ billion years}$$

Used as a geochronometer with Lu/Hf abundance ratios.

Experiment: February 2002

Published: *G.F. Grinyer et al.,
Phys. Rev. C 67, 014302 (2003)*



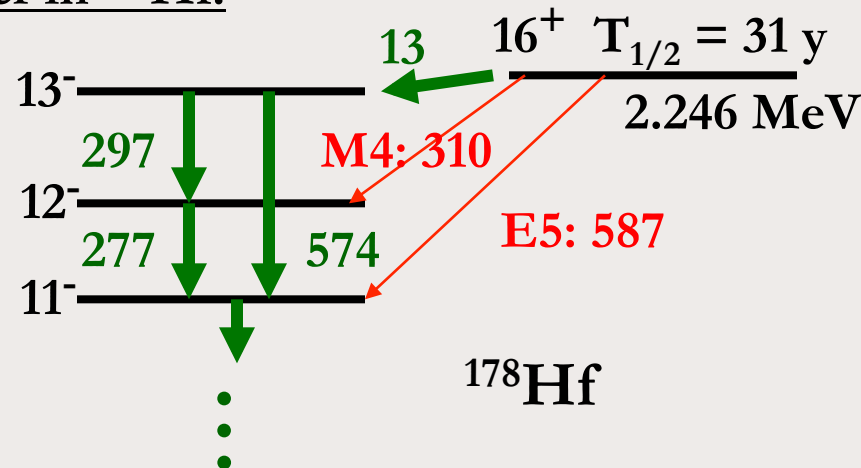
Gamma Decay of the 31-year $K^\pi = 16^+$ Isomer in ^{178}Hf :

First observation of M4 and E5 decay of a high-K isomer

- reduced K hindrances ~ 100

Experiment: December 2002

Published: *M.B. Smith et al.,
Phys. Rev. C 68, 031302(R) (2003).*



ISAC rare isotope facility

ISAC-I and ISAC-II Facility

ISAC II:
> 6 AMeV for $A < 150$

ISAC I:
60 keV & 1.7 AMeV

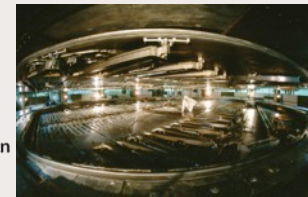
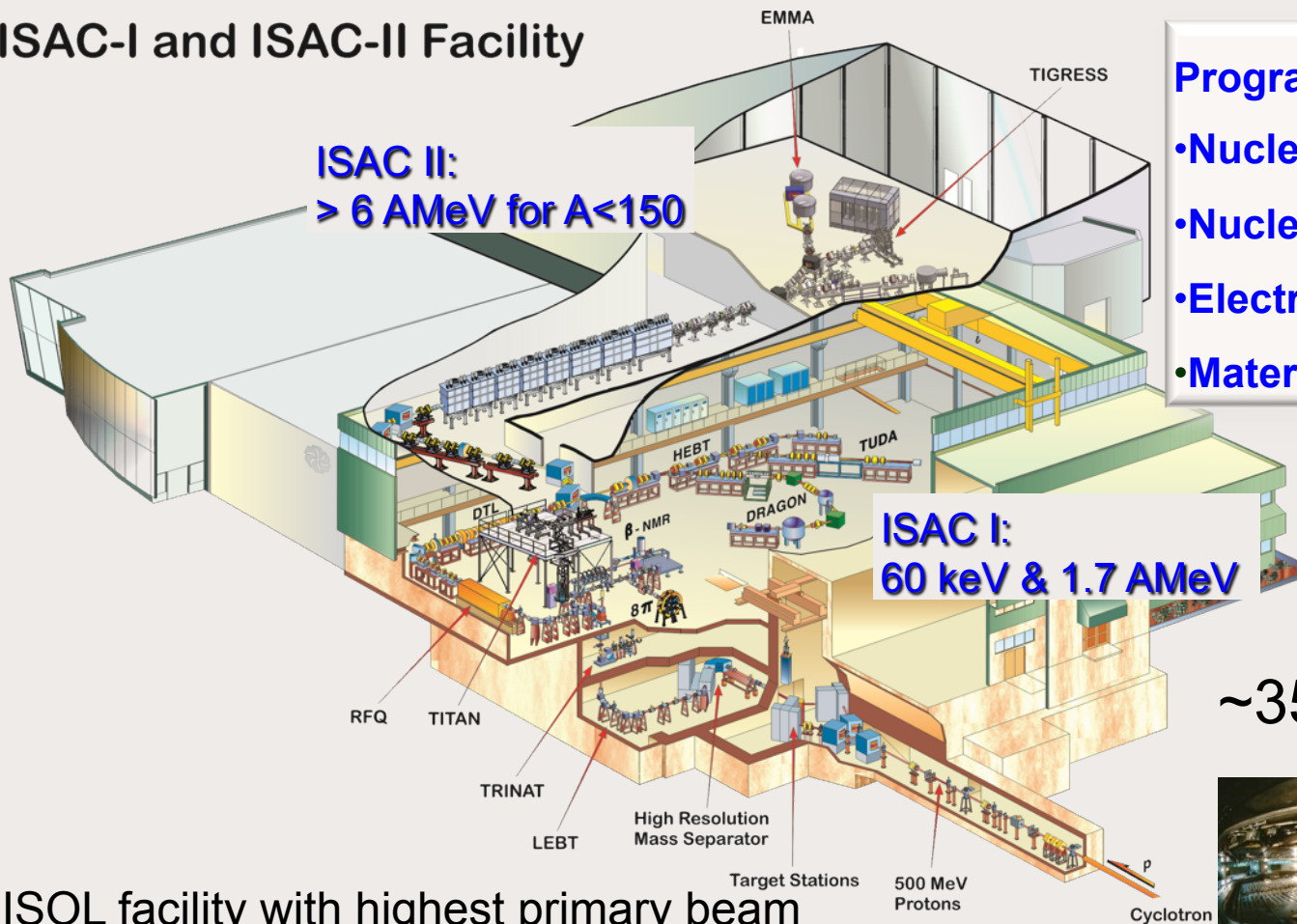
Programs in

- Nuclear Structure & Dynamics
- Nuclear Astrophysics
- Electroweak Interaction Studies
- Material Science

~3500 RIB hours /yr

ISOL facility with highest primary beam intensity (100 μA , 500 MeV protons)

target materials: Si, Ti, Zr, Nb, Ta, U

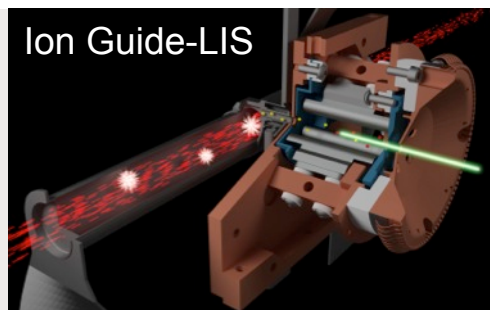


- Surface
- Resonant Laser
- FEBIAD
- IG-LIS

The plot displays the distribution of isotopes in the Z (protons) vs N (neutrons) plane. The color scale represents intensity, ranging from 10^5 (blue) to 10^{12} (red). Key features and labels include:

- Processes:** Surface, Resonant Laser, FEBIAD, IG-LIS.
- Regions:** Nova, X-ray burster, halo program, shell evolution, r-process, symmetry program.
- Isotopes:** Si, Nb, Ta, U.
- Legend:**
 - T RILIS isotopes on-line (green)
 - tested TiSa schemes (incomplete) (blue)
 - TiSa network: Mainz, TRIUMF, ORNL, JYFL, GANIL, ISOLDE (grey)
 - TiSa laser ionization scheme on paper (theory) (light blue)
- Status:** 12/2013 (T RILIS), 11/2013 (tested TiSa schemes).
- Author:** J. Lassen et al.

P. Kunz et al.



Group

1A 1

2A 2

3A 13

4A 14

5A 15

6A 16

7A 17

8A 18

1 H

2 He

3 Li

4 Be

5 B

6 C

7 N

8 O

9 F

10 Ne

11 Na

12 Mg

13 Al

14 Si

15 P

16 S

17 Cl

18 Ar

19 K

20 Ca

21 Sc

22 Ti

23 V

24 Cr

25 Mn

26 Fe

27 Co

28 Ni

29 Cu

30 Zn

31 Ga

32 Ge

33 As

34 Se

35 Br

36 Kr

37 Rb

38 Sr

39 Y

40 Zr

41 Nb

42 Mo

43 Tc

44 Ru

45 Rh

46 Pd

47 Ag

48 Cd

49 In

50 Sn

51 Sb

52 Te

53 I

54 Xe

55 Cs

56 Ba

57-71 * f

72 Hf

73 Ta

74 W

75 Re

76 Os

77 Ir

78 Pt

79 Au

80 Hg

81 Tl

82 Pb

83 Bi

84 Po

85 At

86 Rn

87 Fr

88 Ra

89-103 ** f

104 Rf

105 Db

106 Sg

107 Bh

108 Hs

109 Mt

110 Ds

111 Rg

112 Cn

113

114 Fl

115

116 Lv

117

118

119

120

121

122

123

124

125

126

127

128

129

130

131

132

133

134

135

136

137

138

139

140

141

142

143

144

145

146

147

148

149

150

151

152

153

154

155

156

157

158

159

160

161

162

163

164

165

166

167

168

169

170

171

172

173

174

175

176

177

178

179

180

181

182

183

184

185

186

187

188

189

190

191

192

193

194

195

196

197

198

199

200

201

202

203

204

205

206

207

208

209

210

211

212

213

214

215

216

217

218

219

220

221

222

223

224

225

226

227

228

229

230

231

232

233

234

235

236

237

238

239

240

241

242

243

244

245

246

247

248

249

250

251

252

253

254

255

256

257

258

259

260

261

262

263

264

265

266

267

268

269

270

271

272

273

274

275

276

277

278

279

280

281

282

283

284

285

286

287

288

289

290

291

292

293

294

295

296

297

298

299

300

301

302

303

304

305

306

307

308

309

310

311

312

313

314

315

316

317

318

319

320

321

322

323</

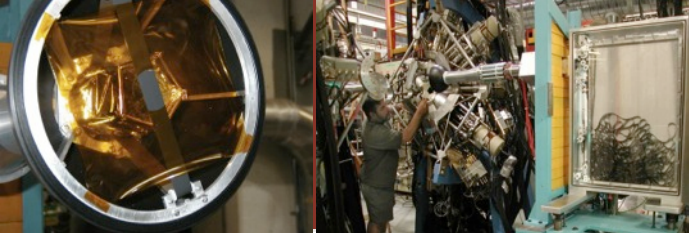
The 8pi Spectrometer at TRIUMF

Sensitive Decay Spectroscopy

ISOBAR 

J^π_{ISOMER} 

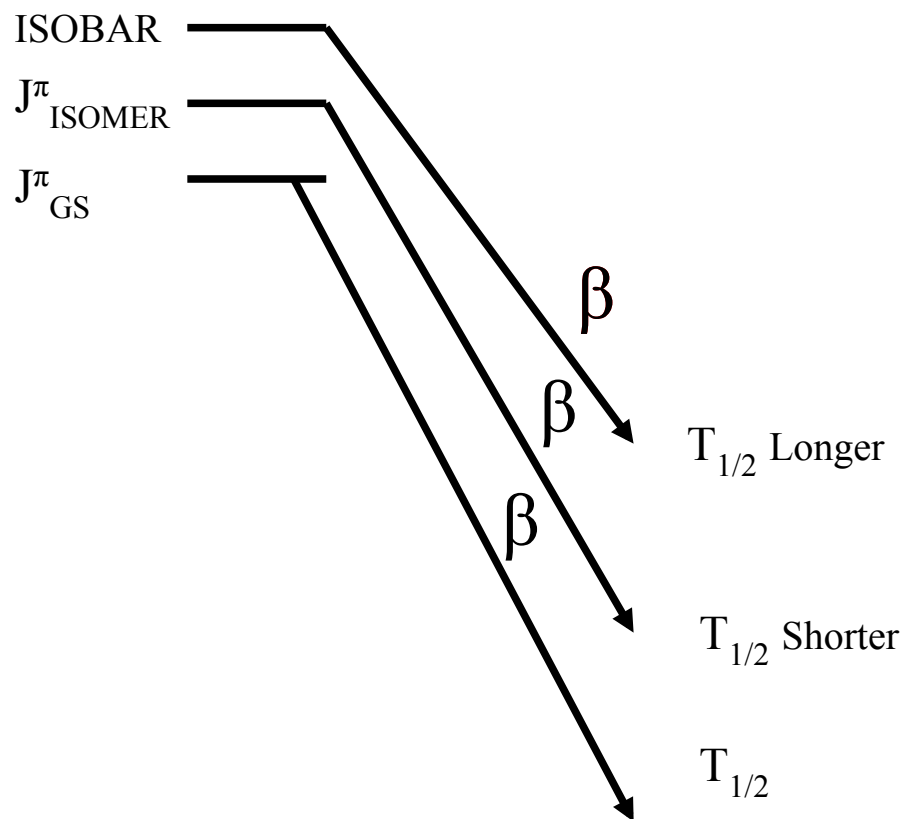
J^π_{GS} 

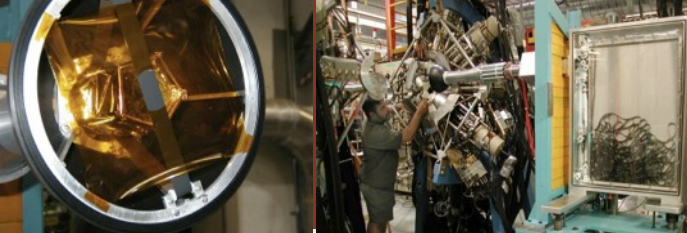


The 8pi Spectrometer at TRIUMF

Sensitive Decay Spectroscopy

Fast, in-vacuum tape system
Enhances decay of interest





The 8pi Spectrometer at TRIUMF

Sensitive Decay Spectroscopy

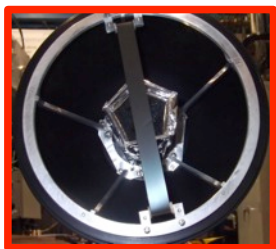
Fast, in-vacuum tape system

Enhances decay of interest

ISOBAR ————— $T_{1/2}$ Longer

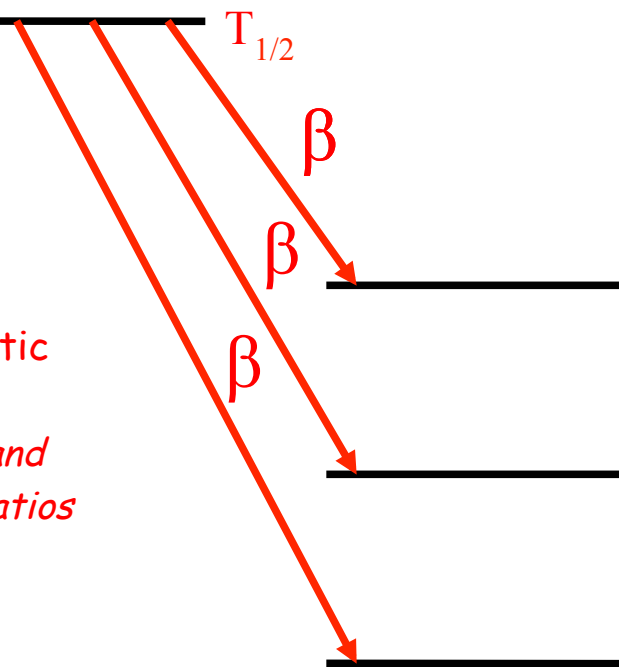
J^π ISOMER ————— $T_{1/2}$ Shorter

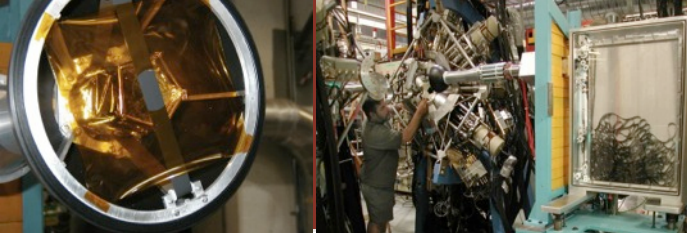
J^π GS ————— $T_{1/2}$



SCEPTAR: 10+10 plastic
scintillators

*Detects beta decays and
determines branching ratios*





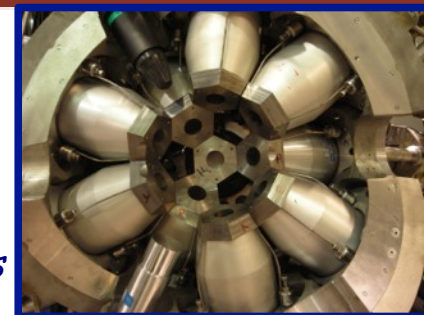
The 8pi Spectrometer at TRIUMF

Sensitive Decay Spectroscopy

Fast, in-vacuum tape system
Enhances decay of interest

8pi Ge: 20 Compton-Suppressed HpGe

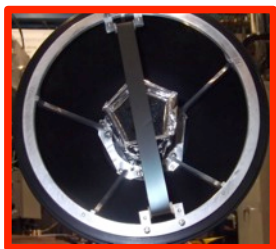
Detect gamma rays and determines branching ratios, multipolarities and mixing ratios



ISOBAR $\text{---} T_{1/2}$ Longer

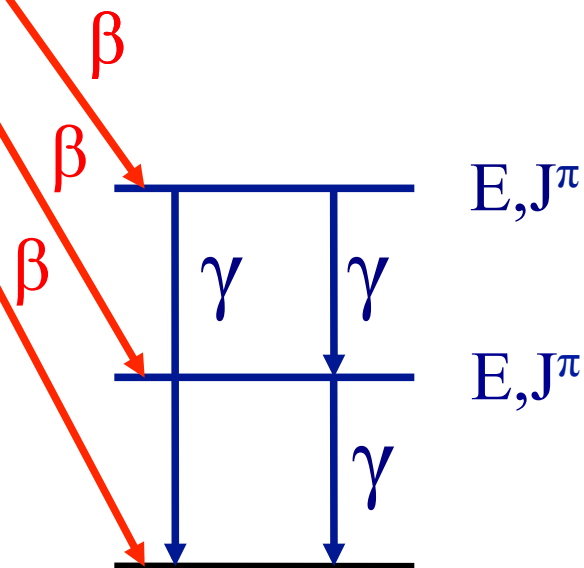
J^π ISOMER $\text{---} T_{1/2}$ Shorter

J^π GS $\text{---} T_{1/2}$



SCEPTAR: 10+10 plastic scintillators

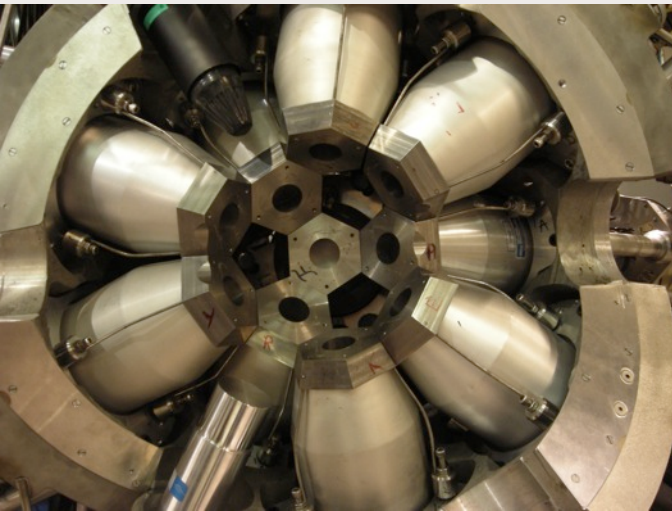
Detects beta decays and determines branching ratios



8pi HPGe Detectors



Twenty Compton-Suppressed coaxial HPGe



Each has 20% relative efficiency, ~1% array total

1.8-2.2keV FWHM at 1.3MeV

Thin Be front windows and delrin vacuum chamber to increase low-energy efficiency

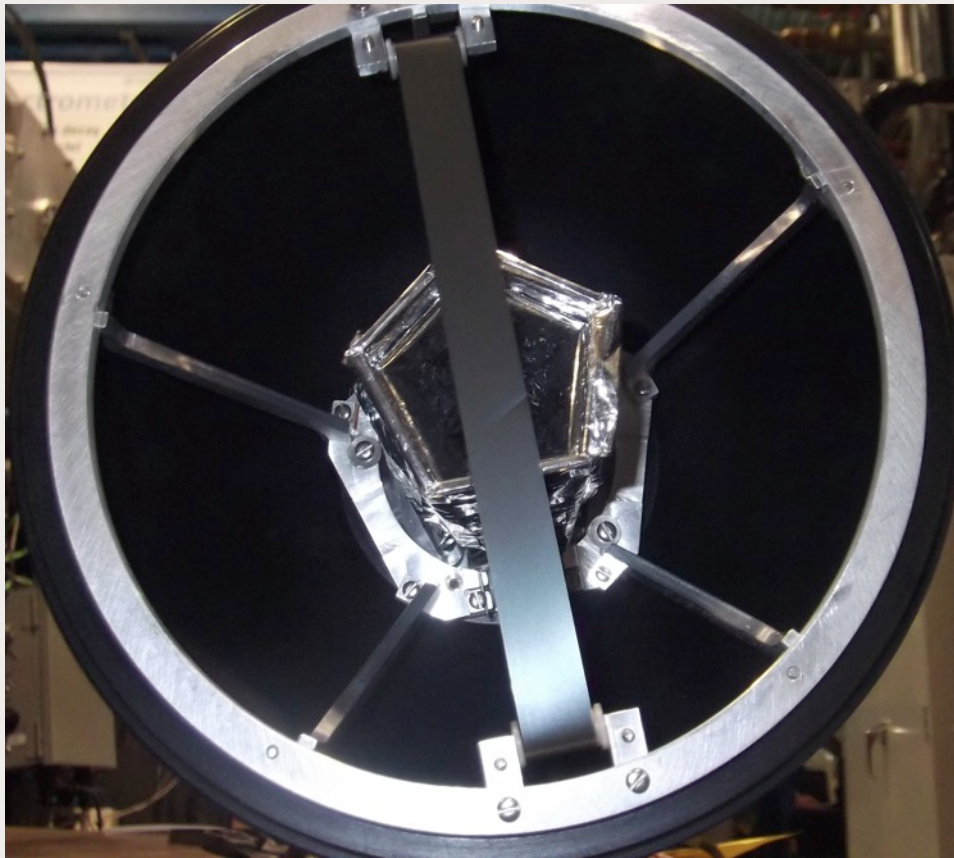


Delrin absorbers to reduce Bremsstrahlung photons from high-energy beta particles

