Beta-delayed neutron emission: New experimental study of angular properties.

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Russbach Winter School
March 2014

(with acknowledgements to
Robert Grzywacz and Jirina Stone)

Outline

History First identified as early as 1939
[Roberts, Meyer and Wang Phys Rev 55 510 and 664]

* Current Motivation

* Outline beta-delayed neutron emission theory

* Examples of beta-delayed neutron emitters

Experiments: Oriented source and angular correlation

Ref. Quantum Barrier Penetration Studies with Oriented Nuclei:
Proton and Neutron Emission from Exotic Isotopes

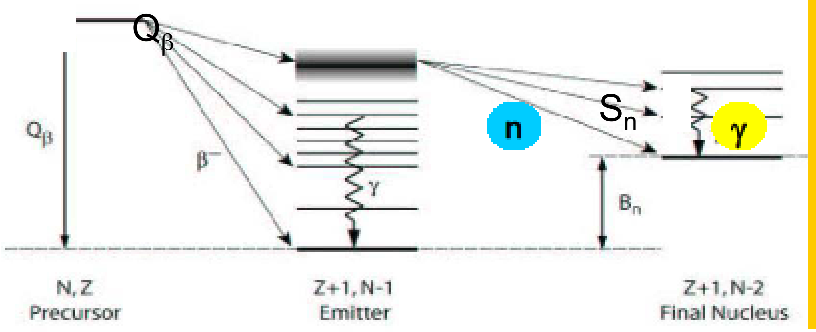
NJS JRS Sun Punan and A Woehr

Hyperfine Interactions 136/137 143 (2001)

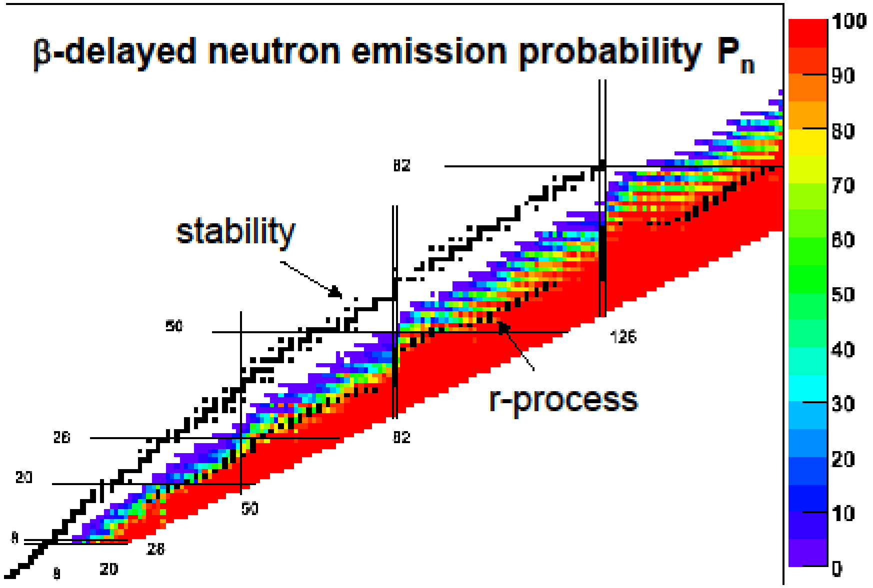
What is beta delayed neutron emission ?

An alternative to beta-gamma decay in neutron rich nuclei

Beta decay of neutron rich nuclei



Going from stability, neutron binding energy S_n in emitter becomes lower than decay energy Q_β.
Beta decay to states above S_n tend to emit neutrons rather than gamma decay.
Far enough from stability **beta-delayed neutron emission** becomes the dominant decay process.



Motivations for more detailed understanding of the process:

1. *Beta delayed neutrons are of great relevance in providing later time neutrons in r-process nucleosynthesis and in the determination of r-process lifetimes.*
2. IEAE Vienna 2011

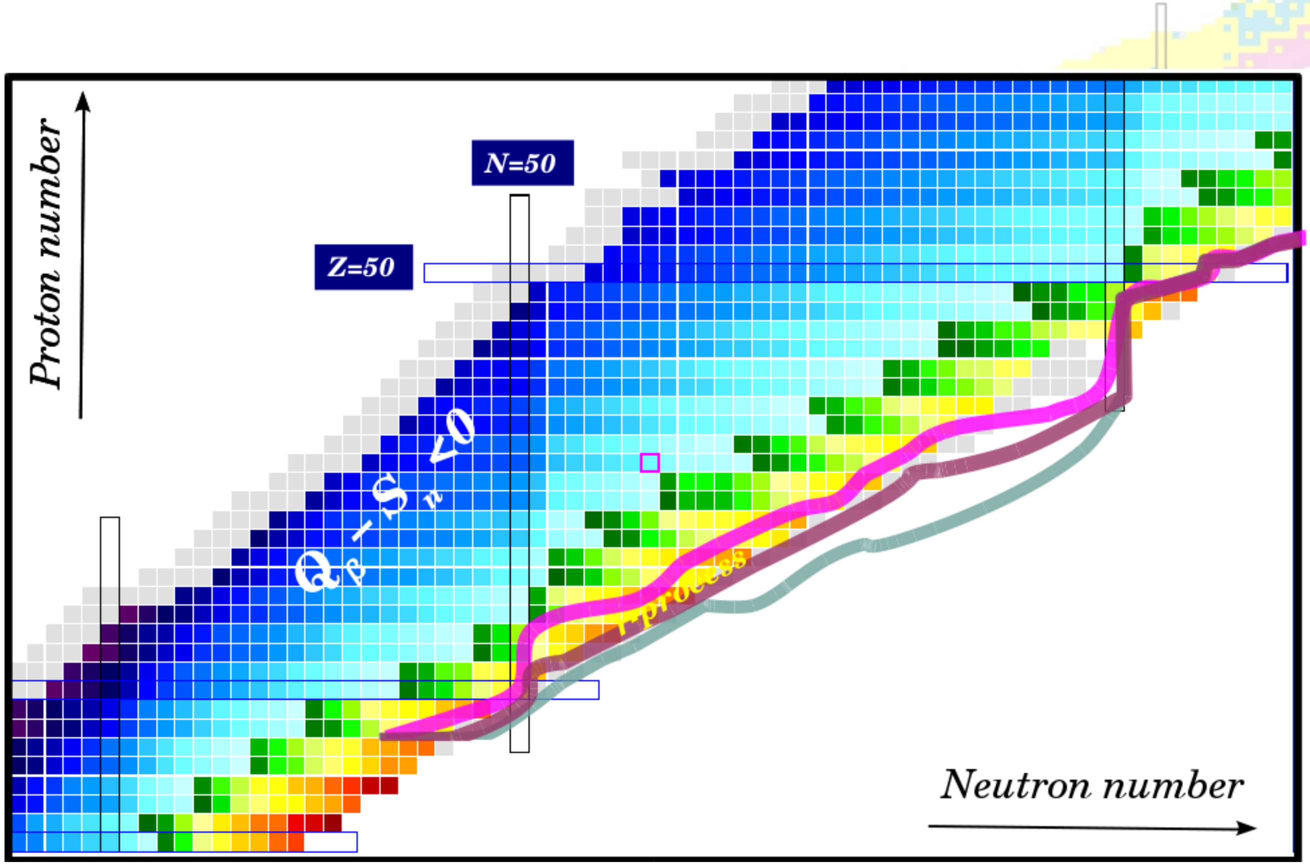
International Nuclear Data Committee Consultants Meeting
INDC(NDS) - 0599
Need for detailed study of the beta-delayed neutron decay mode

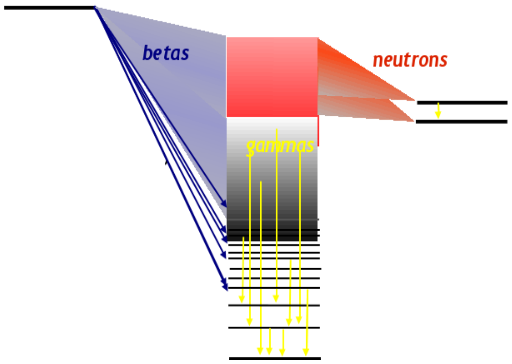
To assist in improving reactor safety and design by enabling better estimates of fission product decay heat and to establish the time scale of reactor response to control changes. Beta-delayed neutrons are relatively few in stable reactor operation, but they persist e.g. after shut-down and limit the rate at which mechanical control changes can be made.

"Excessively large uncertainties in the delayed neutron data used in reactor calculations lead to costly conservatism in the design and operation of reactor control mechanisms"

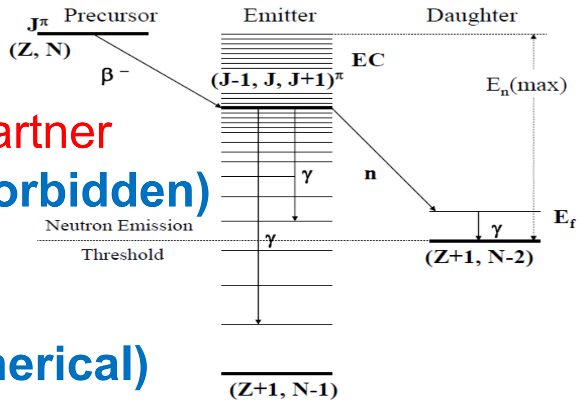
Beta-delayed neutrons and r-process
Marginal experimental knowledge !

All r-process nuclei are beta delayed neutron emitters
Nuclear structure - what are the features of the strength distribution !
Nuclear lifetimes and branching ratios.

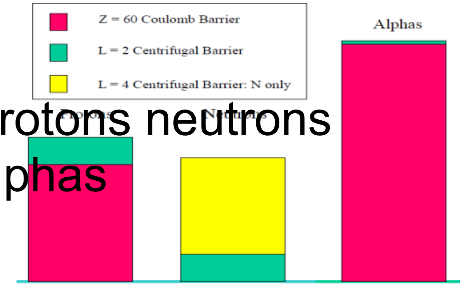




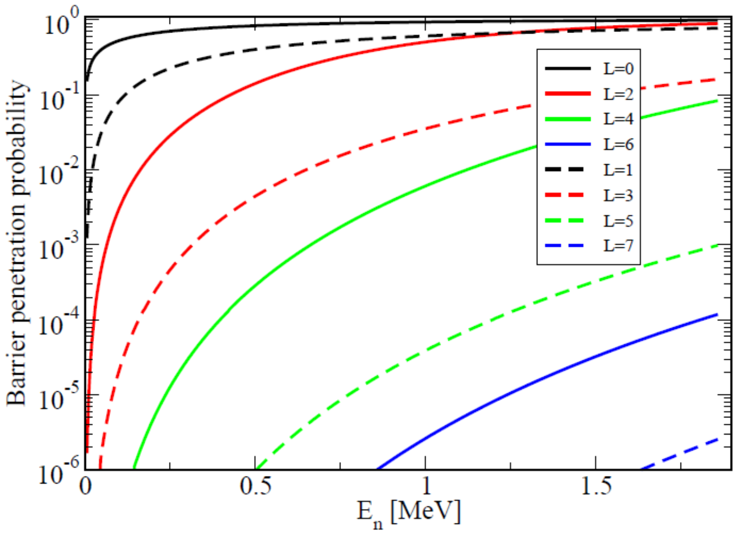
Elements of Theory



1. Beta Decay
   Assumed dominated by Gamow-Teller to S-O partner
   Allowed decay to J, J+/-1 No parity change **(1st forbidden)**
2. Barrier penetration
   for neutrons centrifugal only. **Optical Model**
   gives L dependent transmission coefficients **(spherical)**
3. Gamma competition
   Assumed E1 as fastest.
   Hardy PL B109 242 (82)
4. Level spin density in emitter
   Assumed the Back-shifted Fermi Gas Model
   to estimated **the density** of states of each spin J
   in emitter and its **energy dependence**.
5. Statistical weight
   Each emitter J state has weight (2J + 1) normal
6. Excited states in Daughter
   Separate n spectrum components to
   different daughter states. **[n,γ Coincidence]**