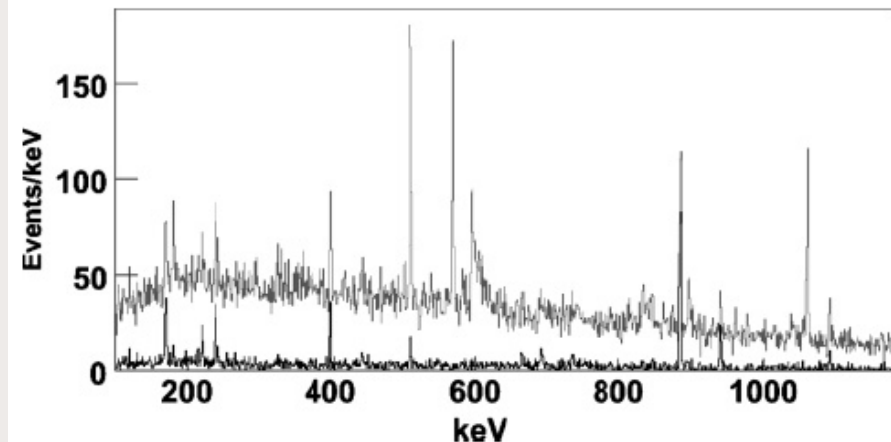
Excellent arrangement for angular distribution measurements

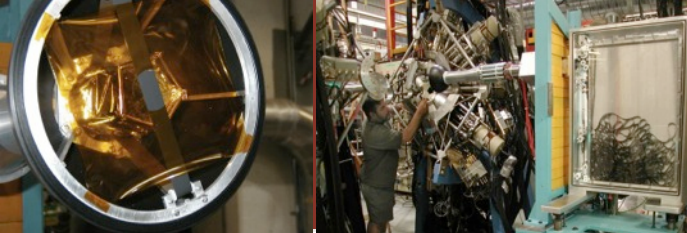
SCEPTAR

SCintillating Electron-Positron Tagging ARray



- Two hemispheres of 10 plastic scintillators
- Detect beta particles with $\sim 80\%$ solid angle coverage
- One-to-one correspondence with the HpGe





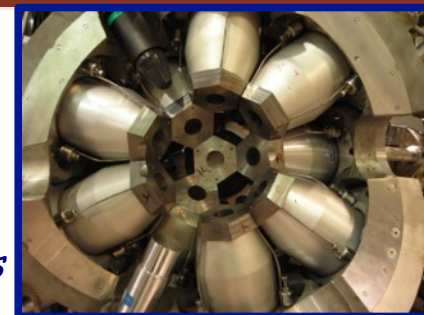
The 8pi Spectrometer at TRIUMF

Sensitive Decay Spectroscopy

Fast, in-vacuum tape system
Enhances decay of interest

8pi Ge: 20 Compton-Suppressed HpGe

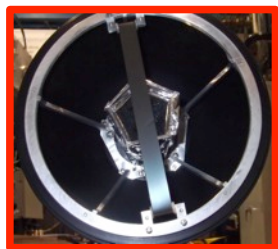
Detect gamma rays and determines branching ratios, multipolarities and mixing ratios



ISOBAR $T_{1/2}$ Longer

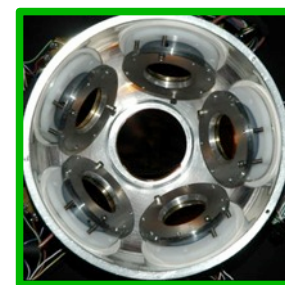
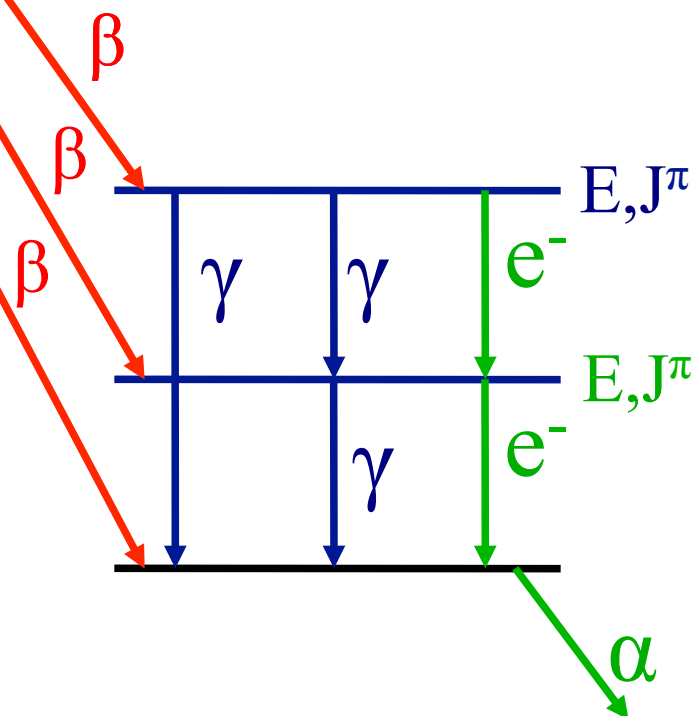
J^π ISOMER $T_{1/2}$ Shorter

J^π GS $T_{1/2}$



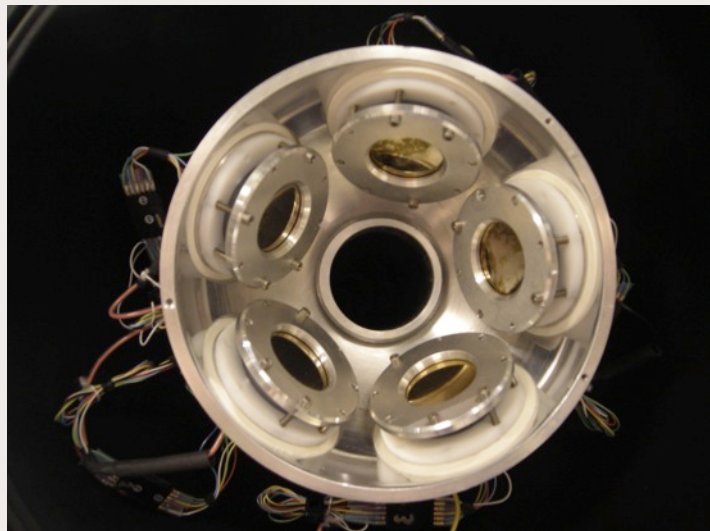
SCEPTAR: 10+10 plastic scintillators

Detects beta decays and determines branching ratios



PACES: 5 Cooled Si(Li)s
Detects Internal Conversion Electrons and alphas/protons

Pentagonal Array for Conversion Electron Spectroscopy



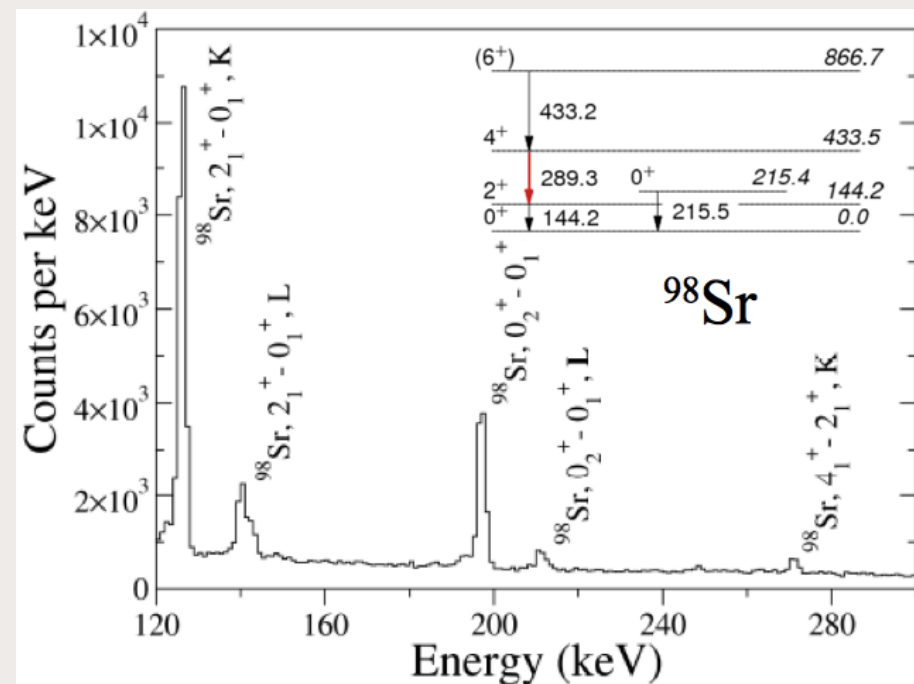
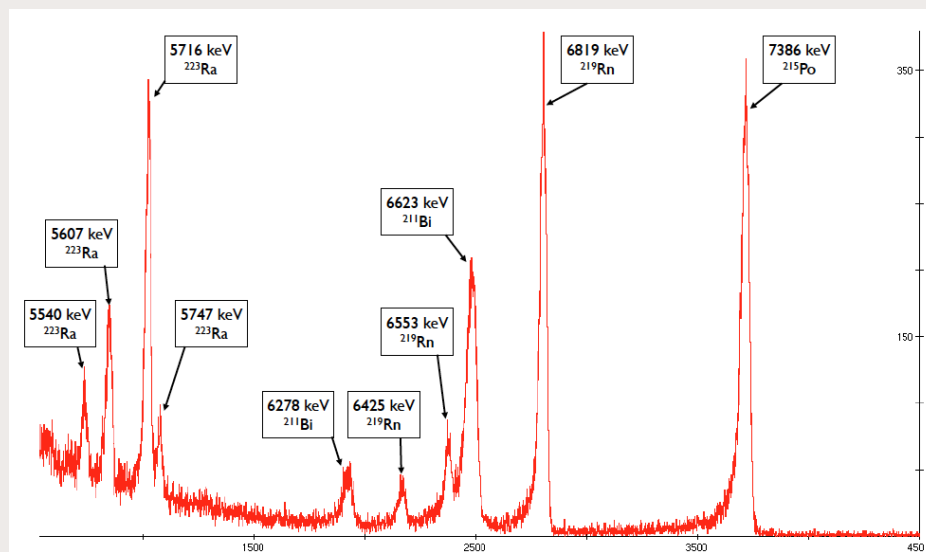
Five 5mm thick, 200mm² Si(Li)

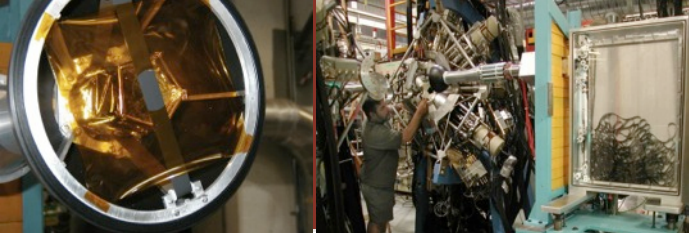
LN₂-cooled Si diode and FET

Solid angle coverage: 1.4% each, 7% total

~2keV resolution for electrons

Dual-Gain data readout – electron, alpha





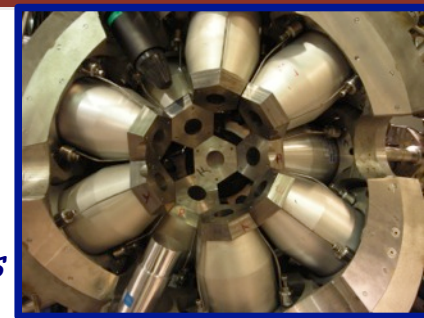
The 8pi Spectrometer at TRIUMF

Sensitive Decay Spectroscopy

Fast, in-vacuum tape system
Enhances decay of interest

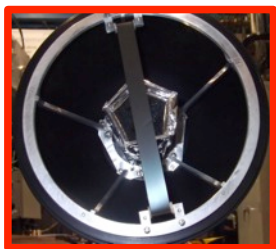
8pi Ge: 20 Compton-Suppressed HpGe

Detect gamma rays and determines branching ratios, multipolarities and mixing ratios



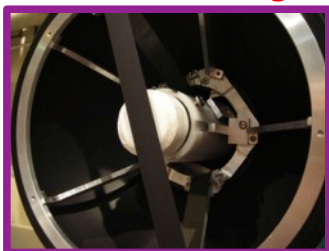
DANTE: 10 BaF₂/LaBr₃
Fast-timing of photons to measure level lifetimes

ISOBAR $T_{1/2}$ Longer
 J^π ISOMER $T_{1/2}$ Shorter
 J^π GS $T_{1/2}$

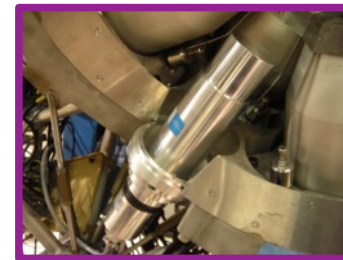
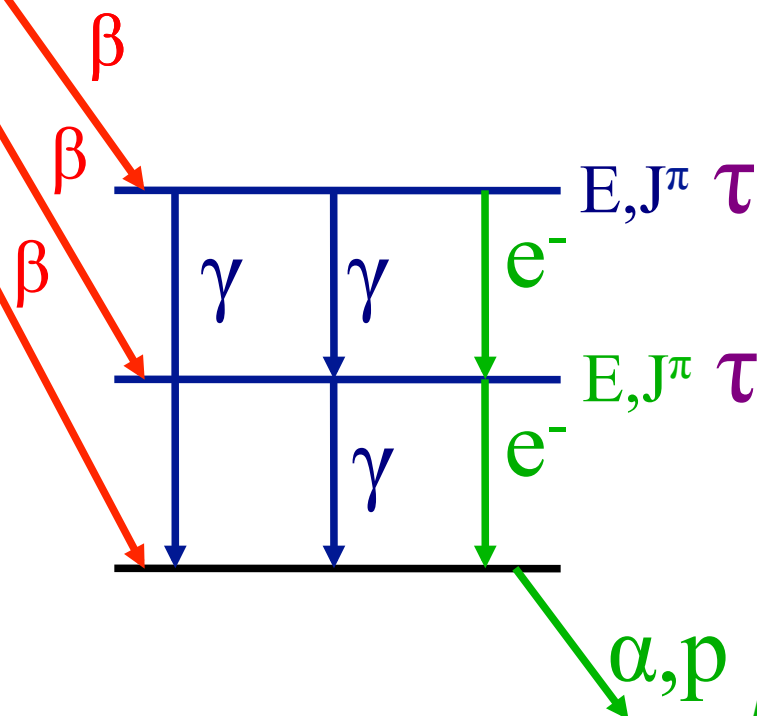


SCEPTAR: 10+10 plastic scintillators

Detects beta decays and determines branching ratios

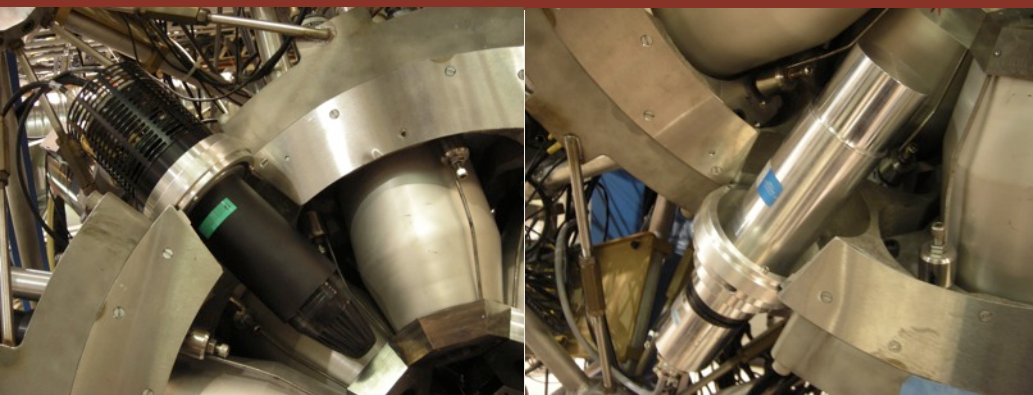


Zero-Degree Fast scintillator
Fast-timing signal for betas



PACES: 5 Cooled Si(Li)s
Detects Internal Conversion Electrons and alphas/protons

Di-pentagonal Array for Nuclear Timing Experiments

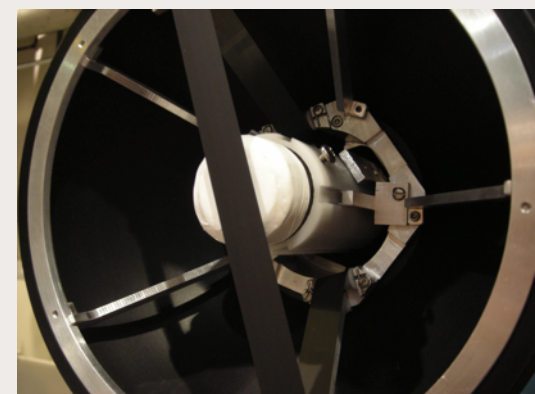
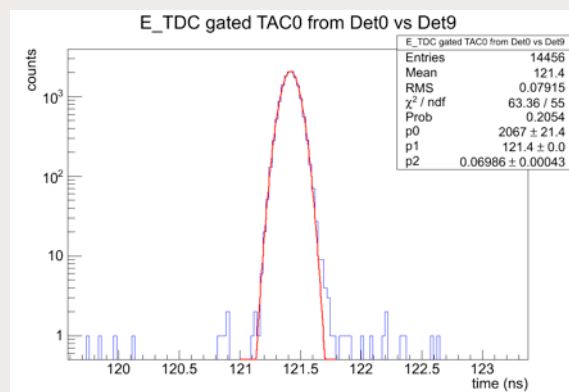
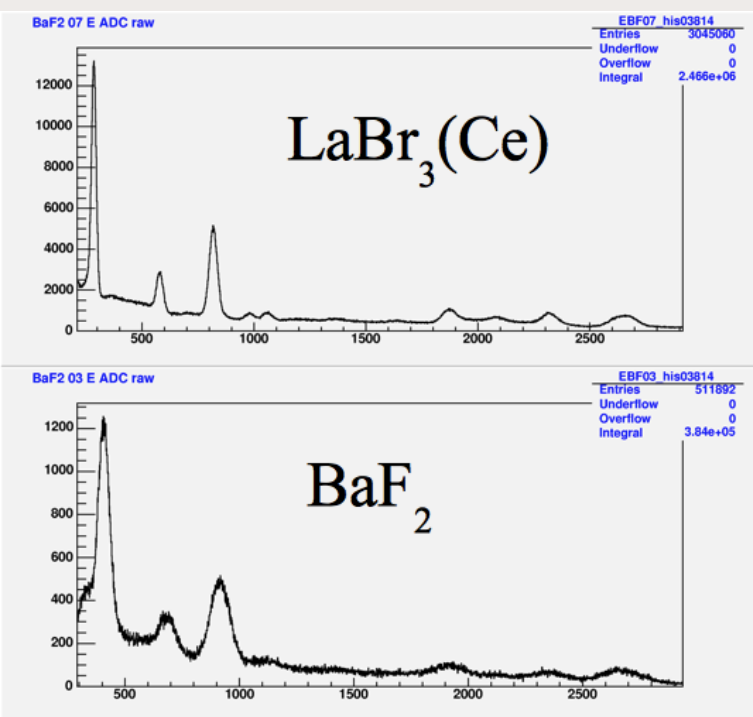


Fast-timing allows the determination of transition rates

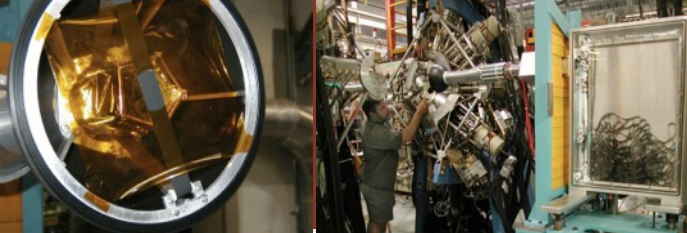
- BaF₂, truncated cone;
base 4cm, front 2cm, length 3cm
- LaBr₃(Ce) 2"x2" cylinder

Superior Energy resolution (x3) and efficiency (x2)

LaBr-LaBr FWHM = 165(1) ps



Fast Zero-degree scintillator for β - γ timing. BC422Q = 0.7ns



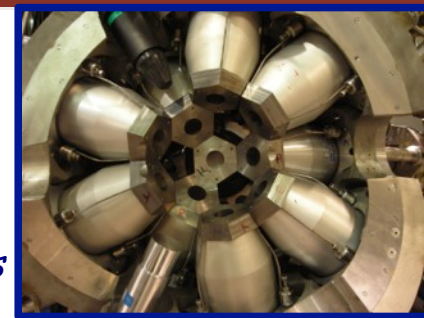
The 8pi Spectrometer at TRIUMF

Sensitive Decay Spectroscopy

Fast, in-vacuum tape system
Enhances decay of interest

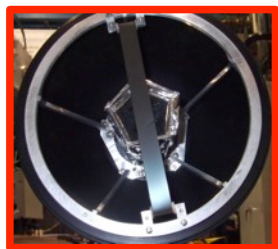
8pi Ge: 20 Compton-Suppressed HpGe

Detect gamma rays and determines branching ratios, multipolarities and mixing ratios



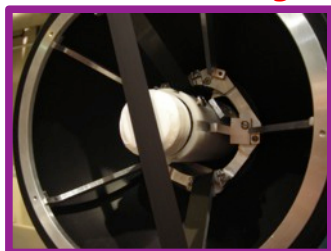
DANTE: 10 BaF₂/LaBr₃
Fast-timing of photons to measure level lifetimes

ISOBAR ————— $T_{1/2}$ Longer
 J^π ISOMER ————— $T_{1/2}$ Shorter
 J^π GS ————— $T_{1/2}$

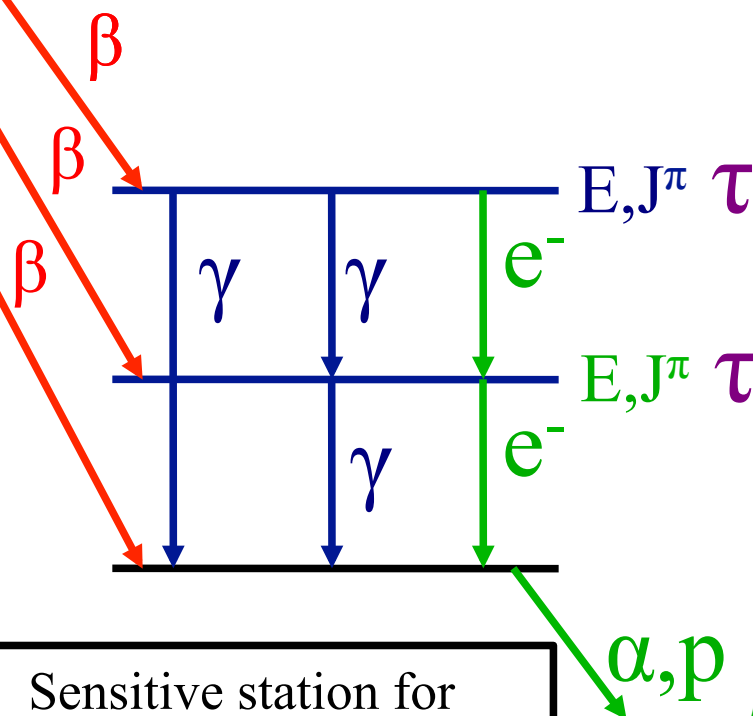


SCEPTAR: 10+10 plastic scintillators

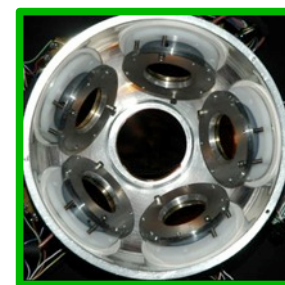
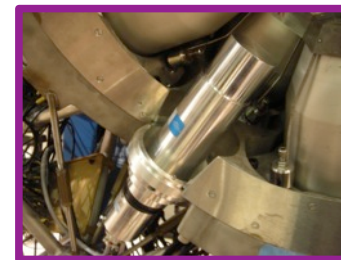
Detects beta decays and determines branching ratios



Zero-Degree Fast scintillator
Fast-timing signal for betas



Sensitive station for
studying radioactive decay

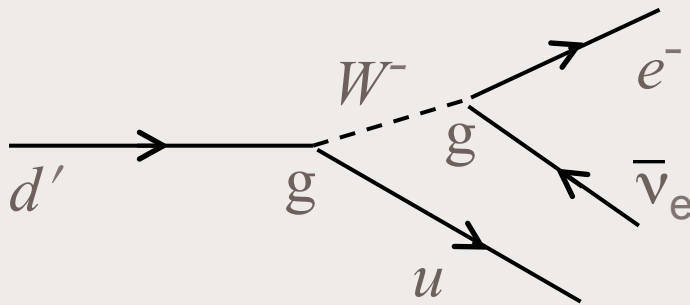


PACES: 5 Cooled Si(Li)s
Detects Internal Conversion Electrons and alphas/protons

The Cabibbo-Kobayashi-Maskawa (CKM) matrix

- The CKM matrix plays a central role in the Standard Model

→ and underpins all quark flavour-changing interactions:
weak interaction eigenstates $\neq$ quark mass eigenstates



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

$$|d'\rangle = V_{ud}|d\rangle + V_{us}|s\rangle + V_{ub}|b\rangle$$

- In the Standard Model the CKM describes a unitary transformation.