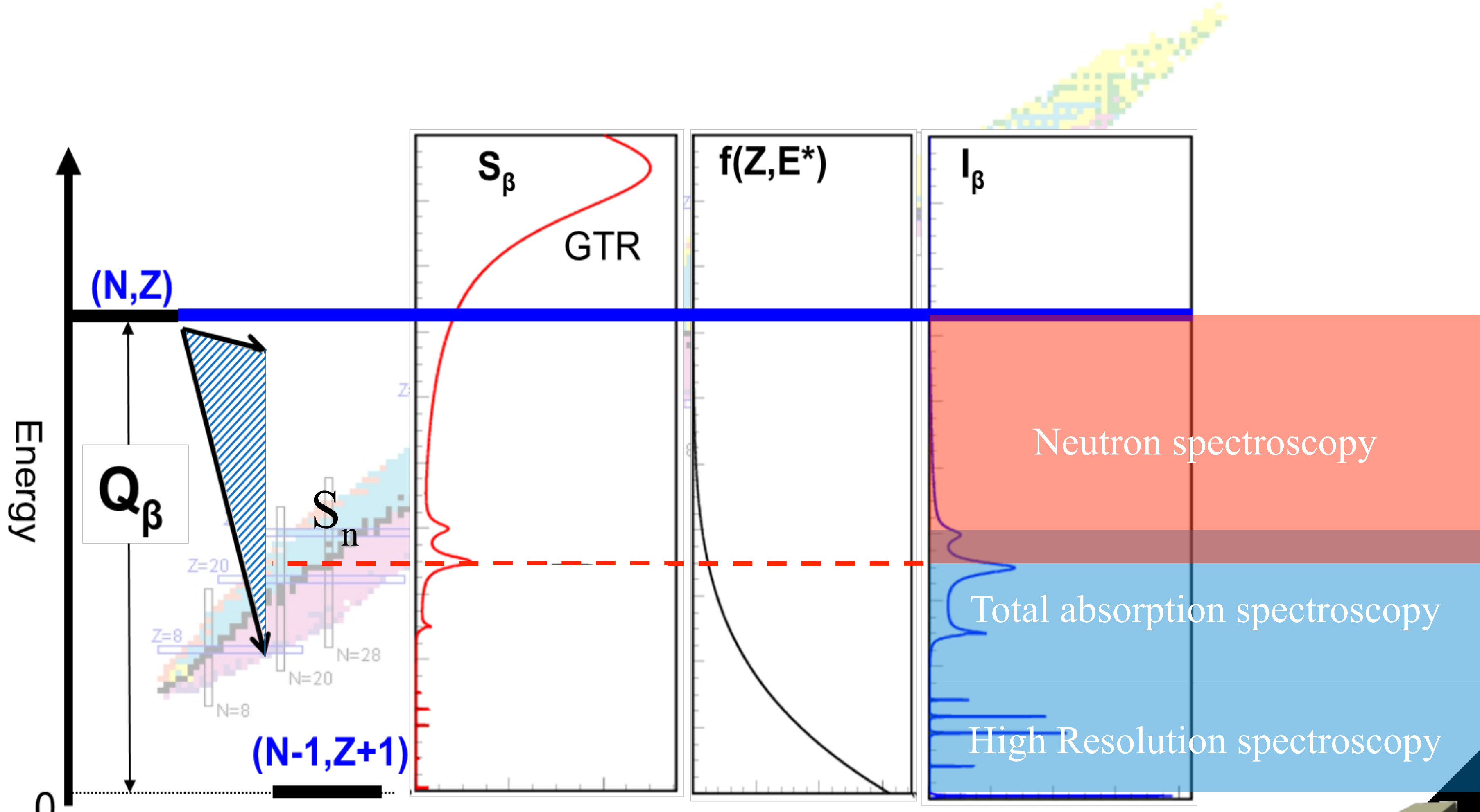
Protons neutrons
alphas



Suffice to give spectrum of emitted neutrons and lifetime estimate.

penetration

Beta strength and nuclear lifetimes/branching ratios



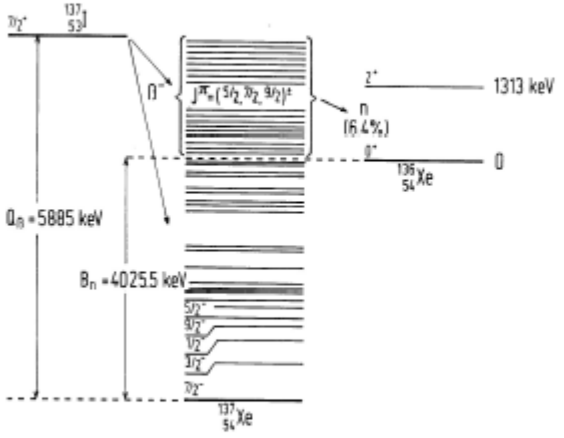
Neutron spectroscopy

Total absorption spectroscopy

High Resolution spectroscopy

Details of neutron and high energy region of gamma spectrum in decay of ^{137}Xe

H.Ohm et al. Z Physik 296 23 (1980)



Competition between gamma and neutron emission

Maximum neutron energy 1860 keV

possible neutron decay to ground (max 1830 keV) and to 1313 keV 2+ state in daughter ^{136}Xe (max n energy 517 keV).

Spins in ^{137}Xe 9/2,7/2,5/2 all + parity if β GT allowed

^{137}I ground state 7/2+ ^{137}Xe ground state 7/2-: E1

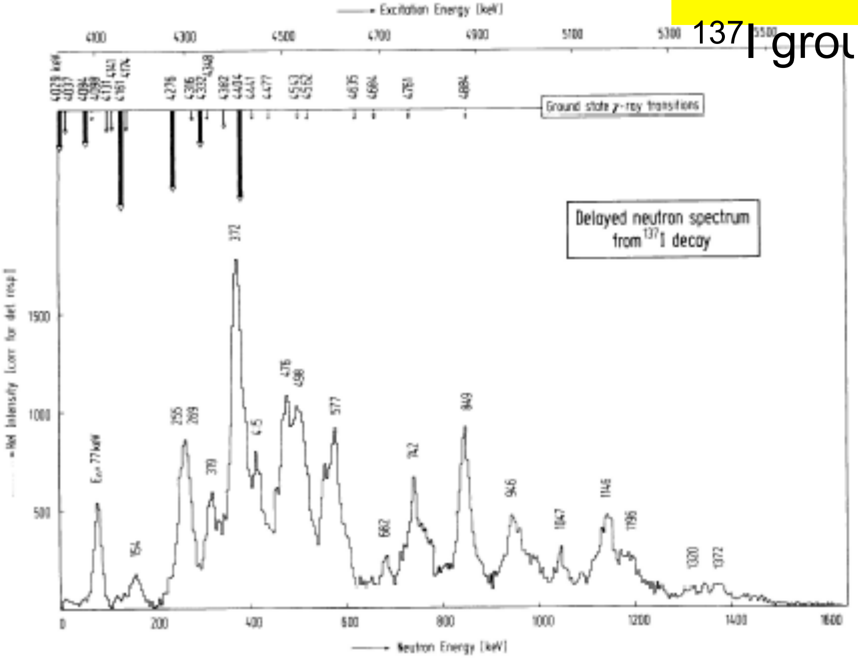


Fig. 3. Delayed neutron spectrum from ^{137}I decay after correction for thermal neutrons, detector response and efficiency. In the upper part, ground state γ-ray transitions from neutron-unbound states in ^{137}Xe are indicated by arrows, their length representing the relative intensity

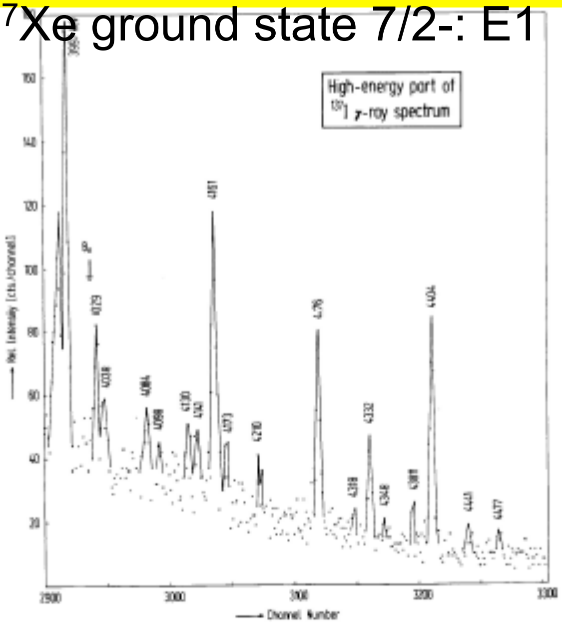


Fig. 4. High-energy part of the ^{137}I γ-ray singles spectrum taken at the mass separator SIRIUS [17]

Look at an example decay in more detail

Delayed Neutron Emission from ^{137}I

S. Shalev* and G. Rudstam
The Swedish Research Council's Laboratory, Studsvik, Nyköping, Sweden
(Received 17 January 1972)

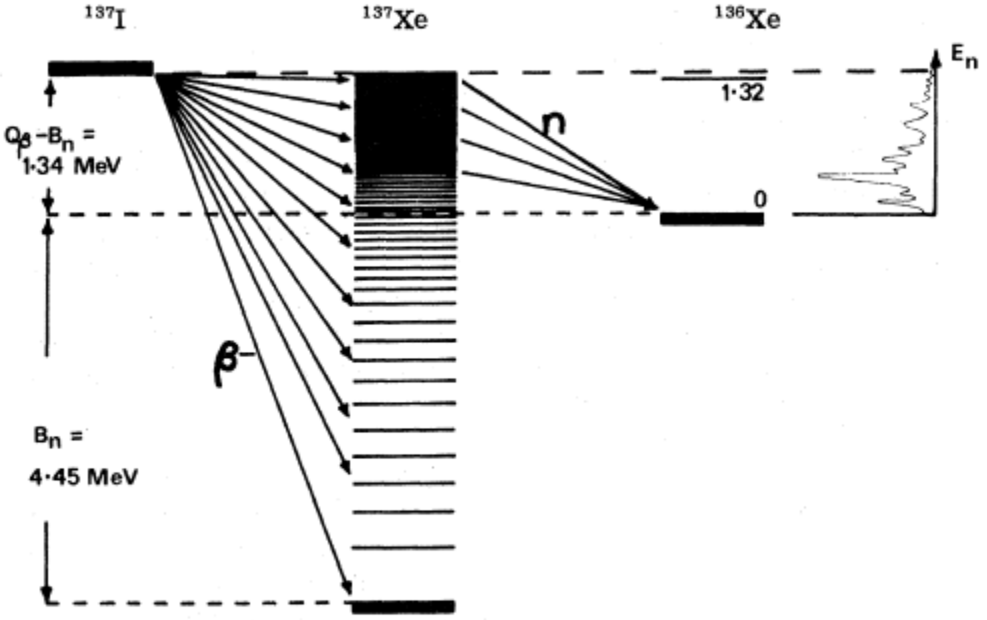


FIG. 2. Energy-level diagram for β-delayed neutron emission from ^{137}Xe.