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$$

The first row of the CKM matrix provides, by far, the most demanding experimental test of this unitarity condition.

V_{ud} from Superallowed Fermi β Decay

To first order, β decay ft values can be expressed as:

$$ft = \frac{K}{|M_{fi}|^2 g^2}$$

phase space (Q-value) $\rightarrow$ f
 half-life, branching ratio $\rightarrow$ t
 constants $\rightarrow$ K
 Weak coupling strength $\rightarrow$ g^2
 matrix element $\rightarrow$ $|M_{fi}|^2$

For the special case of $0^+ \rightarrow 0^+$ (pure Fermi) β decays between isobaric analogue states (superallowed) the matrix element is that of an isospin ladder operator:

$$|M_{fi}|^2 = (T - T_Z)(T + T_Z + 1) = 2 \quad (\text{for } T=1)$$

Strategy: Measure superallowed ft-values, deduce G_V and V_{ud} :

$$G_V^2 = \frac{K}{2 ft} \quad |V_{ud}| = G_V / G_F$$

Vector coupling constant $\rightarrow$ G_V^2
 Fermi coupling constant $\leftarrow$ G_F

Superallowed β Decay Studies at ISAC

$T_{1/2}$, G.C. Ball *et al*, PRL 86 1454 (2001)
BR, A. Piechaczek *et al*, PRC 67, 051305 (2003)
BR, R. Dunlop *et al*, PRC 88, 045501 (2013)
Q: S. Ettenauer *et al.*, PRL 107, 272501 (2011)
CR: E. Mané *et al*, PRL 107, 212502 (2011)

$T_{1/2}$, G.F. Grinyer, PRC 77, 201501 (2008)
BR, B.H. Hyland, PRL 97, 102501 (2006)
BR, P. Finlay PRC 78, 044321 (2008)

BR, K.G. Leach *et al.*, PRL 100, 192504 (2008)
 $T_{1/2}$, G.C. Ball *et al*, PRC 82, 045501 (2010)

$T_{1/2}$ and BR

$38mK$

$34Ar$

$26mAl$

$18Ne$

$14O$

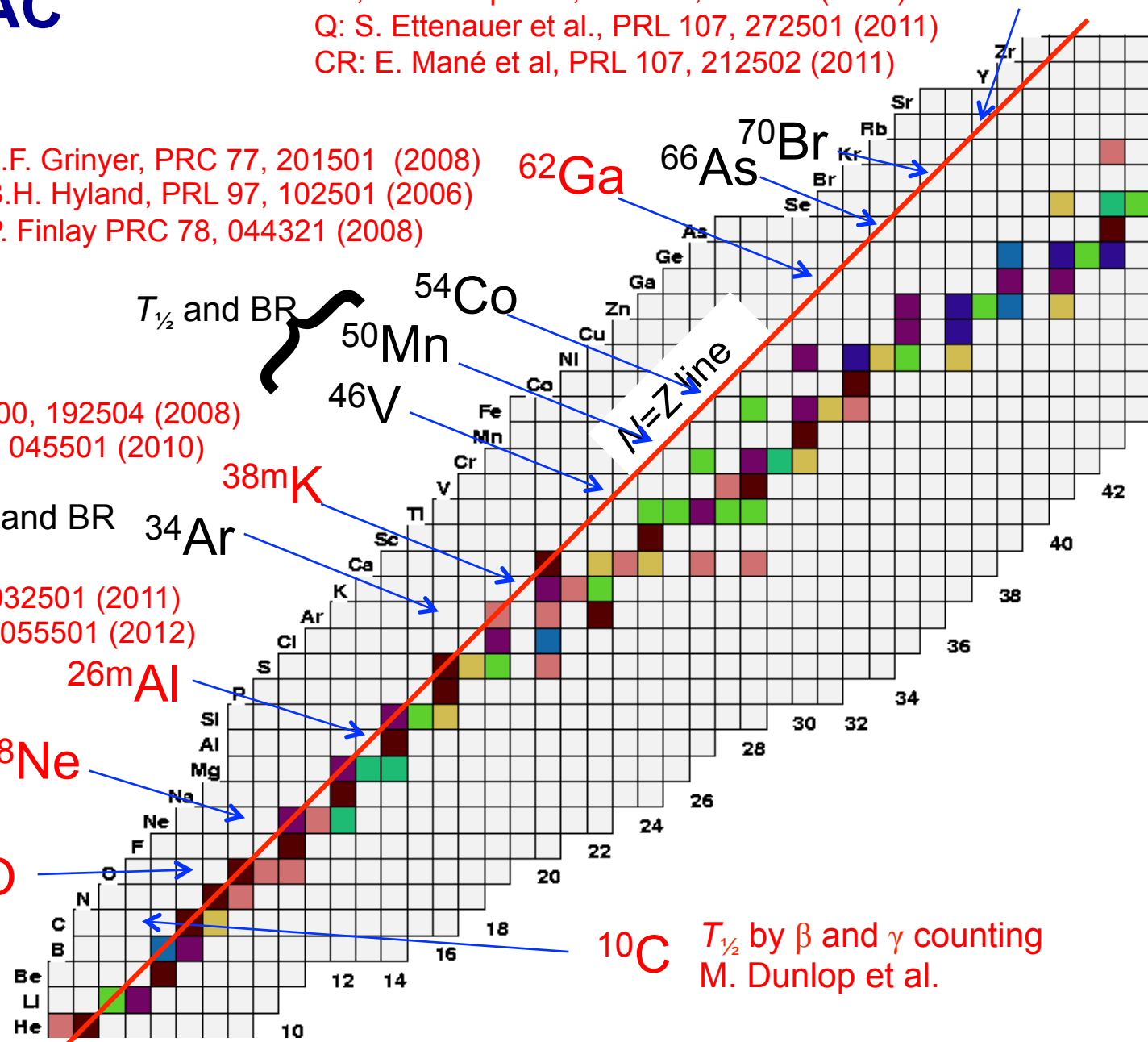
$T_{1/2}$, G.F. Grinyer *et al*,
PRC 76, 025503 (2007)
PRC 87, 045502 (2013)

$T_{1/2}$, A.T. Laffoley *et al*,
PRC 88, 015501 (2013)

$10C$

$T_{1/2}$ by β and γ counting
M. Dunlop *et al.*

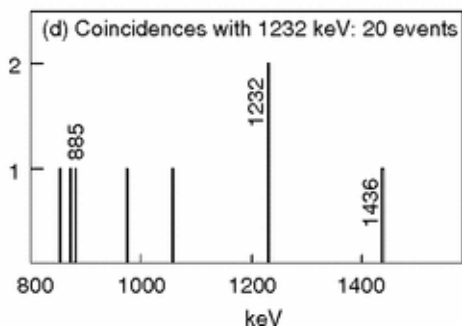
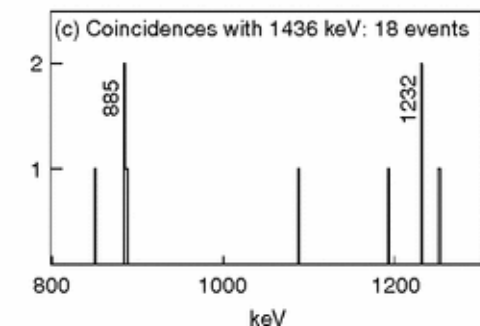
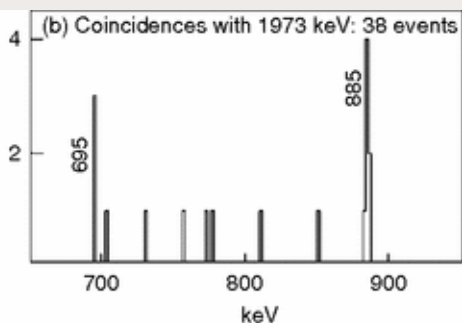
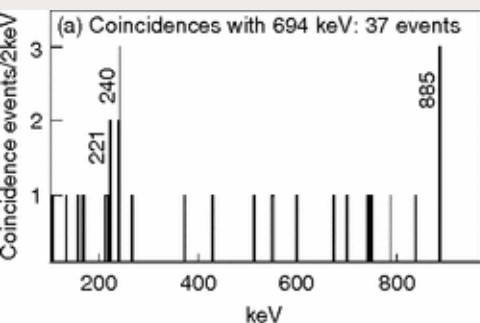
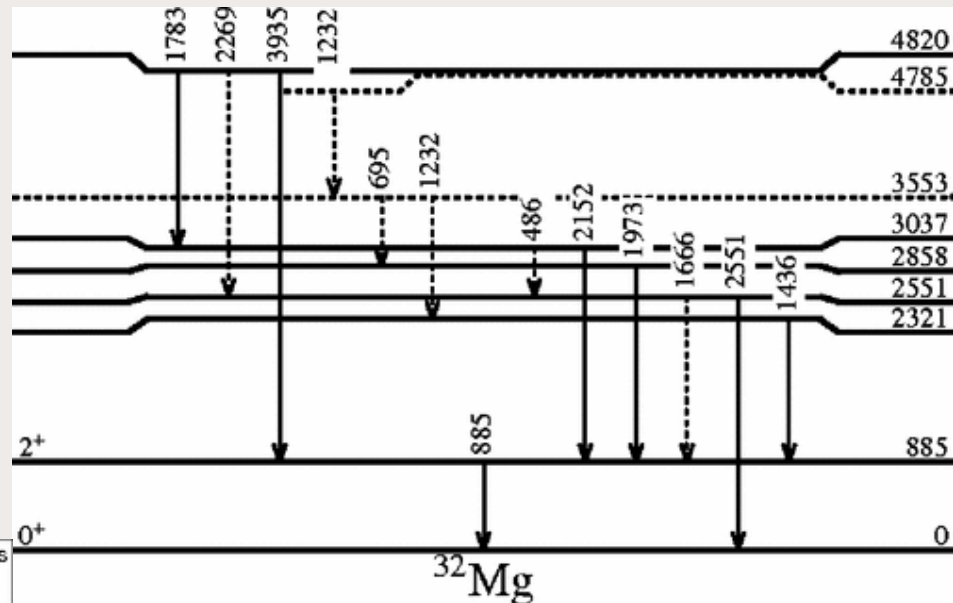
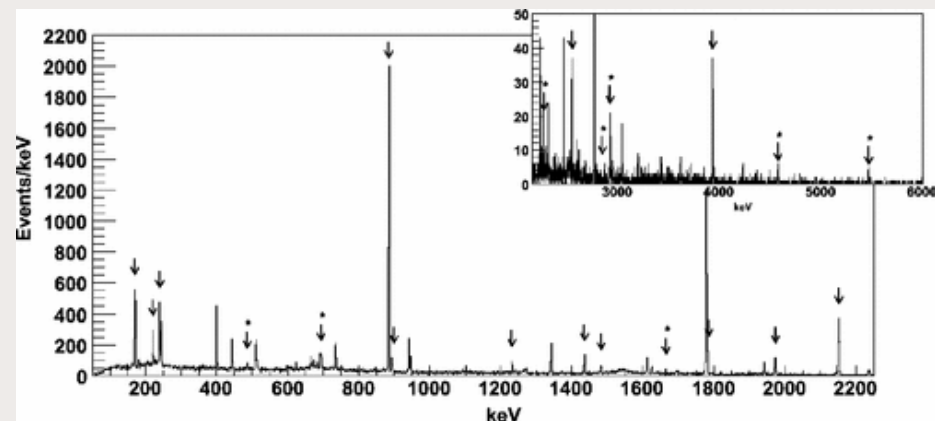
$74Rb$



Nuclear Structure Studies with the 8pi Spectrometer

Beam Intensity	Beam Species	
2-3 pps	^{32}Na	Build level scheme with gamma-gamma coincidences
6 pps	^{102}Sr	
10^4 pps	^{11}Li	
10^5 pps	$^{174\text{m}}\text{Tm}$	
10^6 pps	$^{94}\text{Y}/\text{Sr}/\text{Rb}$	Identity weak branches, angular correlations
10^6 pps	$^{98}\text{Y}/\text{Sr}/\text{Rb}$	
10^7 pps	$^{179\text{m}}\text{Lu}$	
10^9 pps	$^{110,112,116}\text{In},$ $^{110,112}\text{Ag}$ ^{124}Cs	Identity very weak branches

Island of Inversion – Level scheme of ^{32}Mg



- Beam of ^{32}Na at 2-3 pps
- Built level scheme from coincidences, new levels identified
- Spin assignments not possible

C.M. Mattoon *et al.*, Phys. Rev. C 75, 017302 (2007)

Neutron-Rich Rb Isotopes

Z=40

Z=38

Z=37

Zr90 0+ 51.45 *	Zr91 5/2+ 11.22	Zr92 0+ 17.15 β	Zr93 1.53E+6 y 5/2+ β	Zr94 0+ 17.38 β	Zr95 64.02 d 5/2+ β	Zr96 3.9E19 y 0+ β	Zr97 16.91 h 1/2+ β	Zr98 30.7 s 0+ β	Zr99 2.1 s (1/2+) β	Zr100 7.1 s 0+ β	Zr101 2.1 s (3/2+) β	Zr102 2.9 s 0+ β	Zr103 1.3 s (5/2-) β	Zr104 1.2 s 0+ β	Zr105 0.6 s β	Zr106 0+ β
Y89 1/2- 100 *	Y90 64.10 h 2- *	Y91 58.51 d 1/2- *	Y92 3.54 h 2- β	Y93 10.18 h 1/2- β	Y94 18.7 m 2- β	Y95 10.3 m 1/2- β	Y96 5.34 s 0- β	Y97 3.75 s (0)- β	Y98 0.548 s (0)- β	Y99 1.470 s (5/2+) β	Y100 735 ms 1-2- β	Y101 448 ms (5/2+) β	Y102 0.36 s (5/2+) β	Y103 0.23 s (5/2+) β	Y104 β	Y105 β
Sr88 0+ 82.58 β	Sr89 50.53 d 5/2+ β	Sr90 28.78 y 0+ β	Sr91 9.63 h 5/2+ β	Sr92 2.71 h 0+ β	Sr93 7.423 m 5/2+ β	Sr94 75.3 s 0+ β	Sr95 23.90 s 1/2+ β	Sr96 5.34 s 0+ β	Sr97 426 ms 1/2+ β	Sr98 0.653 s 0+ β	Sr99 0.269 s 3/2+ β	Sr100 202 ms 0+ β	Sr101 118 ms (5/2) β	Sr102 69 ms 0+ β	Sr103 β	Sr104 0+ β
Rb87 4.75E10 y 3/2- β	Rb88 17.78 m 2- β	Rb89 15.15 m 3/2- β	Rb90 158 s 0- β	Rb91 58.4 s 3/2(+) β	Rb92 4.492 s 0- β	Rb93 5.84 s 5/2- β	Rb94 2.702 s 3(-) β	Rb95 377.5 ms 5/2- β	Rb96 0.199 s 2+ β	Rb97 169.9 ms 3/2(+) β	Rb98 114 ms (1,0) β	Rb99 50.3 ms (5/2+) β	Rb100 51 ms β	Rb101 32 ms β	Rb102 37 ms β	
Kr86 0+ 17.3 β	Kr87 76.3 m 5/2+ β	Kr88 2.84 h β	Kr89 3.15 m (3/2+,5/2+) β	Kr90 32.32 s 0+ β	Kr91 8.57 s (5/2+) β	Kr92 1.840 s 0+ β	Kr93 1.286 s (1/2+) β	Kr94 0.20 s 0+ β	Kr95 0.78 s 1/2 β	Kr96 0+ β	Kr97 β					
Br85 2.90 m 3/2- β	Br86 55.1 s (2-) β	Br87 55.60 s 3/2- β	Br88 16.34 s (1,2-) β	Br89 4.348 s (3/2-,5/2-) β	Br90 1.910 s β	Br91 0.541 s β	Br92 0.343 s (2-) β	Br93 102 ms (5/2-) β	Br94 70 ms β							
Se84 3.1 m 0+ β	Se85 31.7 s (5/2+) β	Se86 15.3 s 0+ β	Se87 5.29 s (5/2+) β	Se88 1.53 s 0+ β	Se89 0.41 s (5/2+) β	Se90 β	Se91 0.27 s β	Se92 0+ β								
As83 13.4 s (5/2-,3/2-) β	As84 4.02 s *	As85 2.021 s (3/2-) β	As86 0.945 s β	As87 0.48 s (3/2-) β	As88 β	As89 β										
Ge82 4.60 s 0+ β	Ge83 1.85 s (5/2+) β	Ge84 966 ms 0+ β	Ge85 535 ms β	Ge86 0+ β												
Ga81 1.217 s (5/2-) β	Ga82 0.599 s (1,2,3) β	Ga83 0.31 s β	Ga84 85 ms β													
Zn80 0.545 s 0+ β	Zn81 0.29 s β	Zn82 0+ β														
Cu79 188 ms β	Cu80 β															
Ni78 0+ β																

66

62

64

60

58

56

54

52

50

Neutron
mid-shell

Neutron Shell closure

Decay of ^{102}Rb

Z.M. Wang *et al.*, to be published

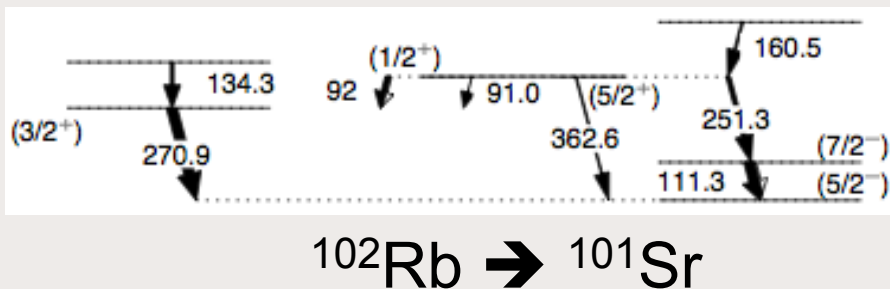
^{102}Rb beam at 6 pps

^{101}Sr populated in beta-delayed neutron emission

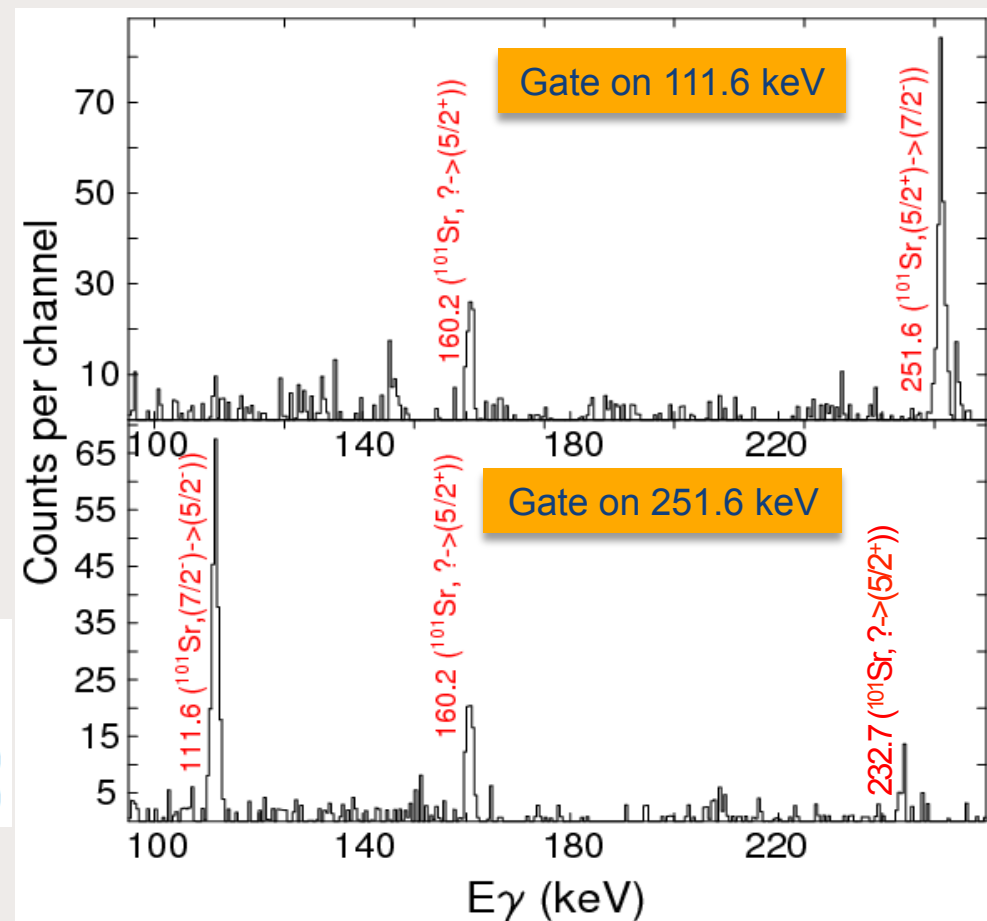
Level scheme consistent with previous beta-decay study

Lhersonneau *et al.*, Z. Phys. A 351, 357 (1995).