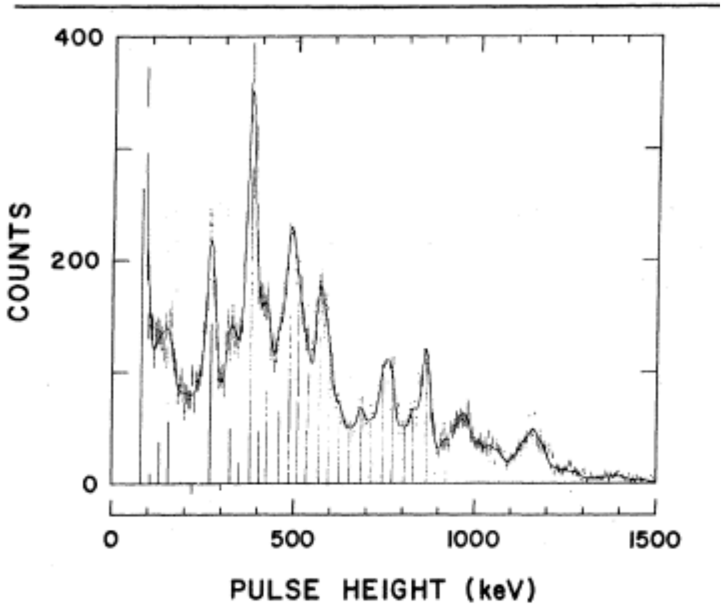


FIG. 1. Experimental pulse-height distribution of delayed neutrons from ^{137}Xe. Error bars on data indicate statistical uncertainty. Solid curve is sum of energy-dependent response functions, whose energy and relative amplitudes are shown as vertical lines.

General shape of neutron spectrum controlled by
at low energy gamma/ cf barrier competition
at high energy falling beta phase space

Many partially resolved components
What's known about them?

What are the elements of the outline theory which give rise to uncertainties in estimated half-lives of beta delayed n emission?

Beta decay

For the heavier nuclei above 78Ni protons and neutrons are filling different major shells. GT allowed beta decay to spin-orbit partners is not readily available as they are at high excitation in daughter nuclei. The possible influence of first forbidden (FF) beta decay has to be considered.

GT decay: takes away **one** unit of angular momentum, **no parity change**
FF decay: takes away **one** unit of angular momentum (*), **parity changes**

Parity change means different neutron partial waves in e.g. decay to 0+ g.s.

Neutron emission

Barrier penetration estimates are for **spherical** nuclei. Deformed barrier penetration is quantitatively more complex.

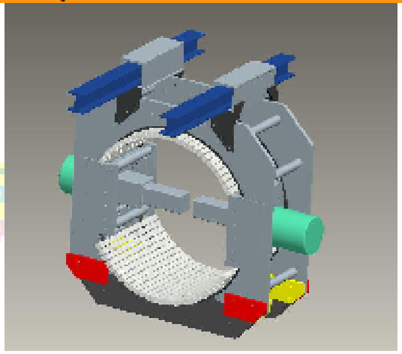
These questions can be approached by experiments on angular properties of decay

Experimental Potential : Detector innovation

True challenge –measure energy of the neutrons !
VANDLE - neutron time of flight detector

Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science

Maximize the detection efficiency in the broad energy range

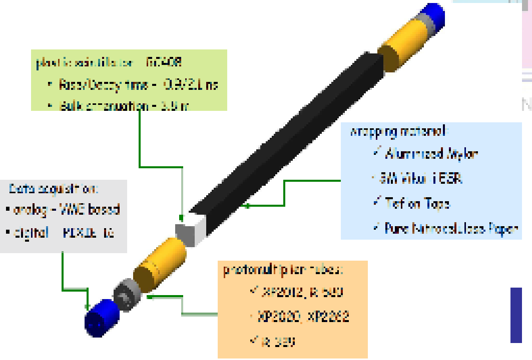


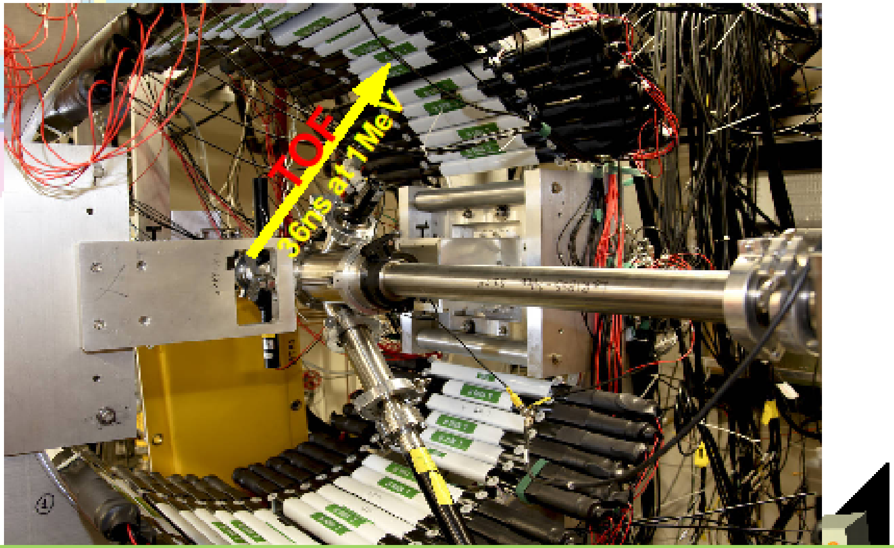
Neutrons (inelastic scattering of the scintillator material)