Confirmed tentative 134, 161keV transitions



Gamma-gamma coincidence



Decay of ^{102}Rb

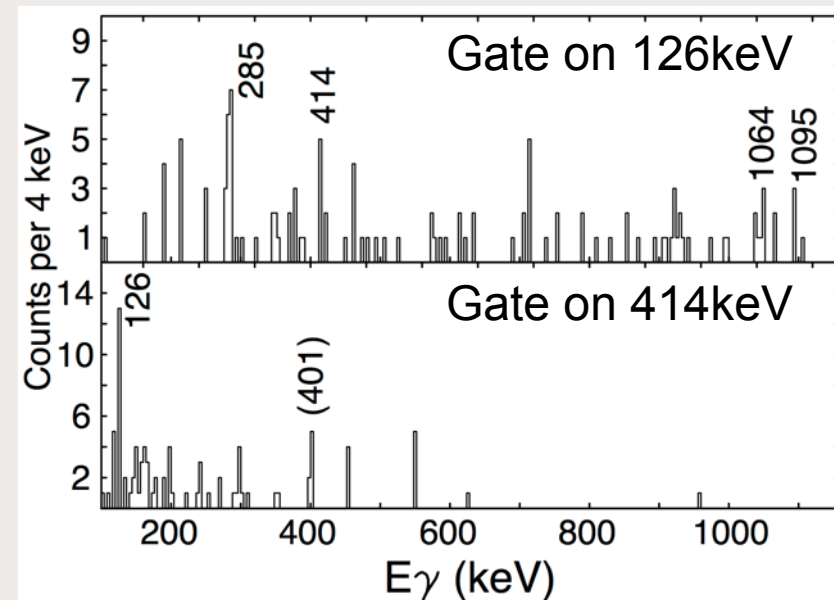
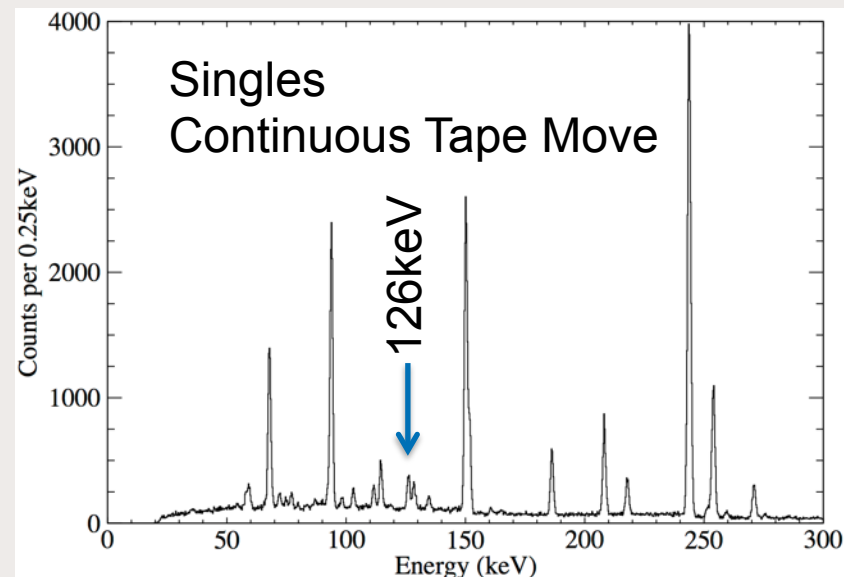
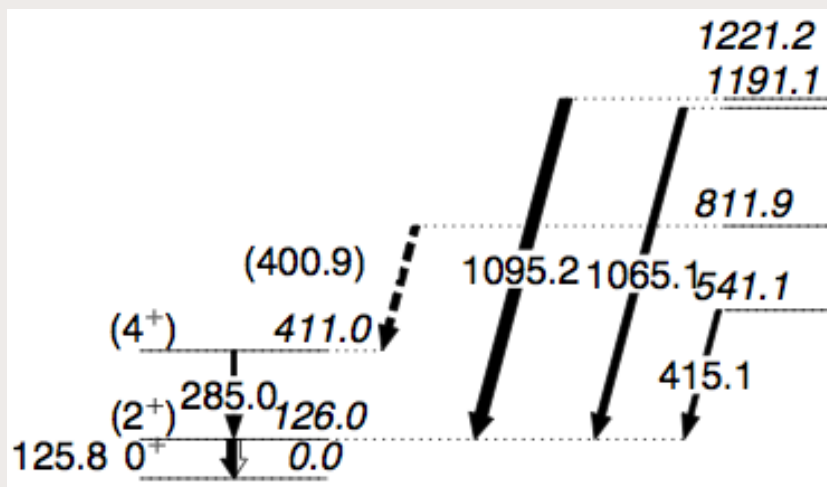
Z.M. Wang *et al.*, to be published

^{102}Sr populated in beta-decay

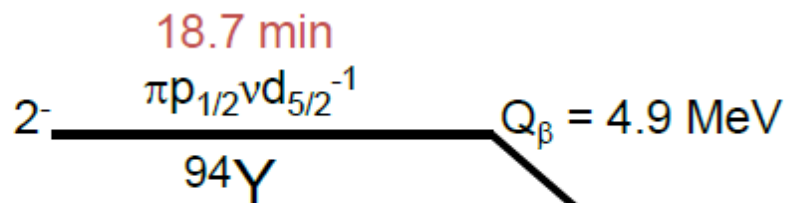
Previously only 126keV known

Lhersonneau *et al.*, Z. Phys. A 351, 357 (1995).

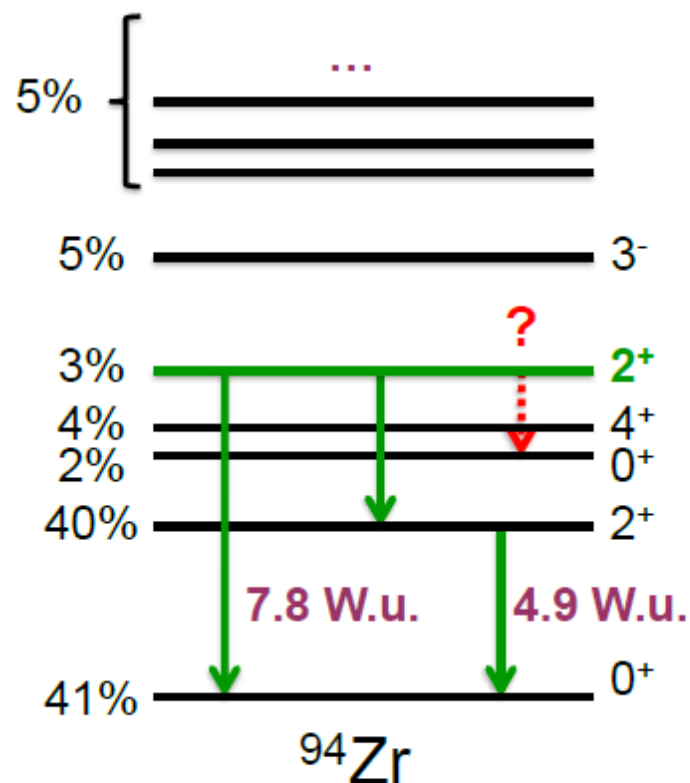
$$E(4+)/E(2+) = 3.26$$



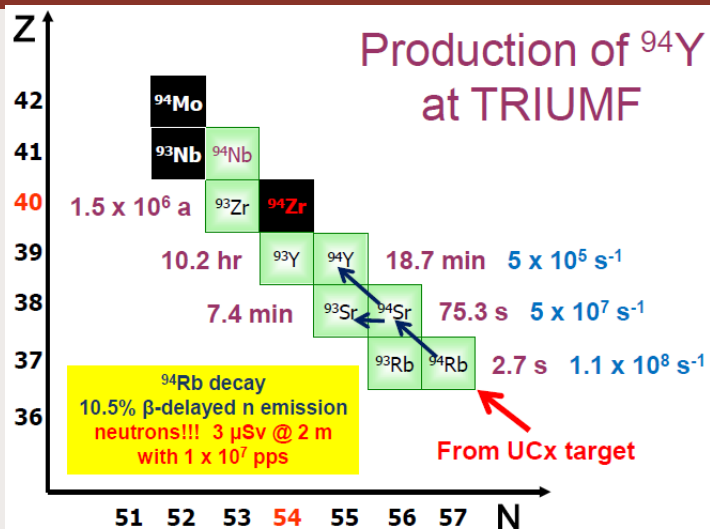
β -decay of ^{94}Y : the anomalous structure of ^{94}Zr : Yates et al Aug 2011



- Recent studies of ^{94}Zr reveal an interesting and unique result—*i.e.*, $B(E2; 2_2^+ \rightarrow 0_1^+) > B(E2; 2_1^+ \rightarrow 0_1^+)$.
- An unexpectedly large number of collective excitations are observed.
- These levels can be classified into sets of states according to their E2 decays to the 2_1^+ and 2_2^+ states.
- Additional properties—*e.g.*, branching ratios, internal conversion coefficients, and multipole mixing ratios—can be measured with the 8π and the auxiliary detection systems.

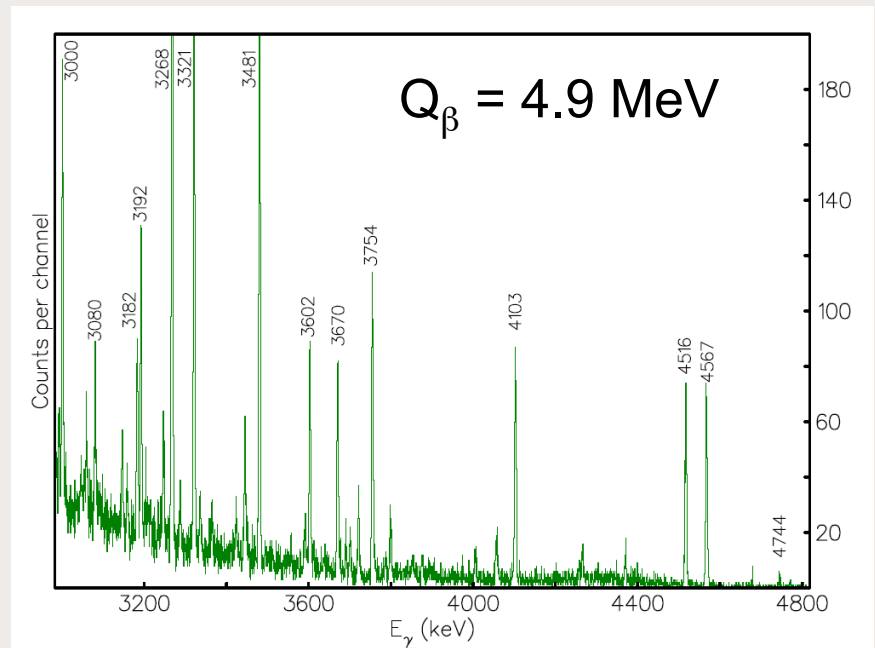
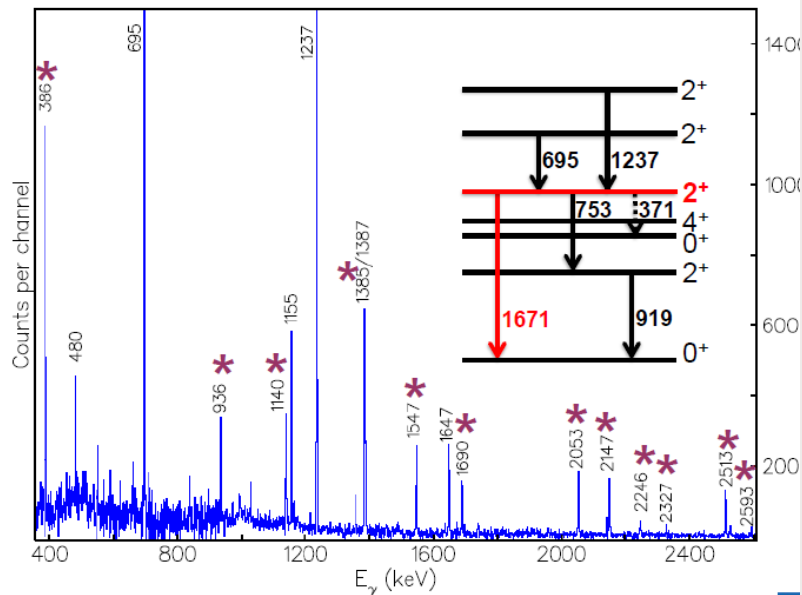


the anomalous structure of ^{94}Zr

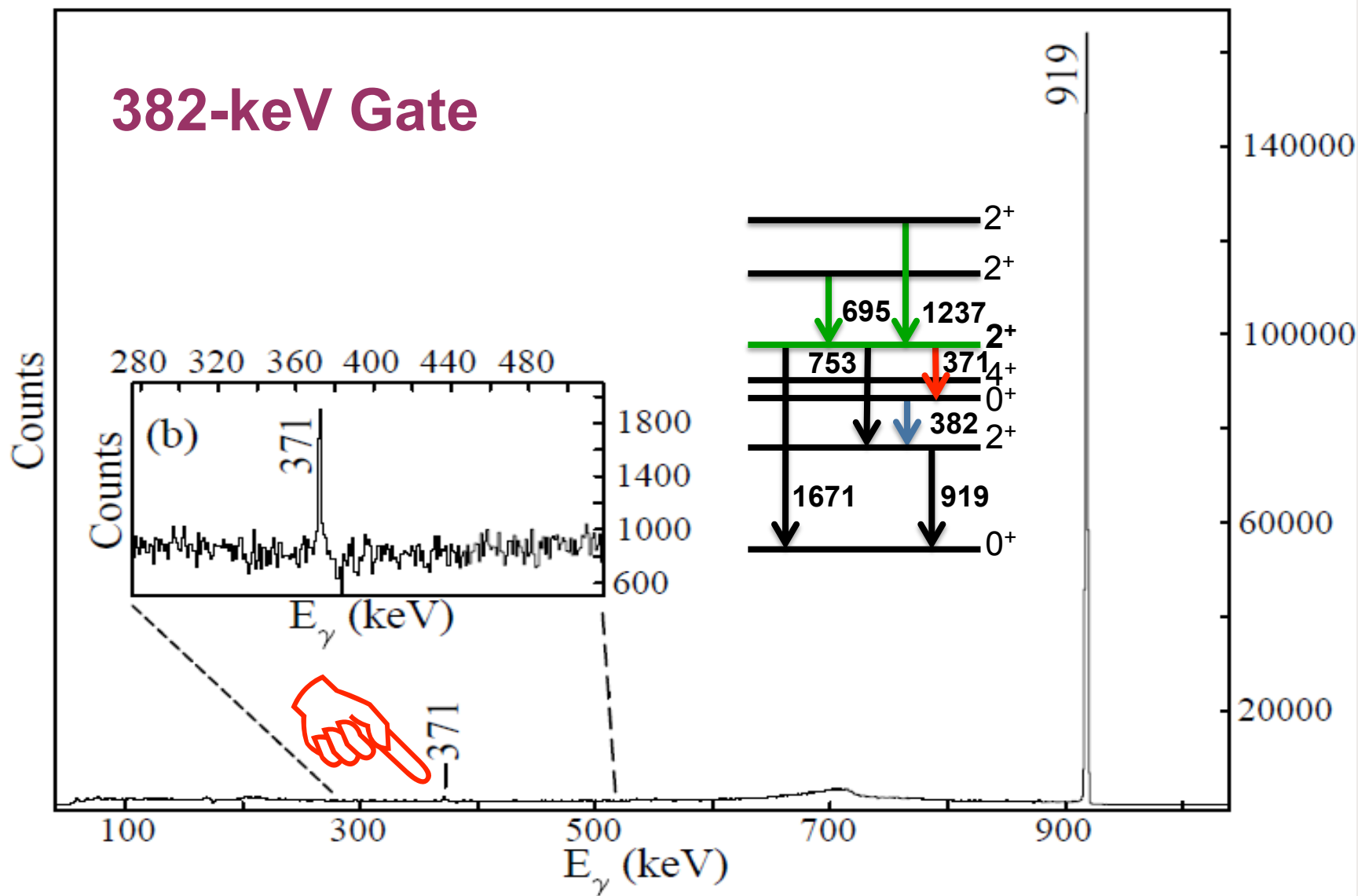


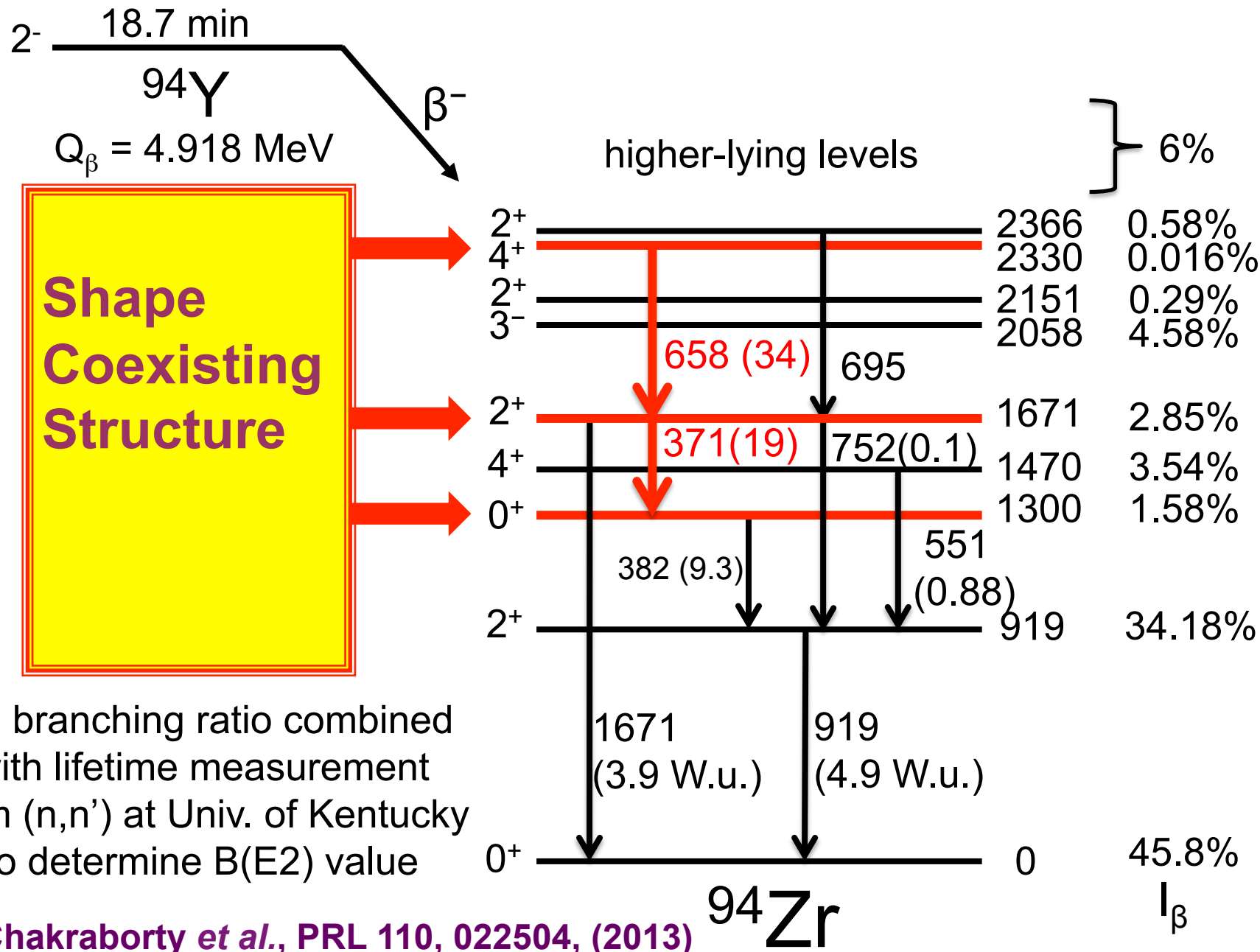
- high- statistics γ - γ data set enables search for weak transitions
- gamma rays from high lying states near Q_β were observed
- large number of new transitions populating the second 2+ level