- **48 bars 3x3 x 60 cm^3**
- **Ω = 26% of 4π**
- **12% total efficiency @ 1MeV**
- **50 cm TOF radius**
- **40-60% efficiency "START"**

Gamma rays:

- **2 clovers, 3% efficient @ 1MeV**





Versatile, modular, excellent resolution, efficiency and angular range

Angular properties of beta delayed neutron emission and neutron-gamma, beta-neutron angular correlations

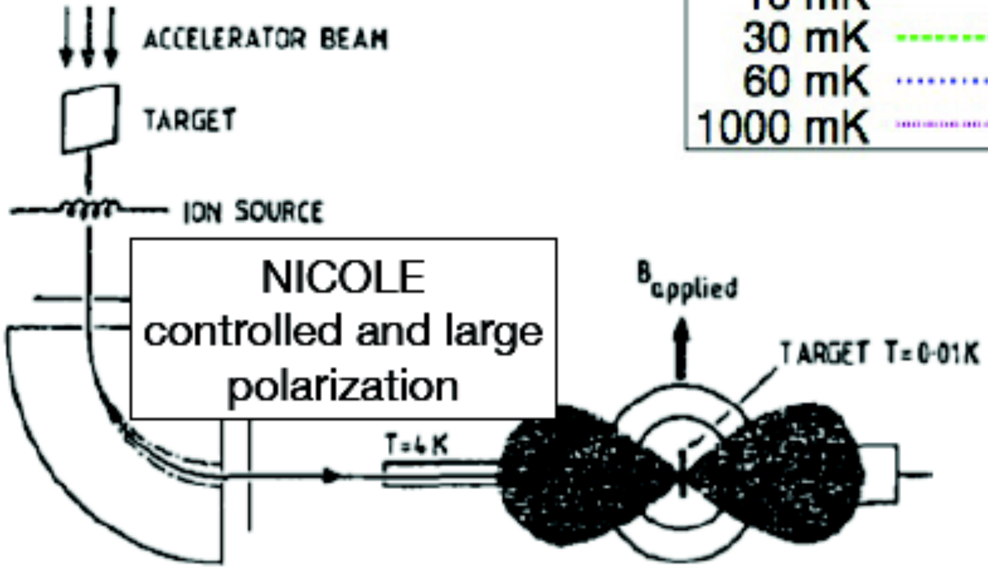
Formalism close to that for gamma-gamma, modified by the use of the R_λ **channel spin** coefficients of Satchler [Direct Nuclear Reactions OUP 1993 p375]
which depend upon the spins of the states, the angular momentum of the emission and the spin of the emitted particle

Channel spin is the vector sum of the particle spin (1/2) and final state spin

Neutrons to different daughter levels are not separated, each has it's own term in the anisotropy and they are summed when at the same energy **unless there is a coincidence condition**.

Question of phase/Interference?

Nuclear orientation experiment with VANDLE at NICOLE



NICOLE
controlled and large
polarization

Fig. Schematic on-line nuclear orientation experiment.