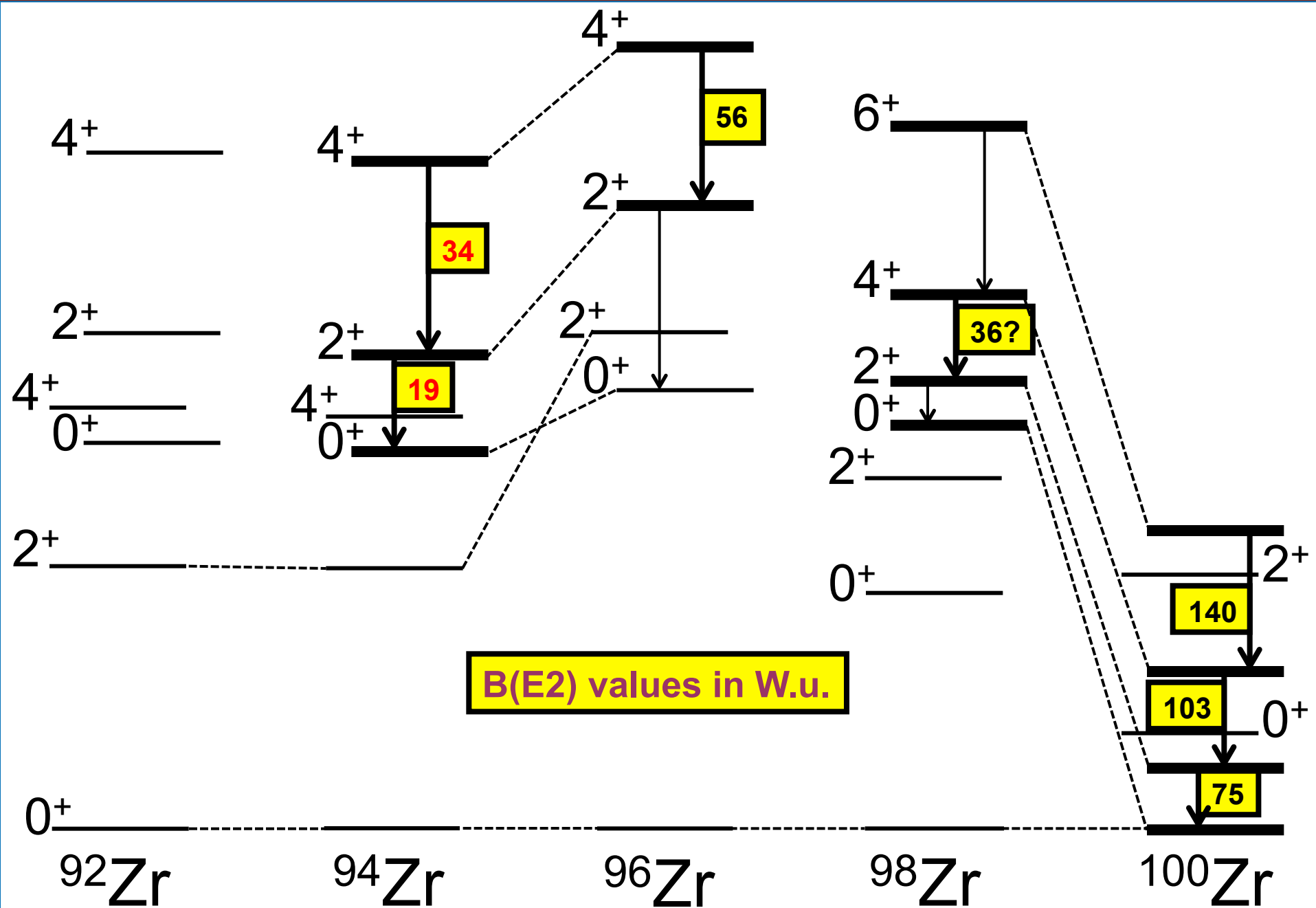
1671-keV Gate from $^{94}\text{Y} \rightarrow ^{94}\text{Zr} \beta^-$ Decay



the anomalous structure of ^{94}Zr







Search for high- K isomers

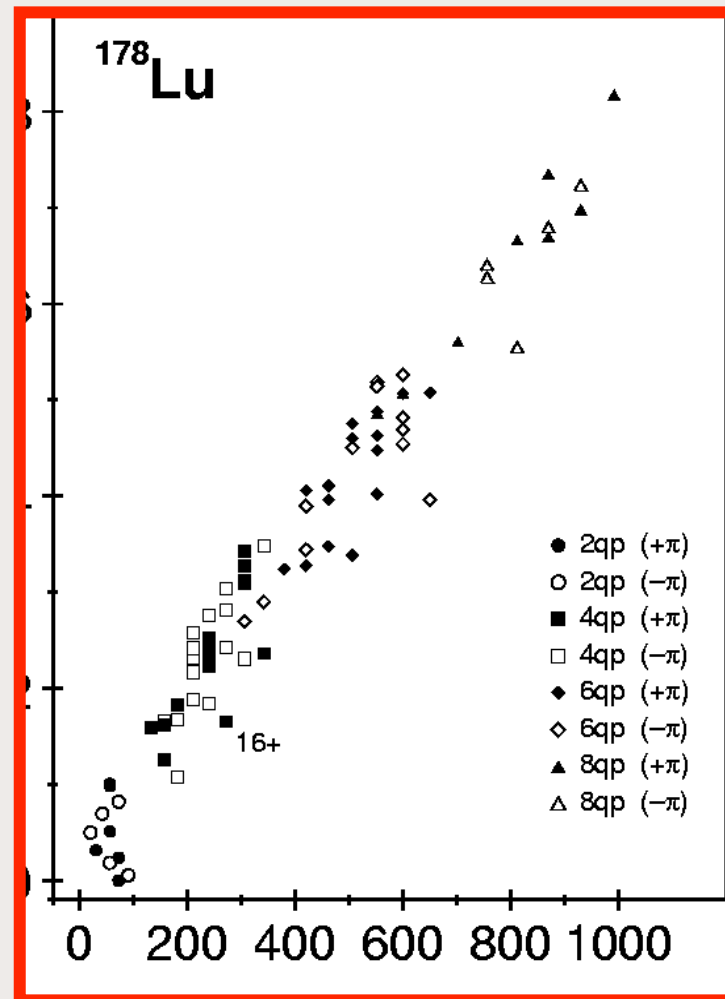
Ta175 10.5 h 7/2+ EC	Ta176 8.09 h (1)- EC	Ta177 56.56 h 7/2+ EC	Ta178 9.31 m 1+ EC	Ta179 1.82 y 7/2+ EC	Ta180 8.152 h 1+ EC, β^- 0.012	Ta181 7/2+ 99.988	Ta182 114.43 d 3- β^-	Ta183 5.1 d 7/2+ β^-
Hf174 2.0E15 y 0+ α 0.162	Hf175 70 d 5/2- EC	Hf176 0+ 5.206	Hf177 7/2- 18.606	Hf178 0+ 27.297	Hf179 9/2+ 13.620	Hf180 0+ 35.100	Hf181 42.39 d 1/2- β^-	Hf182 9E6 y 0+ β^-
Lu173 1.37 y 7/2+ EC	Lu174 3.31 y (1)- EC	Lu175 7/2+ 97.41	Lu176 3.78E10 y 7- β^- 2.50	Lu177 6.734 d 7/2+ β^-	Lu178 28.4 m 1(+) β^-	Lu179 4.59 h 7/2(+) β^-	Lu180 5.7 m (3)+ β^-	Lu181 3.5 m (7/2+) β^-
Yb172 0+ 21.9	Yb173 5/2- 16.12	Yb174 0+ 31.8	Yb175 4.185 d 7/2- β^-	Yb176 0+ 12.7	Yb177 1.911 h (9/2+) β^-	Yb178 74 m 0+ β^-	Yb179 8.0 m (1/2-) β^-	Yb180 2.4 m 0+ β^-
Tm171 1.92 y 1/2+ β^-	Tm172 63.6 h 2- β^-	Tm173 8.24 h (1/2+) β^-	Tm174 5.4 m (4)- β^-	Tm175 15.2 m 1/2+ β^-	Tm176 1.9 m (4+) β^-	Tm177 85 s (1/2+) β^-	Tm178 β^-	Tm179 β^-
Er170 0+ 14.9	Er171 7.516 h 5/2- β^-	Er172 49.3 h 0+ β^-	Er173 1.4 m (7/2-) β^-	Er174 3.3 m 0+ β^-	Er175 1.2 m (9/2+) β^-	Er176 0+ β^-	Er177 β^-	
Ho169 4.7 m 7/2- β^-	Ho170 2.76 m (6+) β^-	Ho171 53 s (7/2-) β^-	Ho172 25 s β^-	Ho173 β^-	Ho174 β^-	Ho175 β^-		
Dy168 8.7 m 0+ β^-	Dy169 39 s (5/2-) β^-	Dy170 0+ β^-	Dy171 β^-	Dy172 0+ β^-	Dy173 β^-			

$N=104$

$Z=66$

110

500 MeV protons on Ta ISOL target
with surface ion source



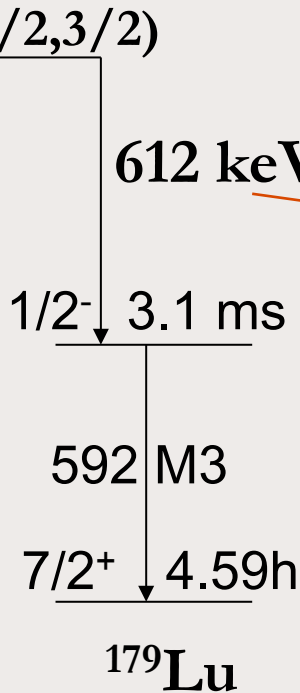
Suggested isomers in both ^{178}Lu
and ^{179}Lu (high K , low E_x)

Possible $T_{1/2}$'s of ms to 500s

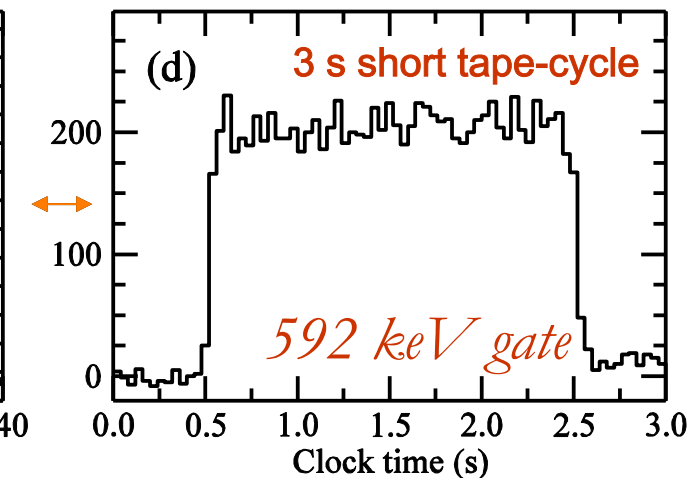
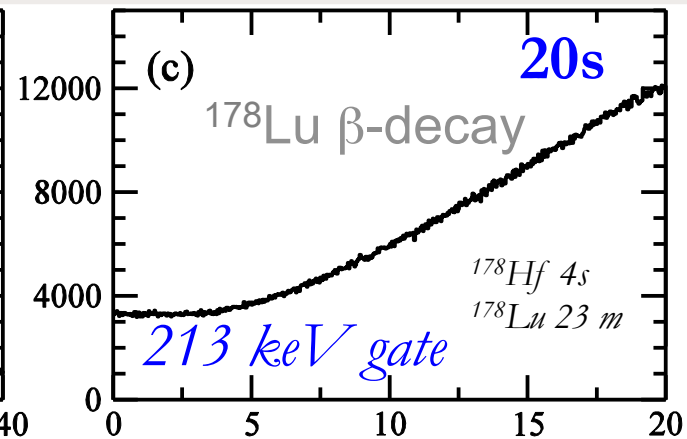
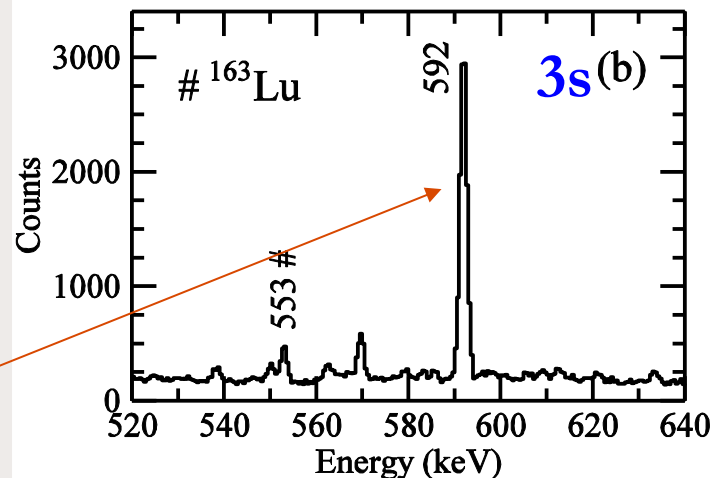
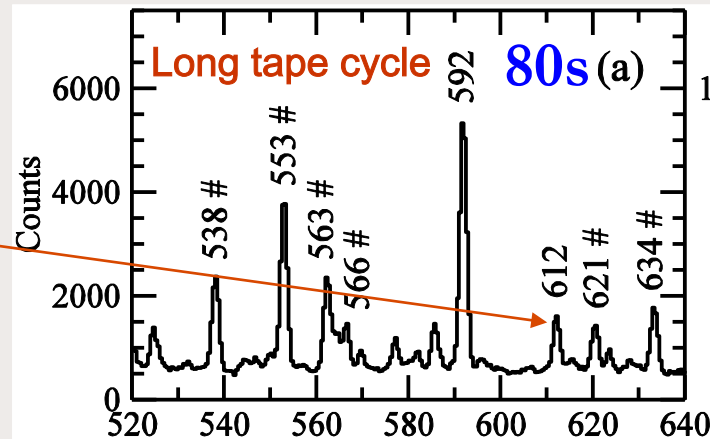
3.1 ms ^{179}Lu isomer beam

Surprise: Fast diffusion of Lu from the target, a new record for ISAC

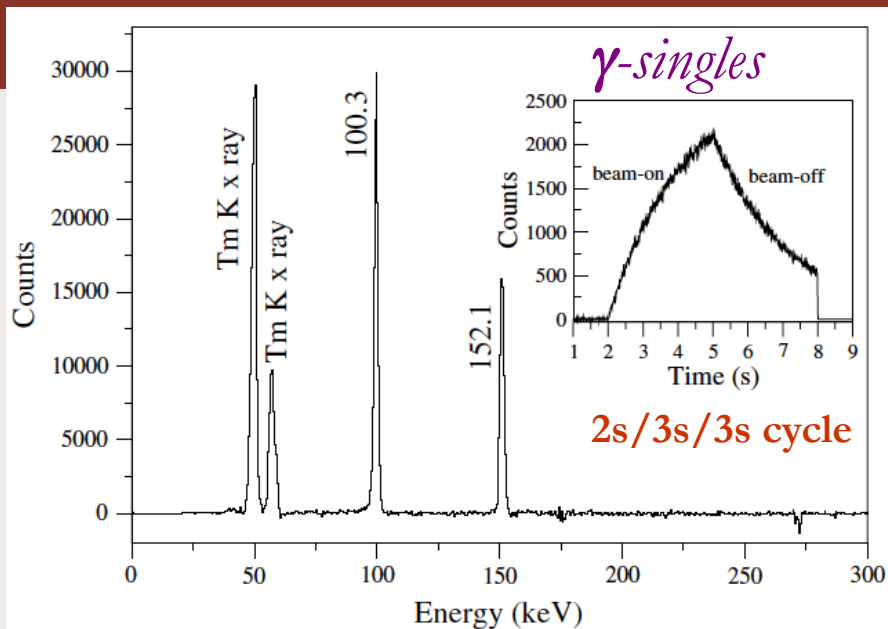
$^{179}\text{Yb} \beta^-$ (8.0 m)



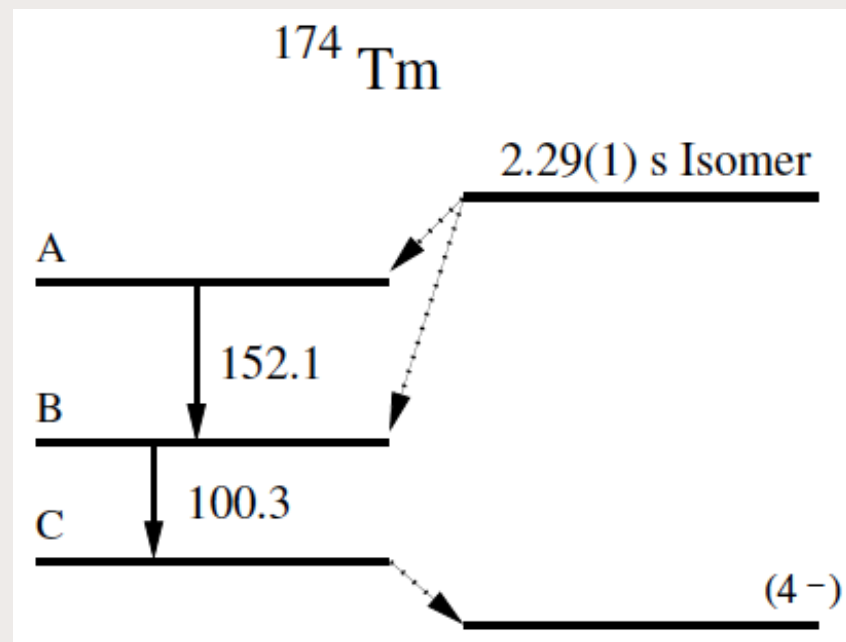
Activity vs Clock consistent with its population directly from the ion-source



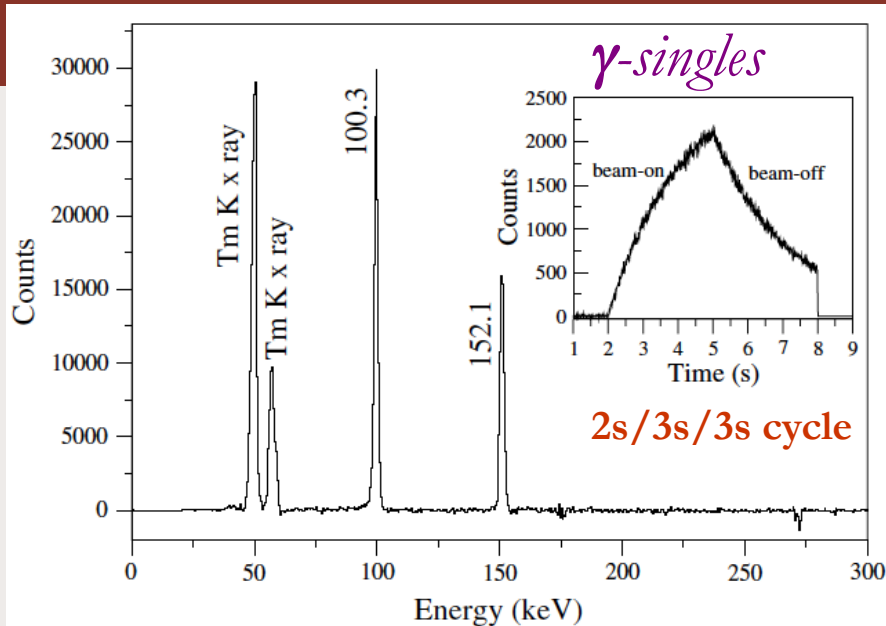
Previously unidentified Isomer in ^{174}Tm



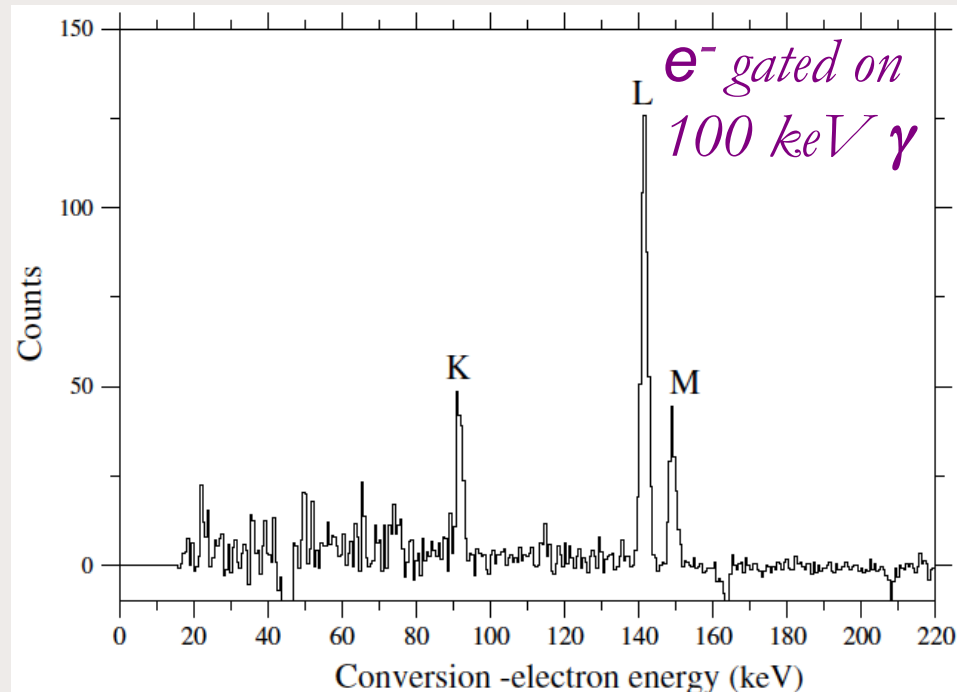
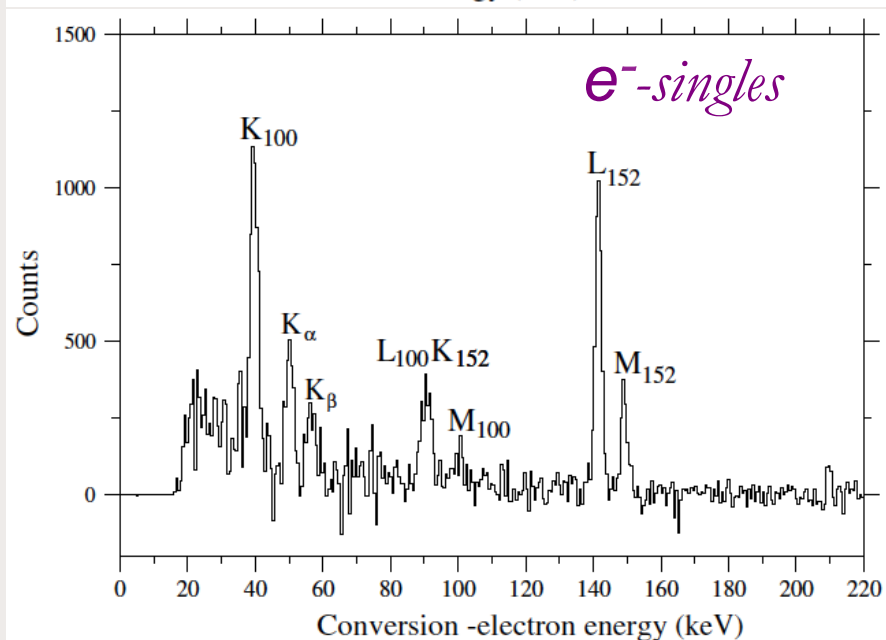
$A=174$ beam mainly Lu (142 d/3yr)
and some Tm GS (5.4 m).



Previously unidentified Isomer in ^{174}Tm



$A=174$ beam mainly Lu (142 d/3yr)
and some Tm GS (5.4 m).

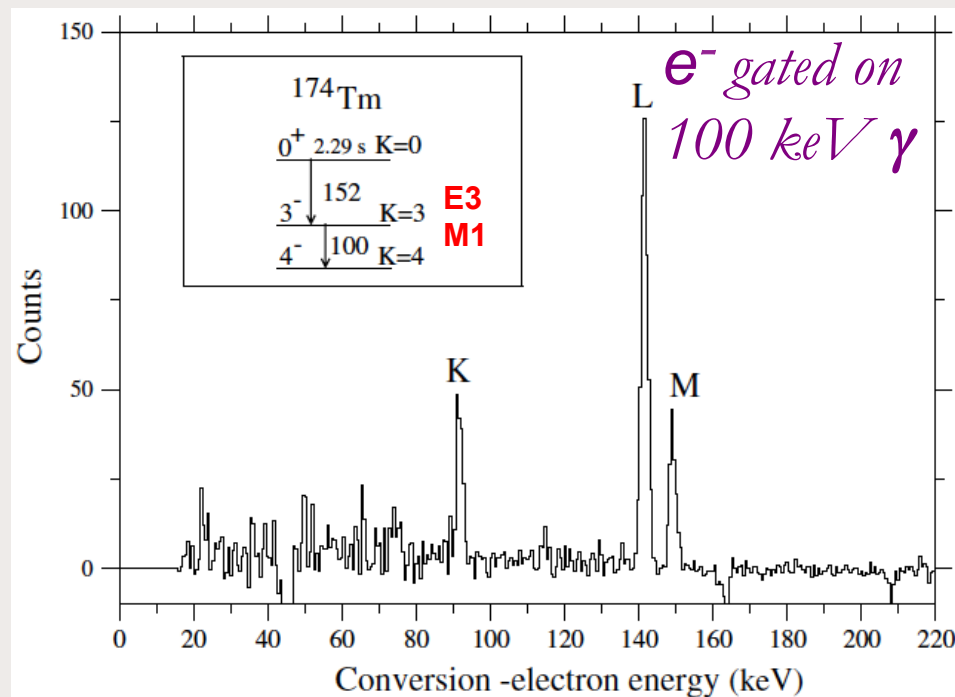
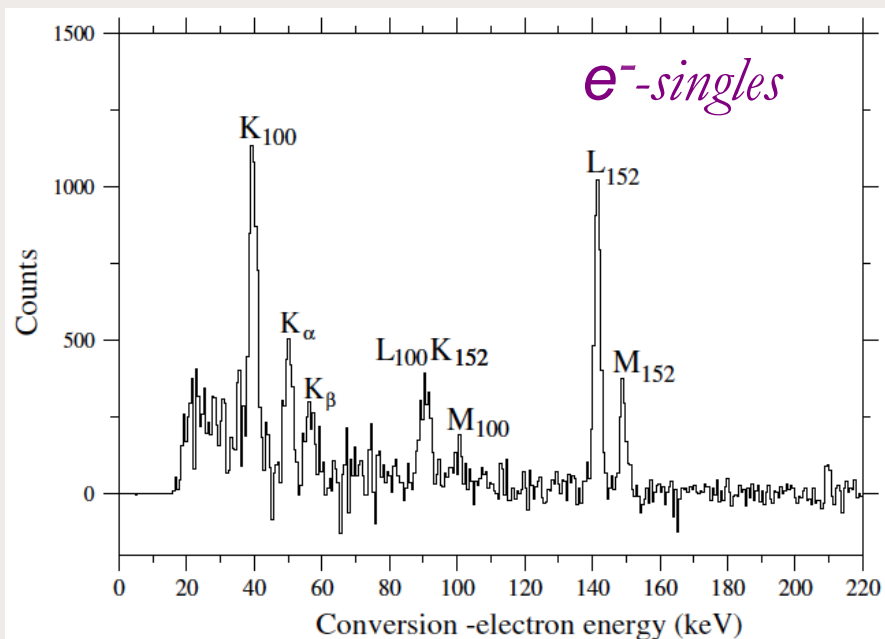


R.S. Chakrawarthy et al., Phys.Rev. C 73, 024306 (2006)
R.S. Chakrawarthy et al., Eur.Phys.J. A 25, Sup. 1, 125 (2005)

Previously unidentified Isomer in ^{174}Tm

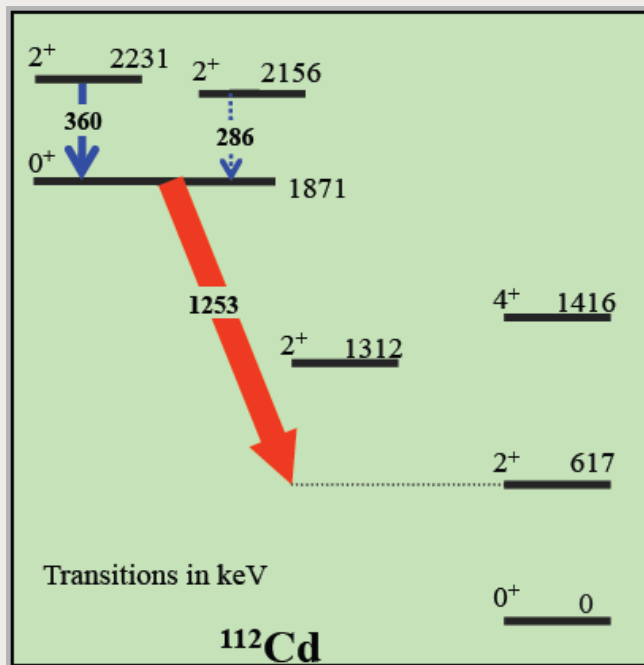
E_γ (keV)	Expt. ICC	Theo. ICC
152.1	$\alpha_K 1.13 \pm 0.06$	$\alpha_K (E3) 1.18$
	$\alpha_L 3.31 \pm 0.48$	$\alpha_L (E3) 4.10$
	$\alpha_M 1.10 \pm 0.12$	$\alpha_M (E3) 0.99$
100.3	$\alpha_K 3.10 \pm 0.01$	$\alpha_K (M1) 2.66$
	$\alpha_L 0.45 \pm 0.10$	$\alpha_L (M1) 0.40$
	$\alpha_M 0.14 \pm 0.03$	$\alpha_M (M1) 0.09$

$A=174$ beam mainly Lu (142 d/3yr)
and some Tm GS (5.4 m).



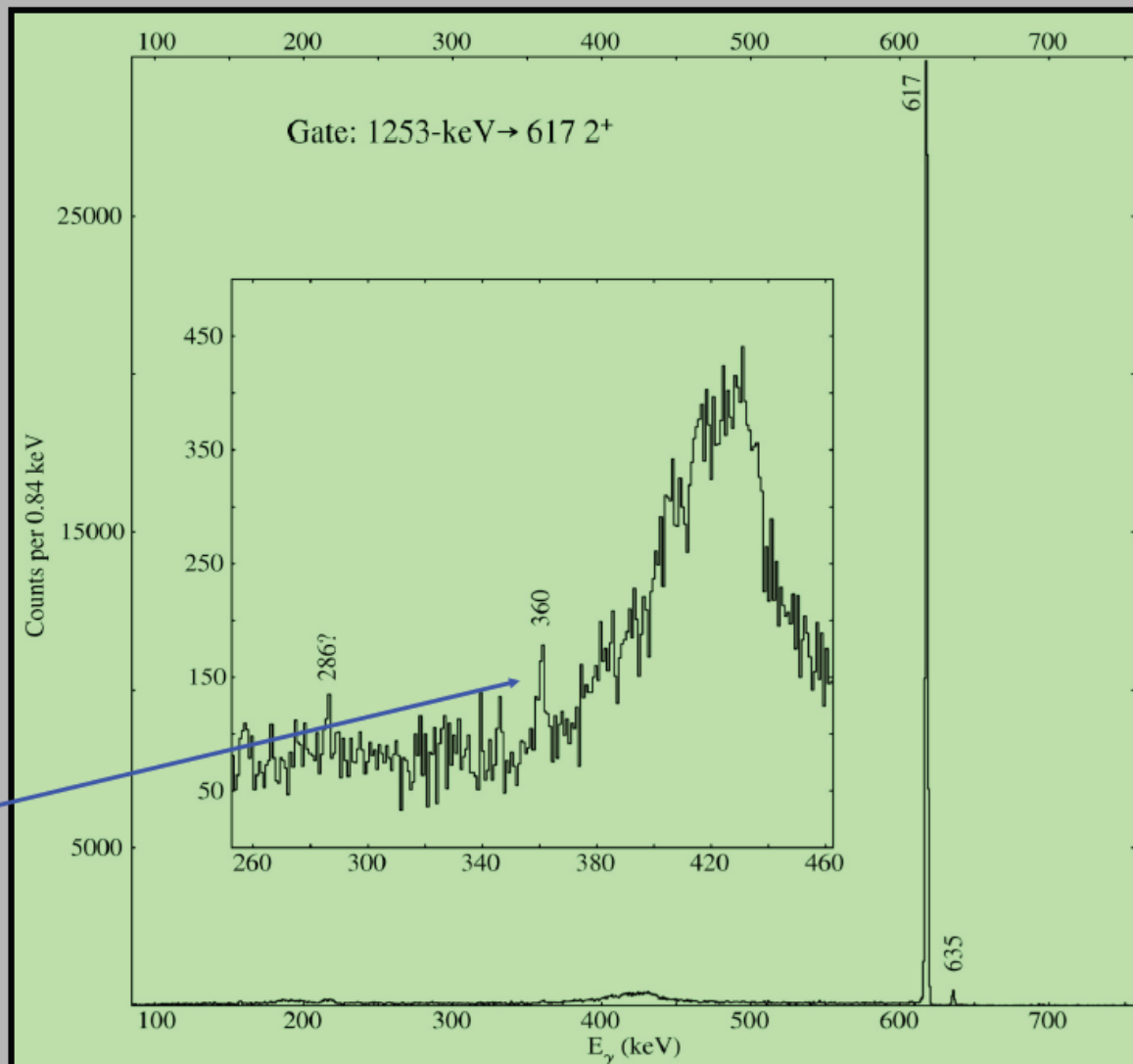
R.S. Chakrawarthy et al., Phys.Rev. C 73, 024306 (2006)
R.S. Chakrawarthy et al., Eur.Phys.J. A 25, Sup. 1, 125 (2005)

Nuclear Structure from High-Statistics Beta-Decay



5×10^{-4} γ branch from
2231-keV level

$I_\gamma(360) \approx 10^{-6}$ of
 $I_\gamma(617\text{-keV}, 2^+ \rightarrow 0^+)$

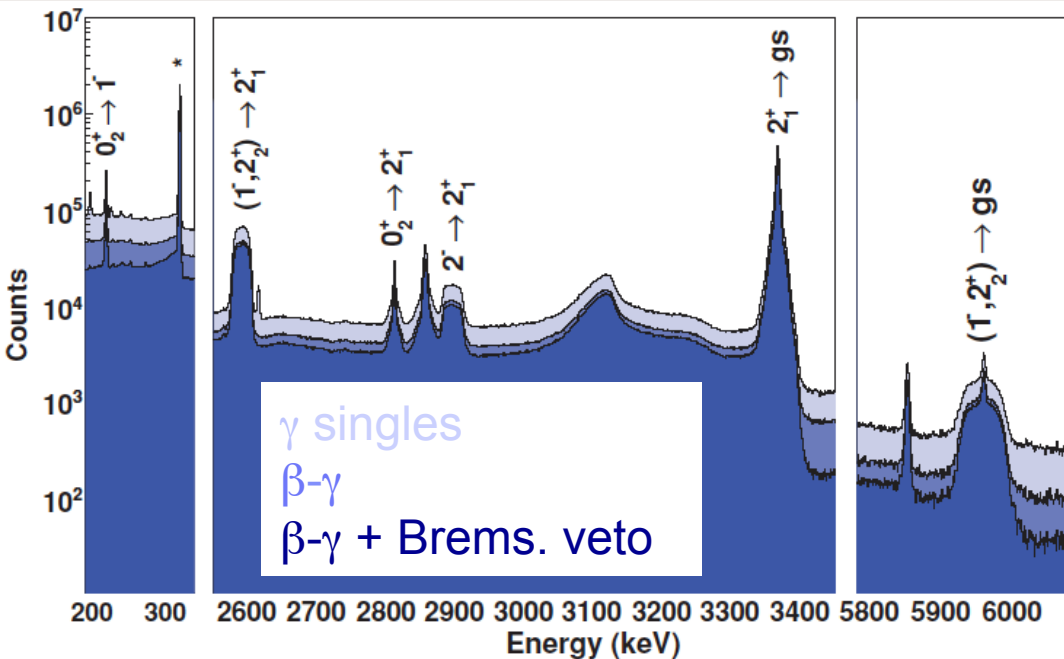


P.E. Garrett, Univ. of Guelph
C. Andreoiu, SFU

								Ba122	Ba123	Ba124	Ba125	Ba126	Ba127	Ba128	Ba129	Ba130
								195 m 0+	2.7 m 5/2+	11.0 m 0+	3.5 m 1/2(+)	100 m 0+	12.7 m 1/2+	2.43 d 0+	2.23 h 1/2+	0+
								EC	EC	EC	EC	EC	EC	EC	EC	0.106
								Cs121	Cs122	Cs123	Cs124	Cs125	Cs126	Cs127	Cs128	Cs129
								155 s 3/2(+)	21.0 s 1+	5.94 m 1/2+	30.8 s 1+	45 m (1/2+)	1.64 m 1+	6.25 h 1/2+	3.66 m 1+	32.06 h 1/2+
								EC	EC	EC	EC	EC	EC	EC	EC	EC
p	α ECp...	ECp	ECp,EC α ...	EC	ECp,EC α ...	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC
Xe112	Xe113	Xe114	Xe115	Xe116	Xe117	Xe118	Xe119	Xe120	Xe121	Xe122	Xe123	Xe124	Xe125	Xe126	Xe127	Xe128
2.7 s 0+	2.74 s	10.0 s 0+	18 s (5/2+)	59 s 0+	61 s 5/2(+)	3.8 m 0+	5.8 m (5/2+)	40 m 0+	40.1 m 5/2(+)	20.1 h 0+	2.08 h (1/2)+	1.6E+14 y 0+	16.9 h (1/2)+	0+	36.4 d 1/2+	0+
EC, α	α ECp...	EC	ECp,EC α ...	EC	ECp	EC	EC	EC	EC	EC	EC	EC	EC	0.09	EC	191
II11	II12	II13	II14	II15	II16	II17	II18	II19	II20	II21	II22	II23	II24	II25	II26	II27
2.5 s (5/2+)	3.42 s	6.6 s	2.1 s 1+	13 m (5/2+)	2.91 s 1+	2.22 m (5/2+)	13.7 m 2-	19.1 m 5/2+	81.0 m 2-	2.12 h 5/2+	3.63 m 1+	13.27 h 5/2+	4.1760 d 2-	59.408 d 5/2+	13.11 d 2-	5/2+
EC, α	EC, α	α EC α ...	ECp	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC, β -	100
Te110	Te111	Te112	Te113	Te114	Te115	Te116	Te117	Te118	Te119	Te120	Te121	Te122	Te123	Te124	Te125	Te126
18.6 s 0+	19.3 s	2.0 m 0+	1.7 m (7/2+)	15.2 m 0+	5.8 m 7/2+	2.49 h 0+	62 m 1/2+	6.00 d 0+	16.03 h 1/2+	0+	16.78 d 1/2+	0+	1E+13 y 1/2+	0+	1/2+	0+
EC, α	ECp	EC	EC	EC	EC	EC	EC	EC	EC	0.096	EC	2.603	0.908	4.816	7.139	18.95
Sb109	Sb110	Sb111	Sb112	Sb113	Sb114	Sb115	Sb116	Sb117	Sb118	Sb119	Sb120	Sb121	Sb122	Sb123	Sb124	Sb125
17.0 s (5/2+)	23.0 s 3+	75 s (5/2+)	51.4 s 3+	6.67 m 5/2+	3.49 m 3+	32.1 m 5/2+	15.8 m 3+	2.80 h 5/2+	3.6 m 1+	38.19 h 5/2+	15.89 m 1+	5/2+	2.7238 d 2-	7/2+	60.20 d 3-	2.7582 y 7/2+
EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	57.36	EC, β -	42.64	β -	β -
Sn108	Sn109	Sn110	Sn111	Sn112	Sn113	Sn114	Sn115	Sn116	Sn117	Sn118	Sn119	Sn120	Sn121	Sn122	Sn123	Sn124
10.30 m 0+	18.0 m 5/2(+)	4.11 h 0+	35.3 m 7/2+	0+	115.09 d 1/2+	0+	1/2+	0+	1/2+	0+	1/2+	0+	27.06 h 3/2+	0+	129.2 d 11/2-	0+
EC	EC	EC	EC	0.97	EC	0.65	0.34	14.53	7.68	24.23	8.59	32.59	β -	4.63	β -	5.79
In107	In108	In109	In110	In111	In112	In113	In114	In115	In116	In117	In118	In119	In120	In121	In122	In123
32.4 m 9/2+	58.0 m 7+	4.2 h 9/2+	4.9 h 7+	2.8047 d 9/2+	14.97 m 1+	9/2+	71.9 s 1+	4.41E+14 y 9/2+	14.10 s 1+	43.2 m 9/2+	5.0 s 1+	2.4 m 9/2+	3.08 s 1+	23.1 s 9/2+	1.5 s 1+	5.98 s 9/2+
EC	EC	EC	EC	EC	EC, β -	43	EC, β -	β -	EC, β -	β -	β -	β -	β -	β -	β -	β -
Cd106	Cd107	Cd108	Cd109	Cd110	Cd111	Cd112	Cd113	Cd114	Cd115	Cd116	Cd117	Cd118	Cd119	Cd120	Cd121	Cd122
0+	6.50 h 5/2+	0+	462.6 d 5/2+	0+	1/2+	0+	1/2+	0+	53.46 h 1/2+	0+	2					

Study of the β -decay of ^{11}Li :

A Neutron Spectroscopy Experiment Without Neutron Detectors

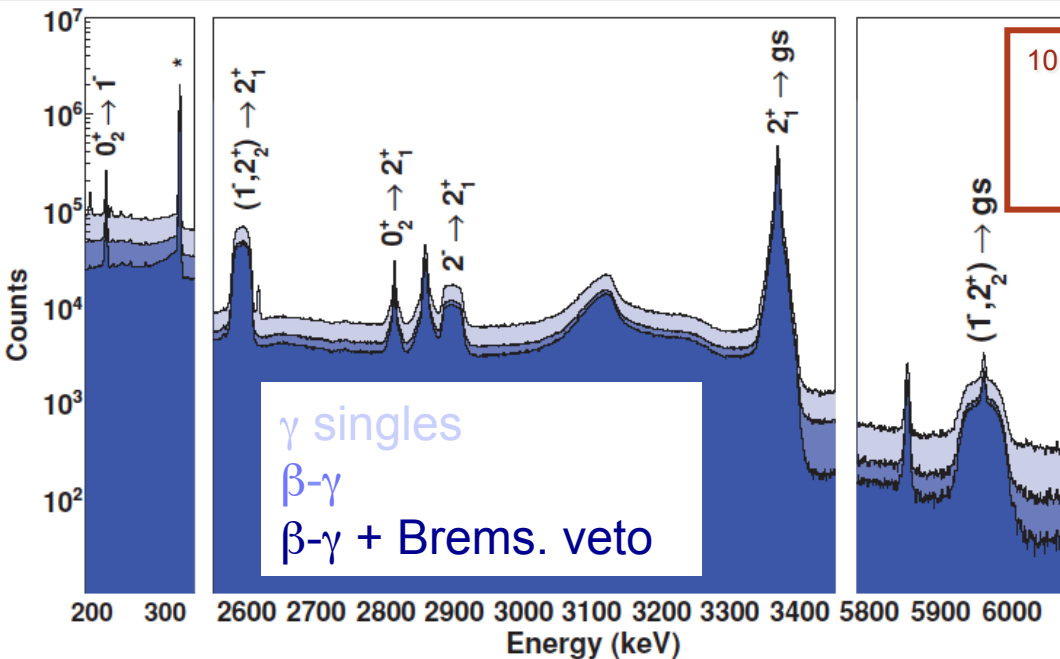


C.M. Mattoon et al., Phys.Rev. C 80, 034318 (2009)

F.Sarazin et al., Phys. Rev. C70 (2004) 31302(R)

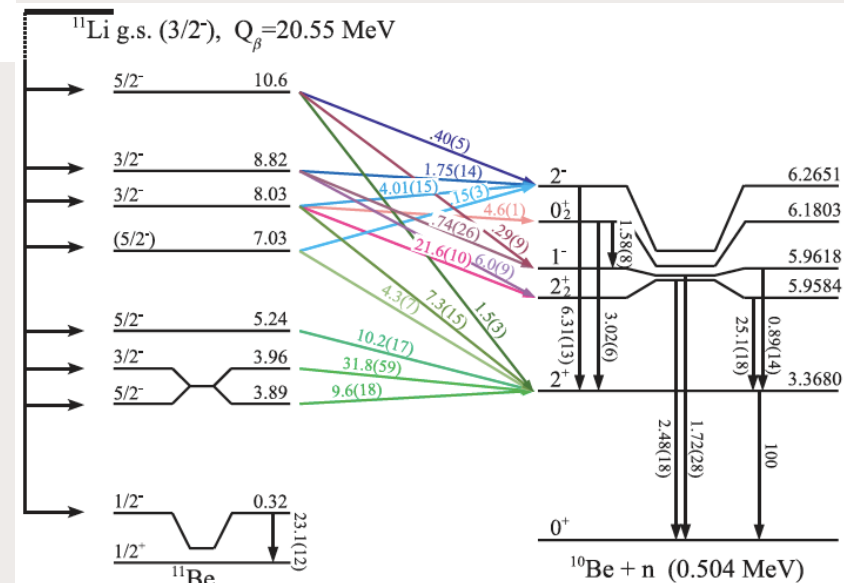
Study of the β -decay of ^{11}Li :

A Neutron Spectroscopy Experiment Without Neutron Detectors

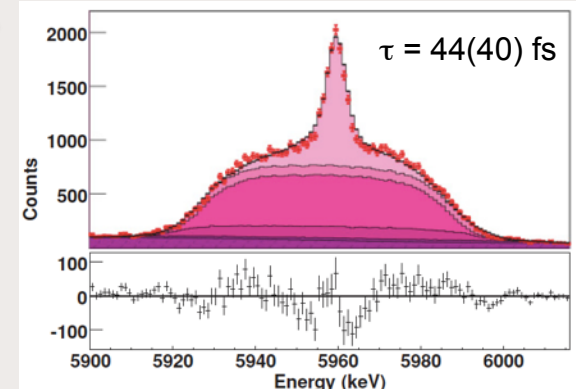
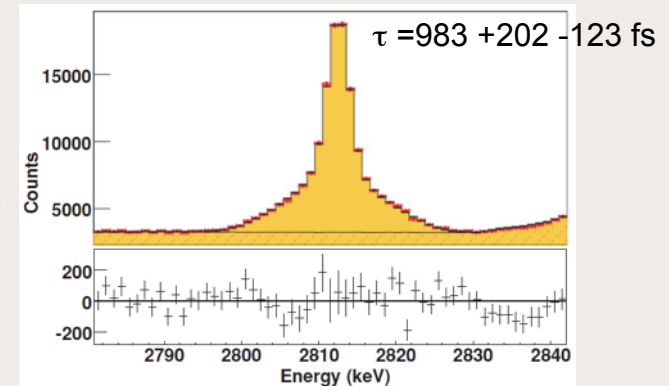
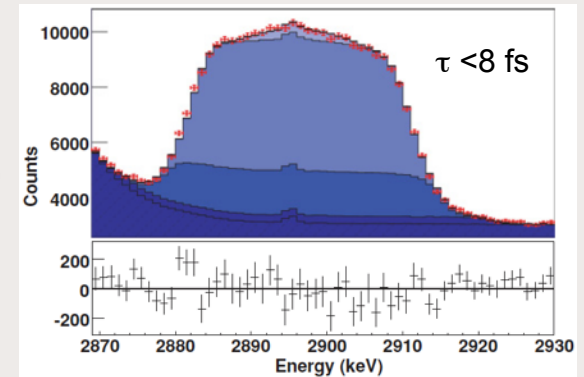
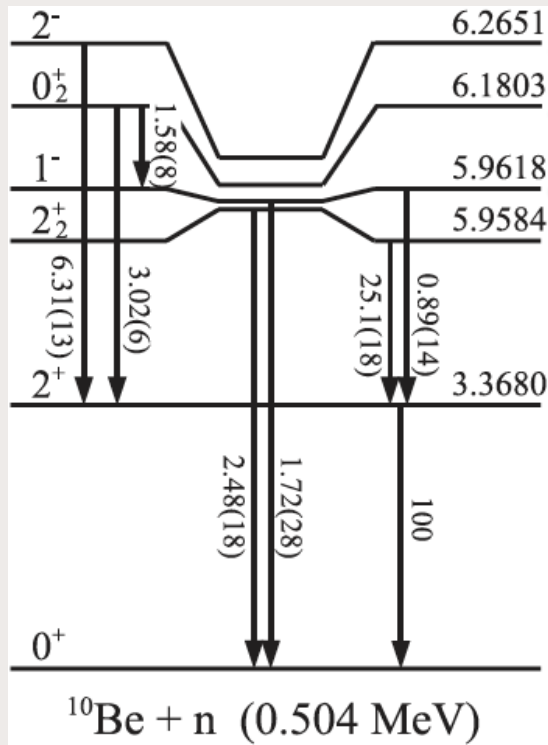


^{10}Be γ -peaks are Doppler Broadened
 Lineshape = $f(\text{Lifetime, Neutron Energy})$
 Max. Width = $f(\text{Neutron Energy})$

-Lineshape analysis by Monte Carlo simulation
 - Resolution on the neutron energies ($\sim 50\text{keV}$)
 comparable to Direct Time-Of-Flight Neutron
 Spectroscopy Experiments



Monte-Carlo Lineshape Analysis



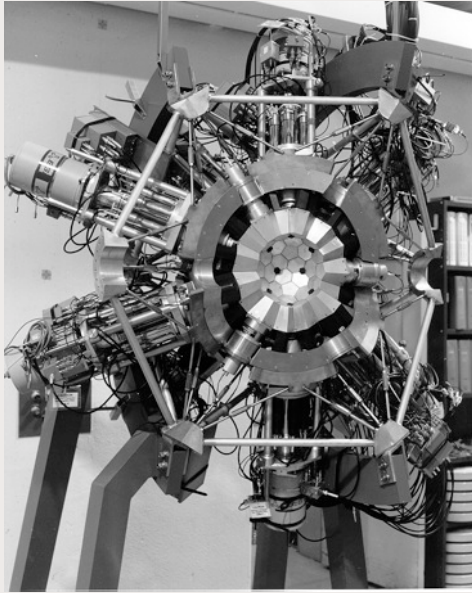
J^π	This work	Fynbo [4]	Sarazin [5]	Tilley [37]
2_2^+	$61.4^{+8.0}_{-6.2}$	>35	60(10)	<55
1^-	44(40)	230(90)	^a	—
0_2^+	983^{+202}_{-123}	760(170)	870(175)	760^{+280}_{-210}
2^-	<8	160(40)	85(12)	—

^aLess than a few hundred fs.