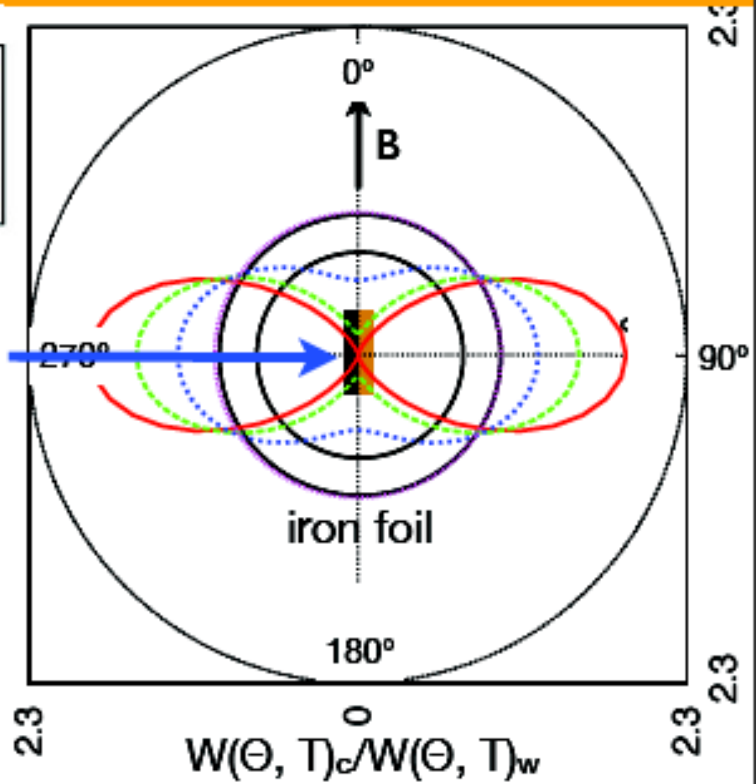
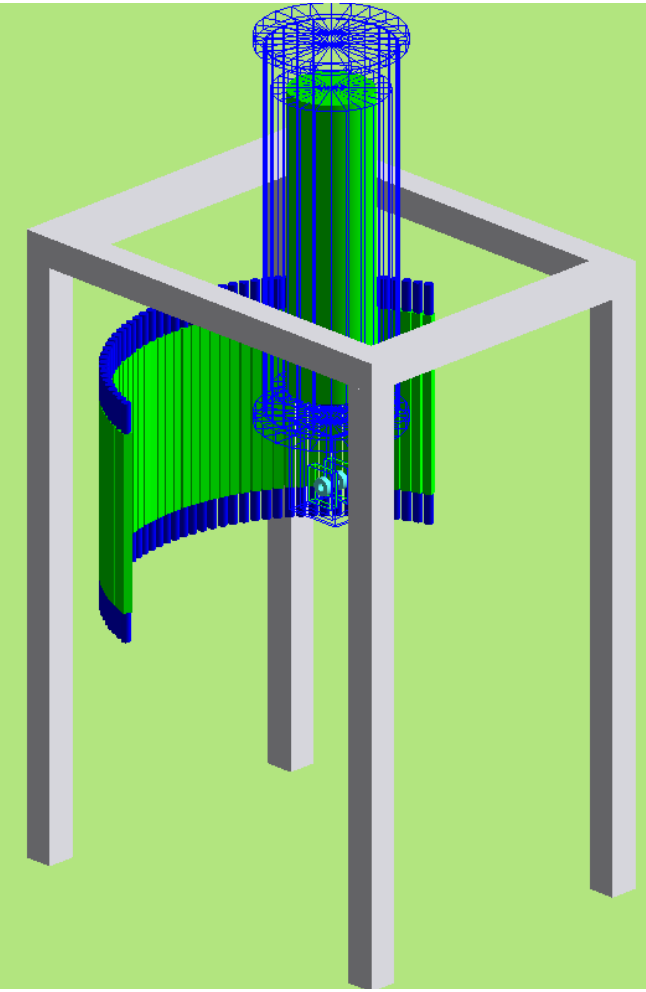
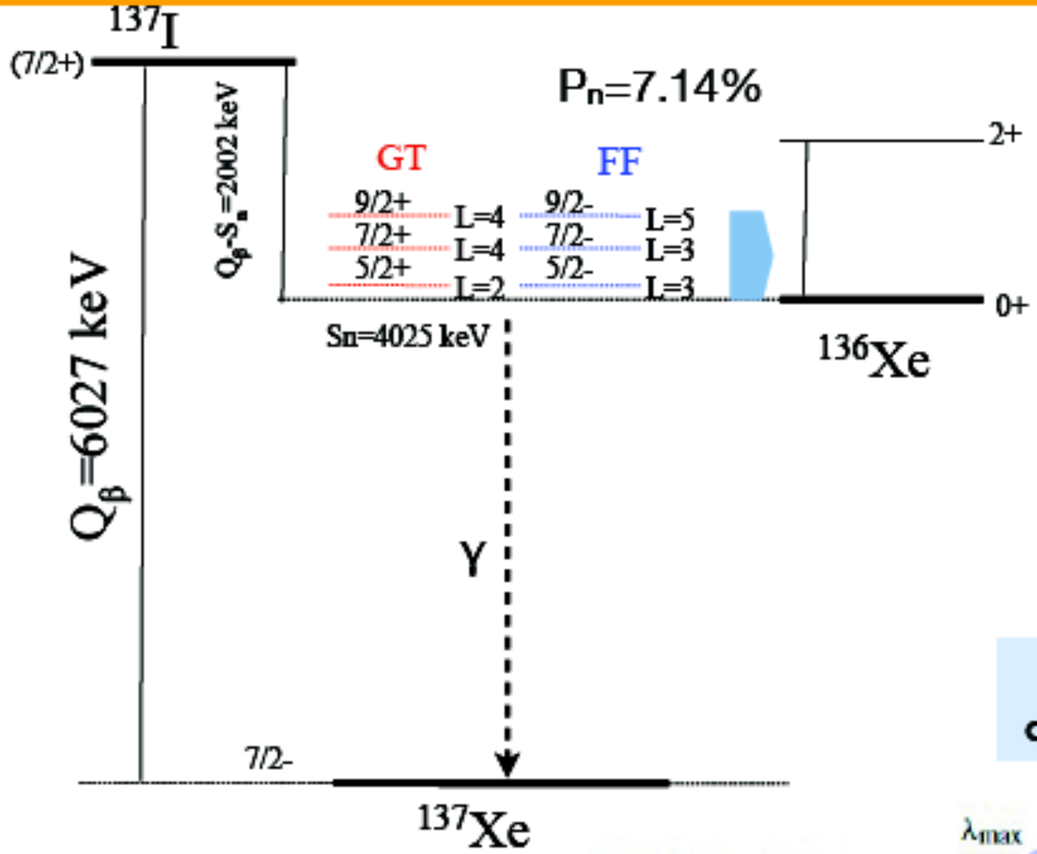


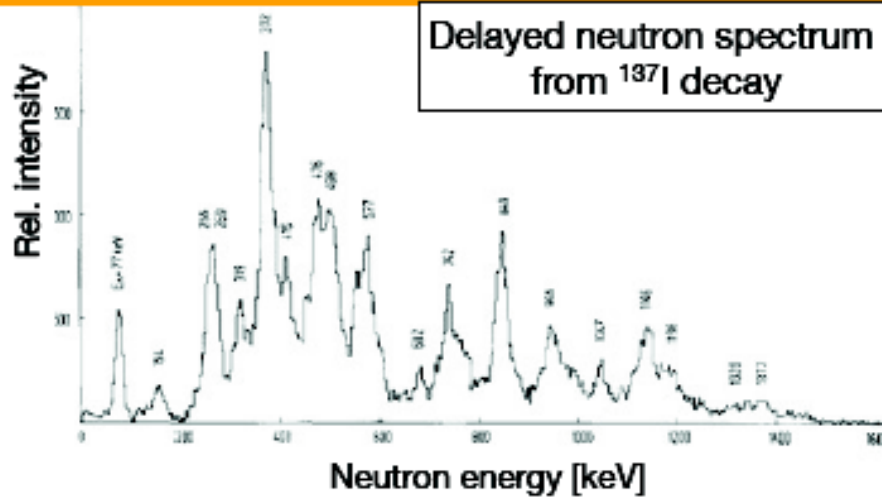
Fig. Neutron angular distribution ($E_n = 500$ keV).