C.M. Mattoon et al., Phys.Rev. C 80, 034318 (2009)

F.Sarazin et al., Phys. Rev. C70 (2004) 31302(R)

The Future... 8pi Spectrometer at Simon Fraser University



K. Starosta and C. Andreoiu

Full 8pi spectrometer using
20 HPGe and 4π BGO filter

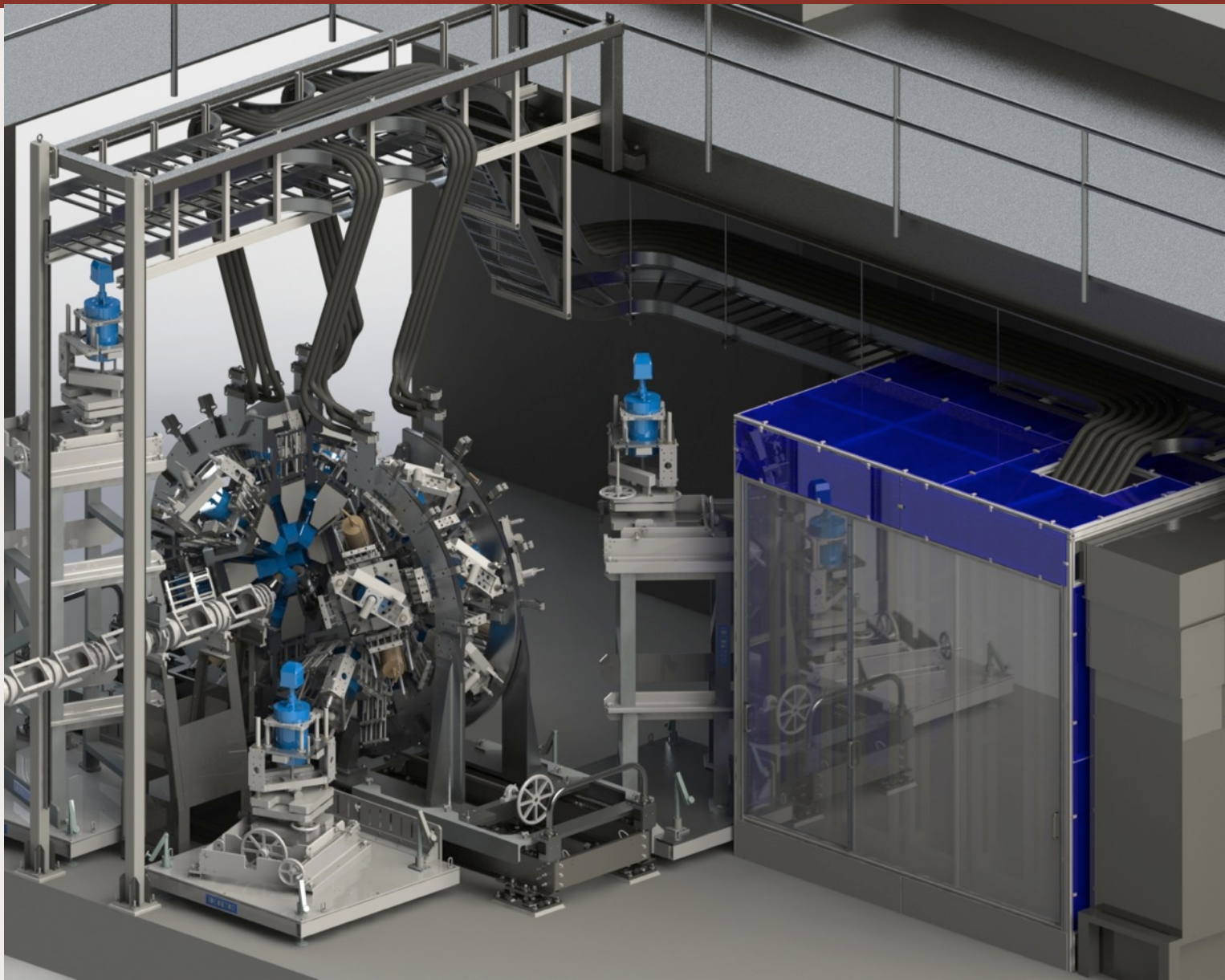
Digital DAQ system

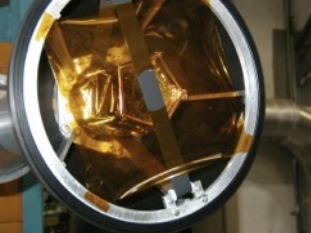


Neutron-induced fission
studies using neutron
generator located one floor
below in shielded vault

Study properties of neutron-
rich nuclei

The Future... GRIFFIN Spectrometer at ISAC



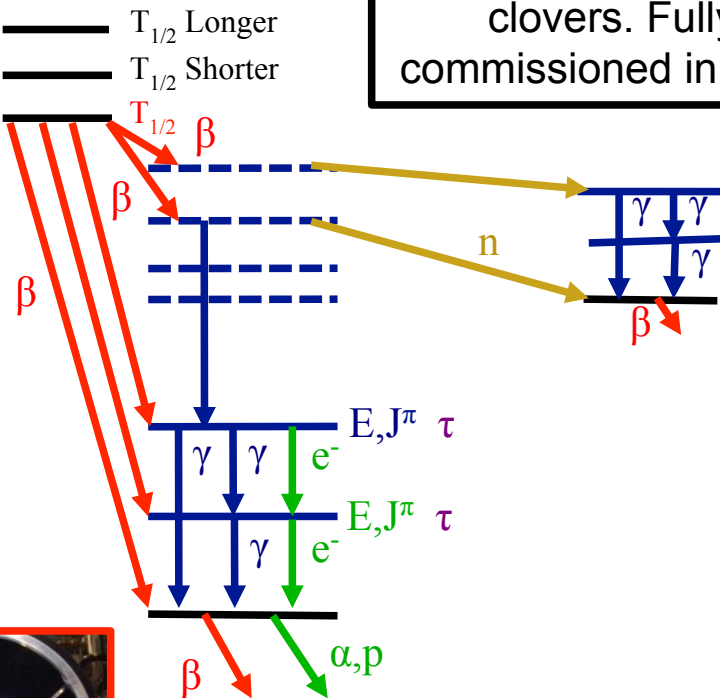


New GRIFFIN Facility at TRIUMF

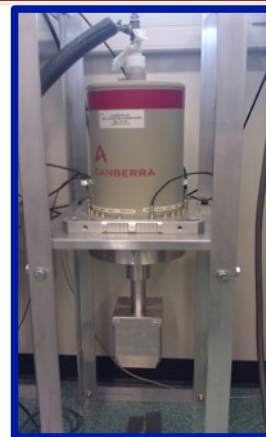
Sensitive Decay Spectroscopy

Fast, in-vacuum tape system
Enhances decay of interest

ISOBAR $T_{1/2}$ Longer
 J^π ISOMER $T_{1/2}$ Shorter
 J^π GS

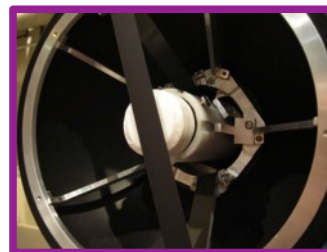


Initial operation in
fall 2014 with 12
clovers. Fully
commissioned in 2015

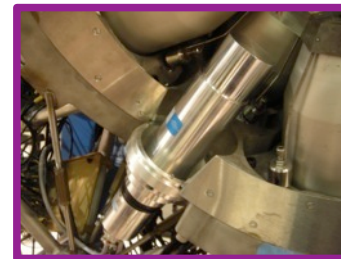


HPGe: 16 Clovers
*Detect gamma rays and
determines branching ratios,
multipolarities and mixing ratios*

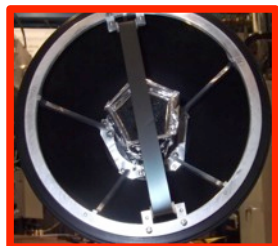
LaBr₃: 8 LaBr₃
*Fast-timing of photons to
measure level lifetimes*



Zero-Degree Fast scintillator
Fast-timing signal for betas



PACES: 5 Cooled Si(Li)s
*Detects Internal Conversion
Electrons and alphas/protons*



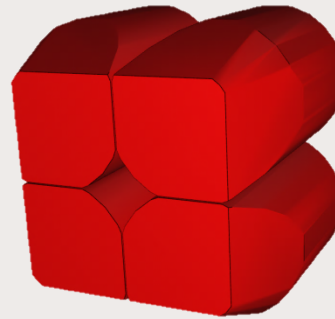
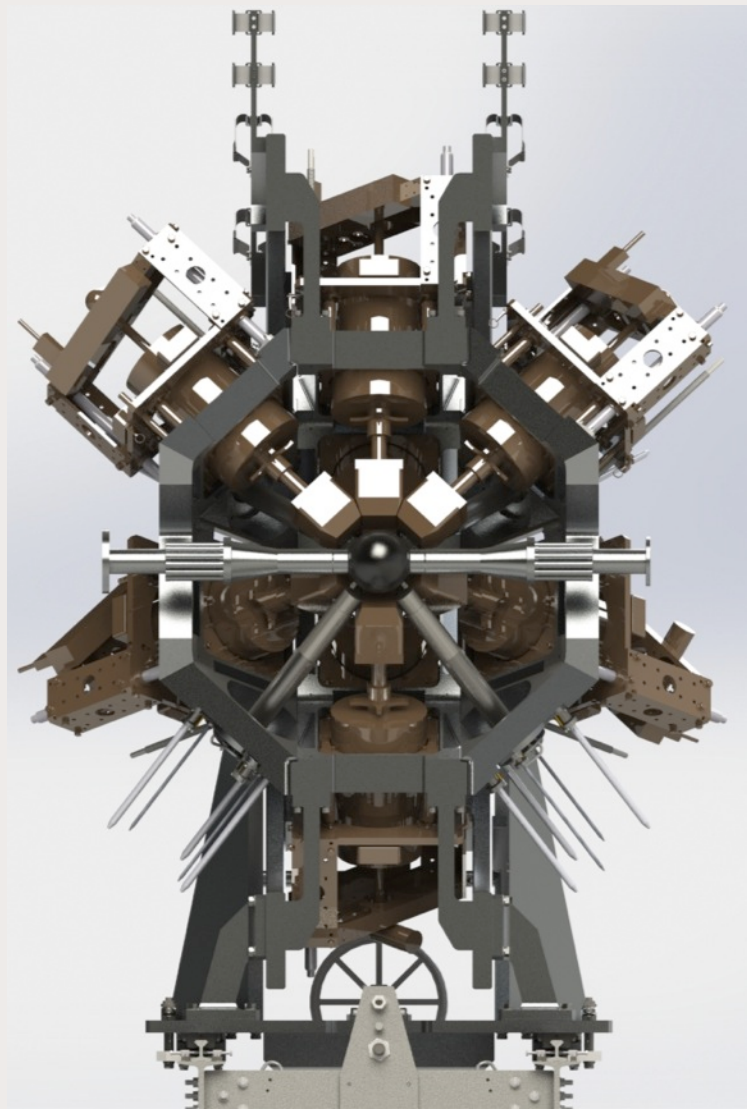
SCEPTAR: 10+10 plastic
scintillators
*Detects beta decays and
determines branching ratios*



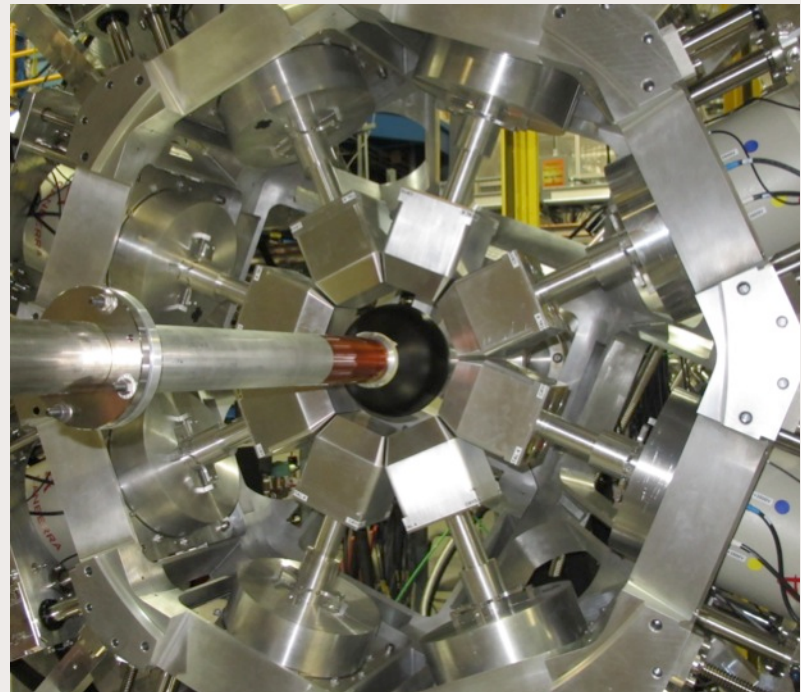
Neutron-Arrays:
DESCANT or VANDLE
*Detects neutrons to
measure beta-delayed
neutron branching ratios*

GRIFFIN HPGe Clover Detectors

An array of 16 large-volume HPGe Clover detectors

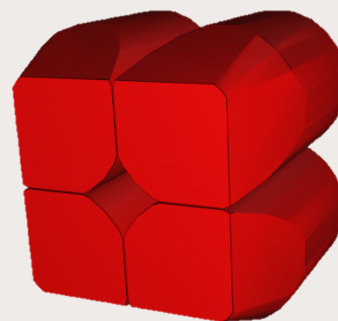


60mm diameter,
tapered crystals.
 ≥ 90 mm length



GRIFFIN HPGe Clover Detectors

An array of 16 HPGe Clover detectors

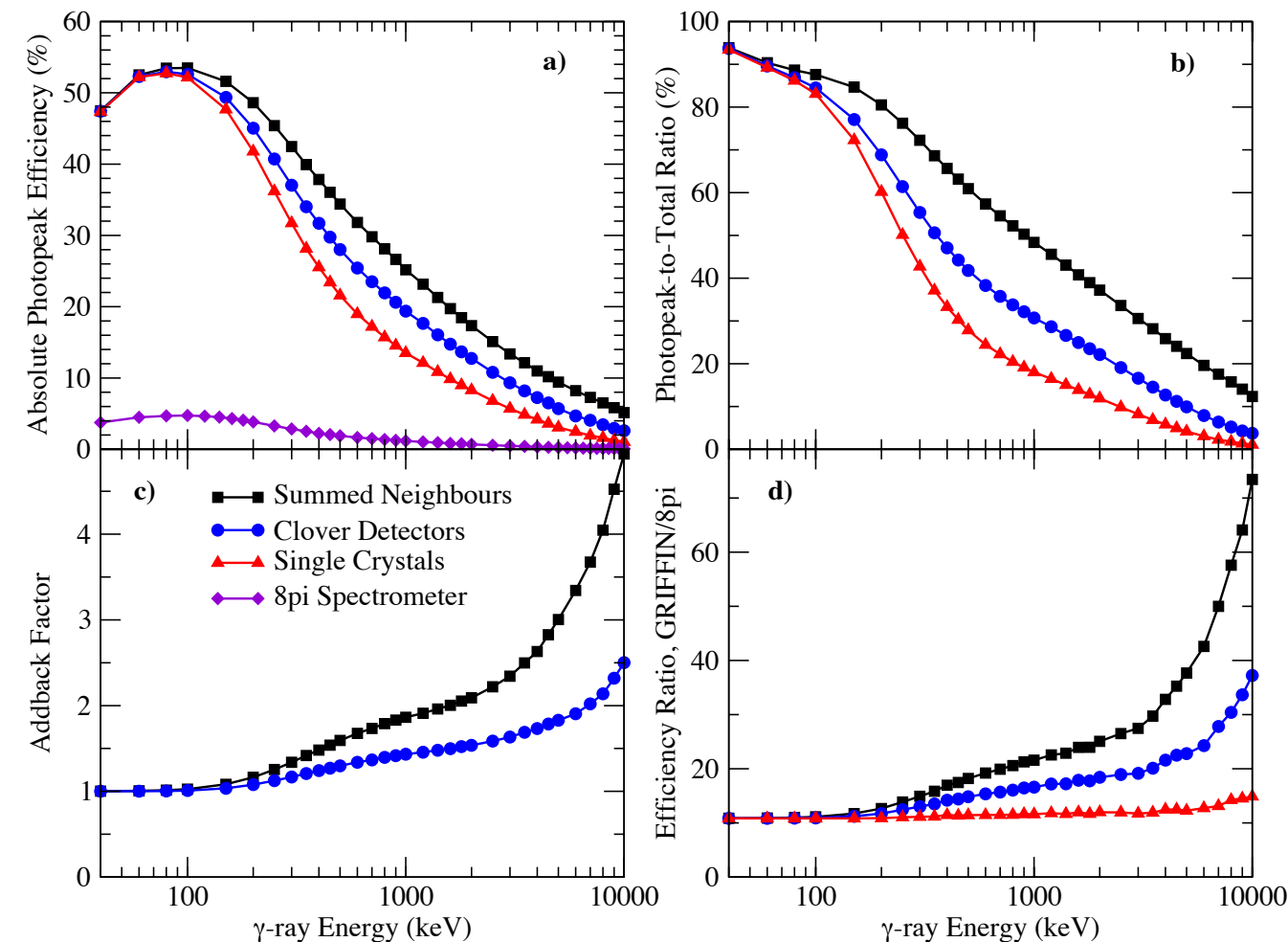


60mm diameter,
tapered crystals.
≥90mm length

Resolution (FWHM):
≤2.2 keV @ 1.3 MeV
≤1.3 keV @ 122 keV

Rel. Eff. @ 1.3 MeV
Crystal ≥38%
Clover ≥215%

Timing ≤6ns



GRIFFIN HPGe Clover Detectors

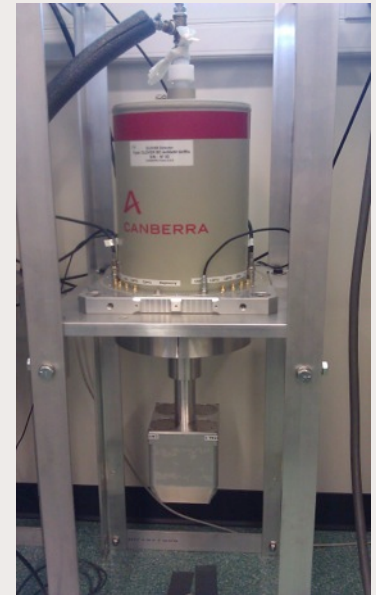
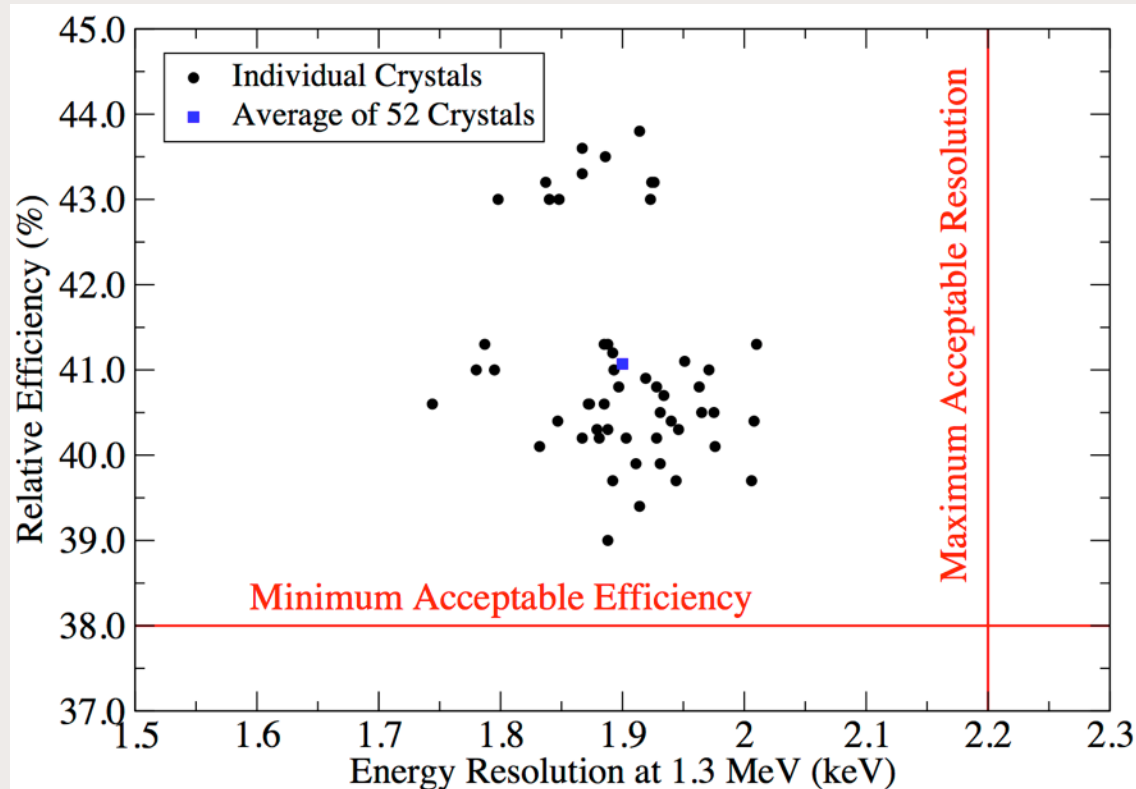
Thirteen of sixteen GRIFFIN clovers fully accepted

Average Performance of first 52 crystals:

Energy resolution@ 121keV = 1.11keV

Energy resolution@ 1.3MeV = 1.90keV

Photo-peak Rel. Eff. @ 1.3MeV = 41.07%



Testing performed at SFU

Dec 2012 4 Accepted

April 2013 8 Accepted

Jan 2014 9 Accepted

May 2014 13 Accepted

April 2015 16 Accepted

May 2015 Complete

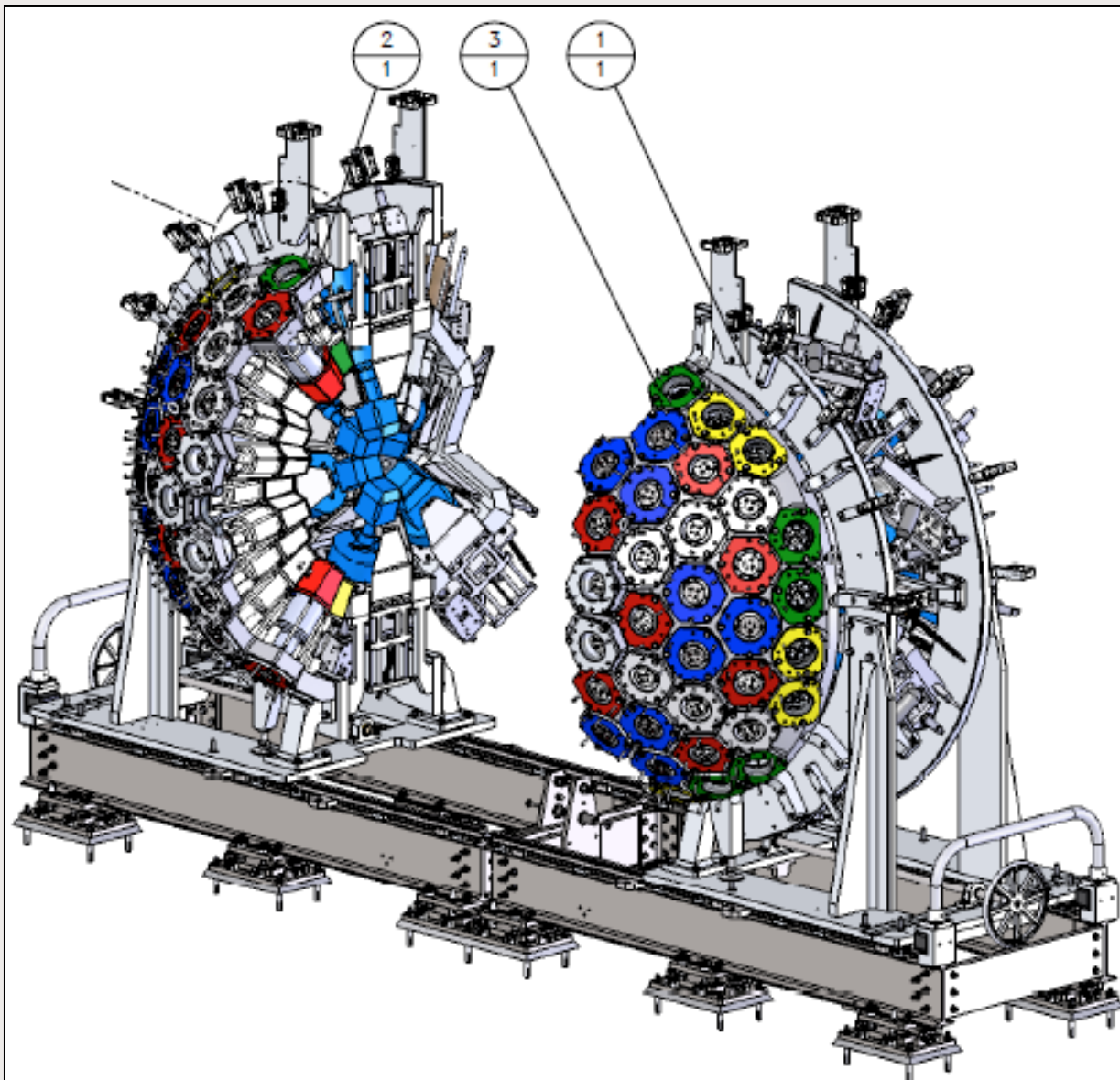
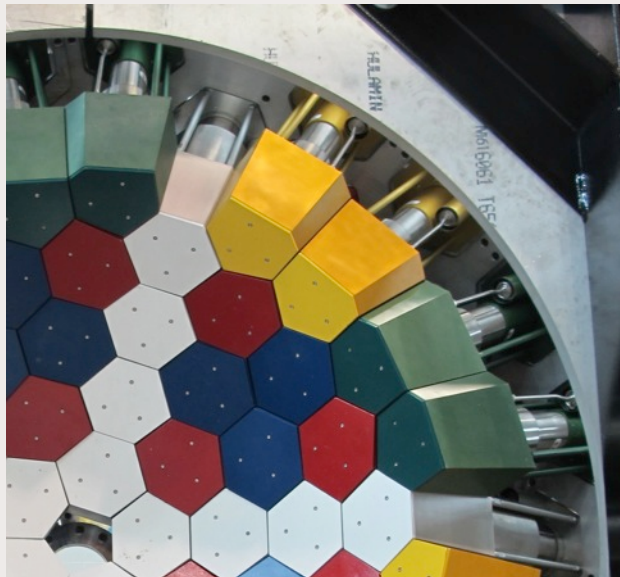
See talk by Vinzenz Bildstein,
Fri 2pm, Session 32

GRIFFIN+DESCANT

70 element array of
deuterated scintillator for
neutron time-of-flight

DESCANT has 27%
neutron efficiency with 12
HPGe Clovers

Uses GRIF-4G digitizers

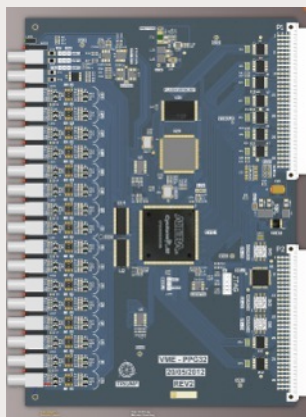


GRIFFIN DAQ System

Custom Digital Electronics Modules designed and built by
Universite de Montreal and TRIUMF

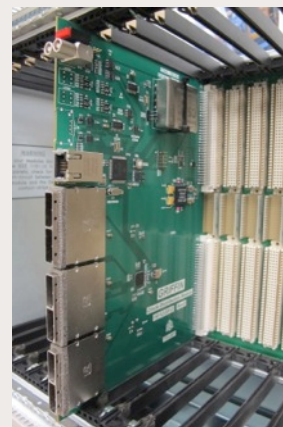
Programmable Logic Pulse Generator

32 Channels
NIM or TTL



Clock Distribution Module

10MHz Atomic
Clock
Low-jitter fan-out
to all modules



GRIF-16 Module

16 chans
100MHz,
14bit



GRIF-4G Module

4 chans
1GHz,
14bit



Master and Collector Module

650MB/s link to
each digitizer
2GB RAM with
peak transfer of
8.5Gb/s.



Custom Digital Electronics Modules designed and built by
Universite de Montreal and TRIUMF

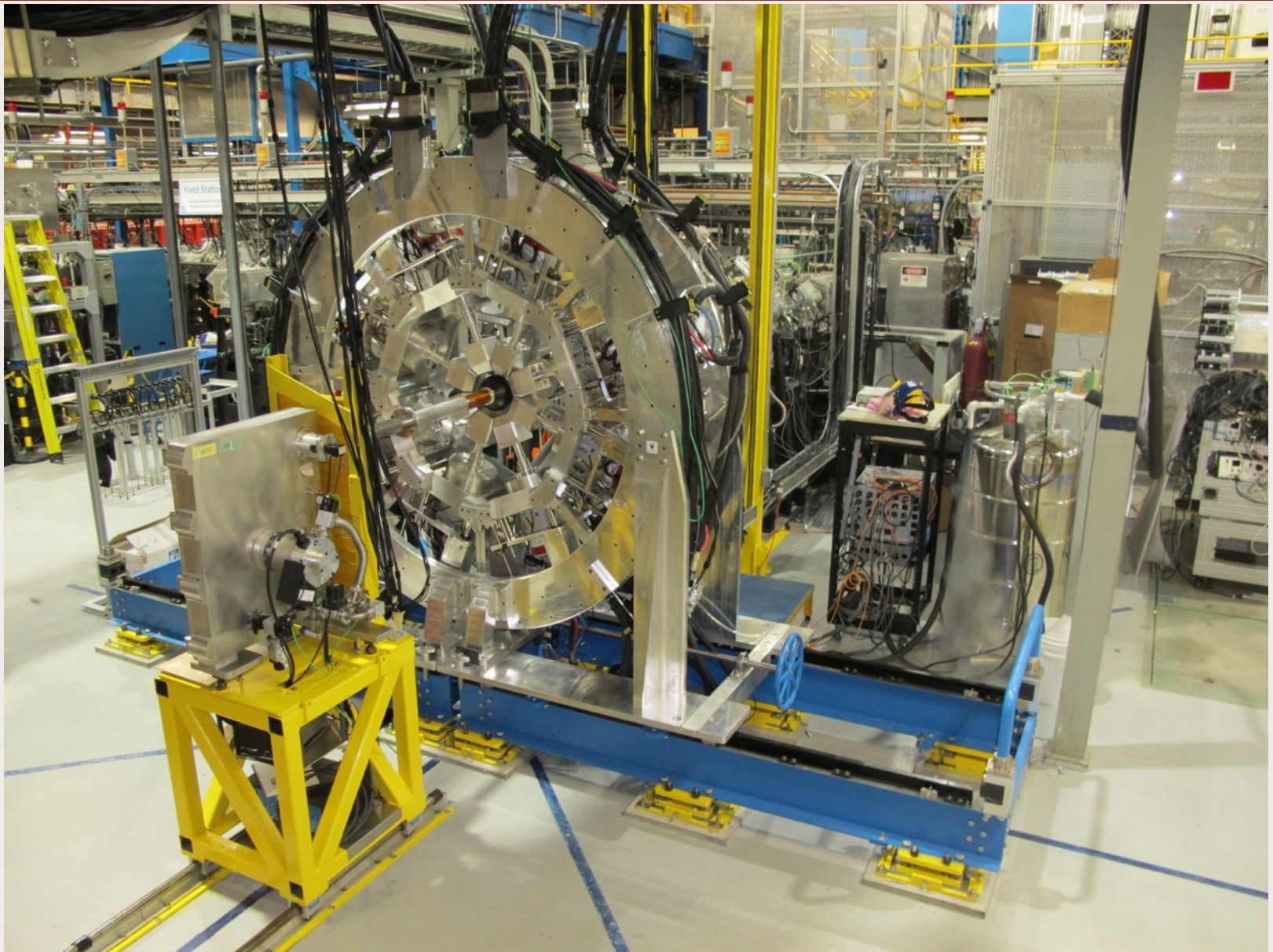
High data through-put:

Each crystal running at 50kHz
300MB/s of filtered data, 1TB per hour
 $\approx 5 \times 10^9$ gamma-gamma coincidences/hour
...to enable ultra-high-statistics studies

High accountability:

Accurate deadtime knowledge
Pile-up handling
Event traceability from threshold crossing to disk
...to enable high-precision half-life/BR measurements

GRIFFIN Installation - July 4th



Acknowledgements

G.C. Ball, R.S. Chakrawarthy, G. Hackman, M.B. Smith, S.J. Williams
(TRIUMF)

V. Bildstein, R. Dunlop, P. Finlay, P.E. Garrett, K.L. Green, G.F. Grinyer,
B. Hyland, A.T. Laffoley, K.G. Leach, C.E. Svensson, S. Triambak
(University of Guelph)

C.M. Mattoon, F. Sarazin (Colorado School of Mines)

J.L. Wood (Georgia Institute of Technology)

A. Piechaczek, E.F. Zganyar (Louisiana State University)

C. Andreoiu, D.S. Cross (SFU)

A. Chakraborty, S.W. Yates (University of Kentucky)

P.M. Walker (University of Surrey)

Plus many other students and post docs

The 8π Spectrometer at TRIUMF-ISAC

32 publications including 4 PRLs
19 on Nuclear Structure
13 on Superalowed beta decay

Superalowed Beta Decay

^{10}C , ^{14}O , ^{18}Ne , ^{19}Ne , ^{26}mAl , ^{38}mK , ^{62}Ga , ^{74}Rb

R. Dunlop et al., PRC 88, 045501 (2013)
G.F. Grinyer et al., PRC 87, 045502 (2013)
A.T. Laffoley et al., PRC 88, 015501 (2013)
P. Finlay et al., PRC 85, 055501 (2012)
S. Triambak et al., PRL 109, 042301 (2012)
P. Finlay et al., PRC 78, 025502 (2008)
K.G. Leach et al., PRL 100, 192504 (2008)
G.F. Grinyer et al., PRC 76, 025503 (2007)
E.F. Zganyar et al., Acta Phys.Pol. B38, 1179 (2007)
B. Hyland et al., PRL 97, 102501 (2006)
B. Hyland et al., AIP Conf.Proc. 819, 105 (2006)
G.F. Grinyer et al., PRC 71, 044309 (2005)
A. Piechaczek et al., PRC 67, 051305 (2003)

High-statistics studies of Cd, Sn, Xe

P.E. Garrett et al., PRC 86, 044304 (2012)
P.E. Garrett et al., Acta Phys.Pol. B42, 799 (2011)
P.E. Garrett et al., AIP Conf.Proc. 1377, 211 (2011)
K.L. Green et al., PRC 80, 032502 (2009)

Half Life of geochronometer, ^{176}Lu
G.F. Grinyer et al., PRC 67, 014302 (2003)

Structure of $^{219-223}\text{Rn}$ towards a RnEDM search

Isomer decay in ^{174}Tm , ^{178}Hf , ^{179}Lu
R.S. Chakrawarthy et al., PRC 73, 024306 (2006)
R.S. Chakrawarthy et al., EPJ. A 25, S1, 125 (2005)
M.B. Smith et al., NPA746, 617c (2004)
M.B. Smith et al., PRC 68, 031302 (2003)

Shape coexistence in neutron-rich Sr, Zr
A. Chakraborty et al., PRL 110, 022504 (2013)

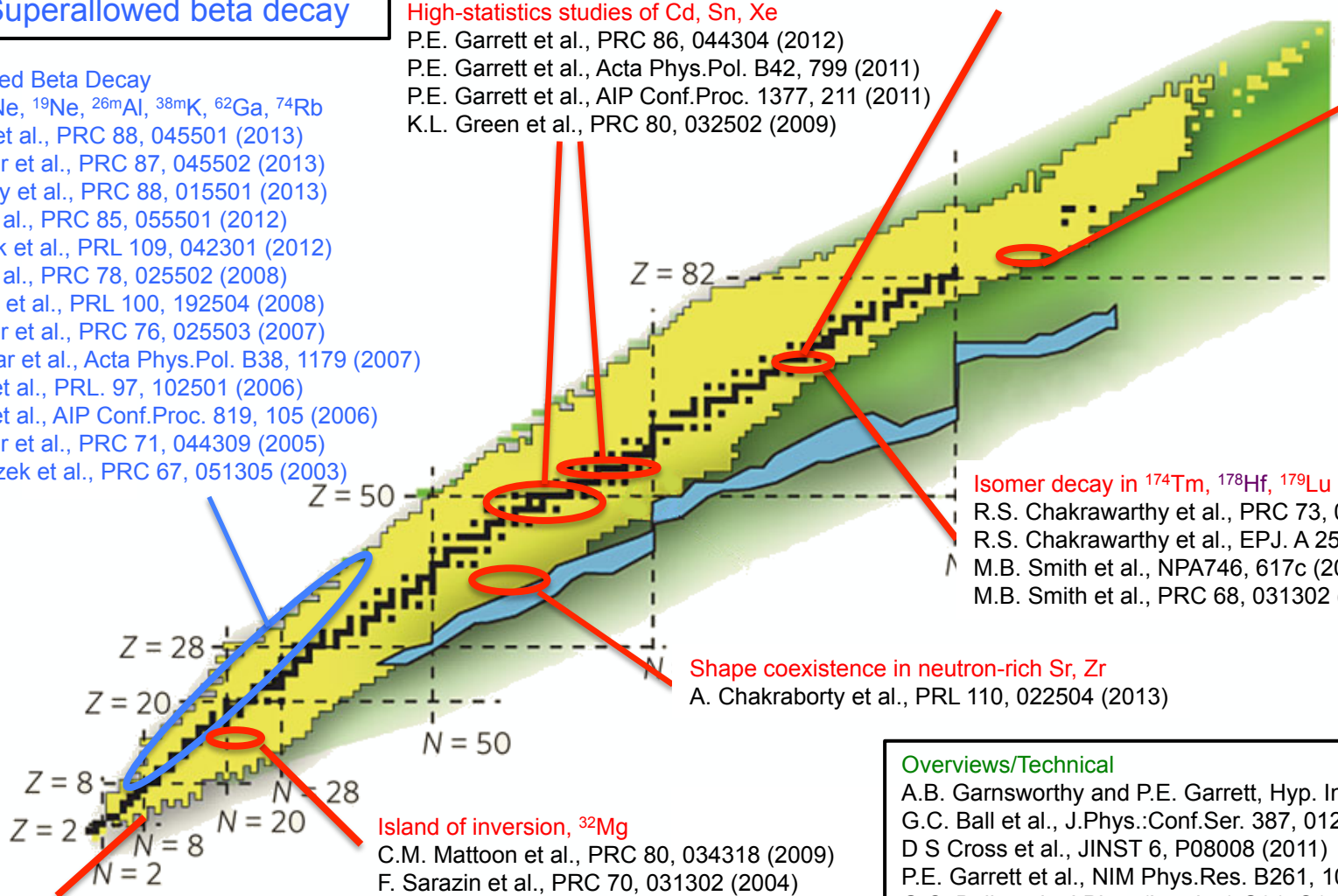
Island of inversion, ^{32}Mg

C.M. Mattoon et al., PRC 80, 034318 (2009)
F. Sarazin et al., PRC 70, 031302 (2004)

Overviews/Technical

A.B. Garnsworthy and P.E. Garrett, Hyp. Int. 225, 121 (2014)
G.C. Ball et al., J.Phys.:Conf.Ser. 387, 012014 (2012)
D S Cross et al., JINST 6, P08008 (2011)
P.E. Garrett et al., NIM Phys.Res. B261, 1084 (2007)
G.C. Ball et al., J.Phys.(London) G31, S1491 (2005)
S.J. Williams et al., J.Phys.(London) G31, S1979 (2005)

^{11}Li beta-delayed neutron emission
C.M. Mattoon et al., PRC 75, 017302 (2007)



The 8π Spectrometer at TRIUMF-ISAC

A.B. Garnsworthy and P.E. Garrett, Hyperfine Interactions 225, 121 (2014)

A. Chakraborty et al., Phys.Rev.Lett. 110, 022504 (2013)

[R. Dunlop et al., Phys.Rev. C 88, 045501 \(2013\)](#)

[G.F. Grinyer et al., Phys.Rev. C 87, 045502 \(2013\)](#)

[A.T. Laffoley et al., Phys.Rev. C 88, 015501 \(2013\)](#)

G.C. Ball et al., J.Phys.:Conf.Ser. 387, 012014 (2012)

[P. Finlay et al., Phys.Rev. C 85, 055501 \(2012\)](#)

P.E. Garrett et al., Phys.Rev. C 86, 044304 (2012)

[S. Triambak et al., Phys.Rev.Lett. 109, 042301 \(2012\)](#)

D S Cross et al., JINST 6, P08008 (2011)

P.E. Garrett et al., Acta Phys.Pol. B42, 799 (2011)

P.E. Garrett et al., AIP Conf.Proc. 1377, 211 (2011)

K.L. Green et al., Phys.Rev. C 80, 032502 (2009)

C.M. Mattoon et al., Phys.Rev. C 80, 034318 (2009)

[P. Finlay et al., Phys.Rev. C 78, 025502 \(2008\)](#)

[K.G. Leach et al., Phys.Rev.Lett. 100, 192504 \(2008\)](#)

P.E. Garrett et al., NIM Phys.Res. B261, 1084 (2007)

[G.F. Grinyer et al., Phys.Rev. C 76, 025503 \(2007\)](#)

C.M. Mattoon et al., Phys.Rev. C 75, 017302 (2007)

[E.F. Zganyar et al., Acta Phys.Pol. B38, 1179 \(2007\)](#)

R.S. Chakrawarthy et al., Phys.Rev. C 73, 024306 (2006)

[B. Hyland et al., Phys.Rev.Lett. 97, 102501 \(2006\)](#)

[B. Hyland et al., AIP Conf.Proc. 819, 105 \(2006\)](#)

G.C. Ball et al., J.Phys.(London) G31, S1491 (2005)

R.S. Chakrawarthy et al., Eur.Phys.J. A 25, Sup. 1, 125 (2005)

[G.F. Grinyer et al., Phys.Rev. C 71, 044309 \(2005\)](#)

S.J. Williams et al., J.Phys.(London) G31, S1979 (2005)

F. Sarazin et al., Phys.Rev. C 70, 031302 (2004)

M.B. Smith et al., Nucl.Phys. A746, 617c (2004)

G.F. Grinyer et al., Phys.Rev. C 67, 014302 (2003)

[A. Piechaczek et al., Phys.Rev. C 67, 051305 \(2003\)](#)

M.B. Smith et al., Phys.Rev. C 68, 031302 (2003)

8pi operated at TRIUMF-ISAC-I
from 2000 to 2013

32 publications including 4 PRLs

19 Nuclear Structure (Black)

[13 Superaligned beta decay \(Blue\)](#)

Researchers from 24 institutions
from 8 countries.

25 post-docs,
5PhD, 12MSc, 1MPhys

12 Grad. Students in progress so
more publications still to come...

The 8 π Spectrometer at TRIUMF-ISAC