→ the anisotropy of the angular distribution is defined by the ratio of cold to warm intensities at a given angle and temperature.



Experiment and theory





Delayed neutron spectrum from ^{137}I decay

[H. Ohm et al. Physik A - Atoms and Nuclei 296, 23-33 (1980)]

parent orientation

β-decay (GT or FF)

The angular distribution:

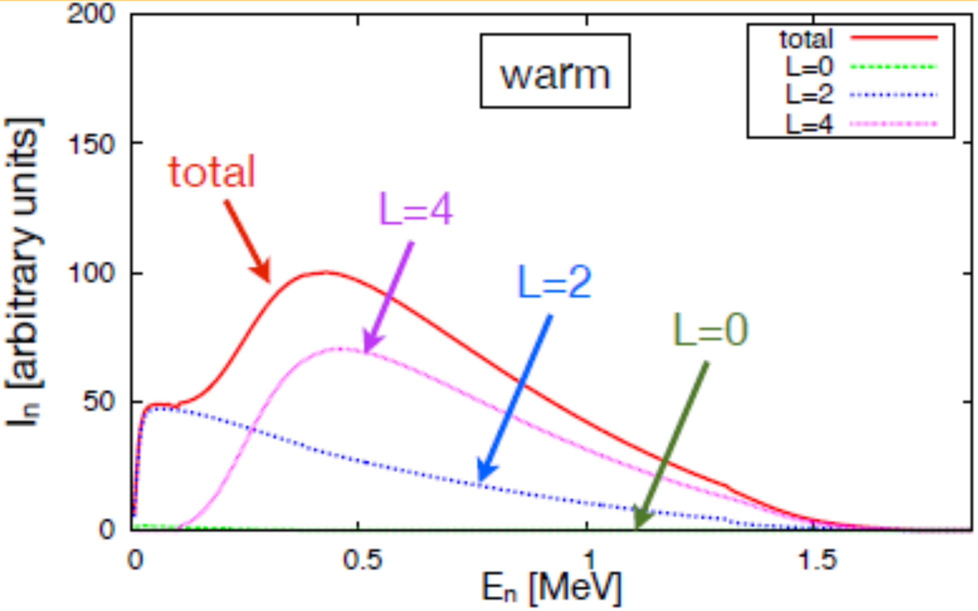
$$I_n^{\text{cold}}(E_n, T, \theta) = \sum_{\lambda=0}^{\lambda_{\max}} B_\lambda(T) Q_\lambda \left\{ \sum_m \omega(m) U_\lambda(m) \right. \times \left[I_\beta(E_1^*) I_n^m(E_1^*, L, 1/2) R_\lambda(L, I_c) + I_\beta(E_2^*) \sum_{L, I_c} I_n^m(E_2^*, L, I_c) R_\lambda(L, I_c) \right]\Big] \Big\} P_\lambda(\cos\theta).$$

neutron emission angular distribution

[N. Stone et al. Hyperfine Interactions 136/137: 143–148, 2001.]

Orientation experiment - schematic model

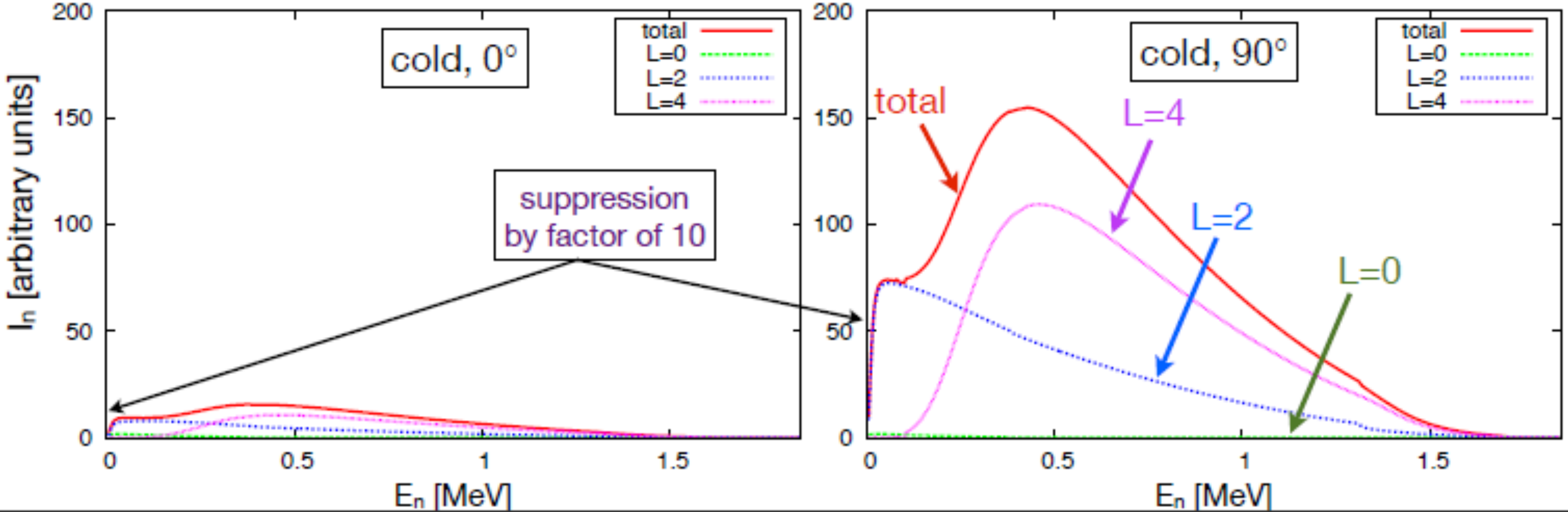
[N. Stone et al. Hyperfine Interactions 136/137: 143–148, 2001]

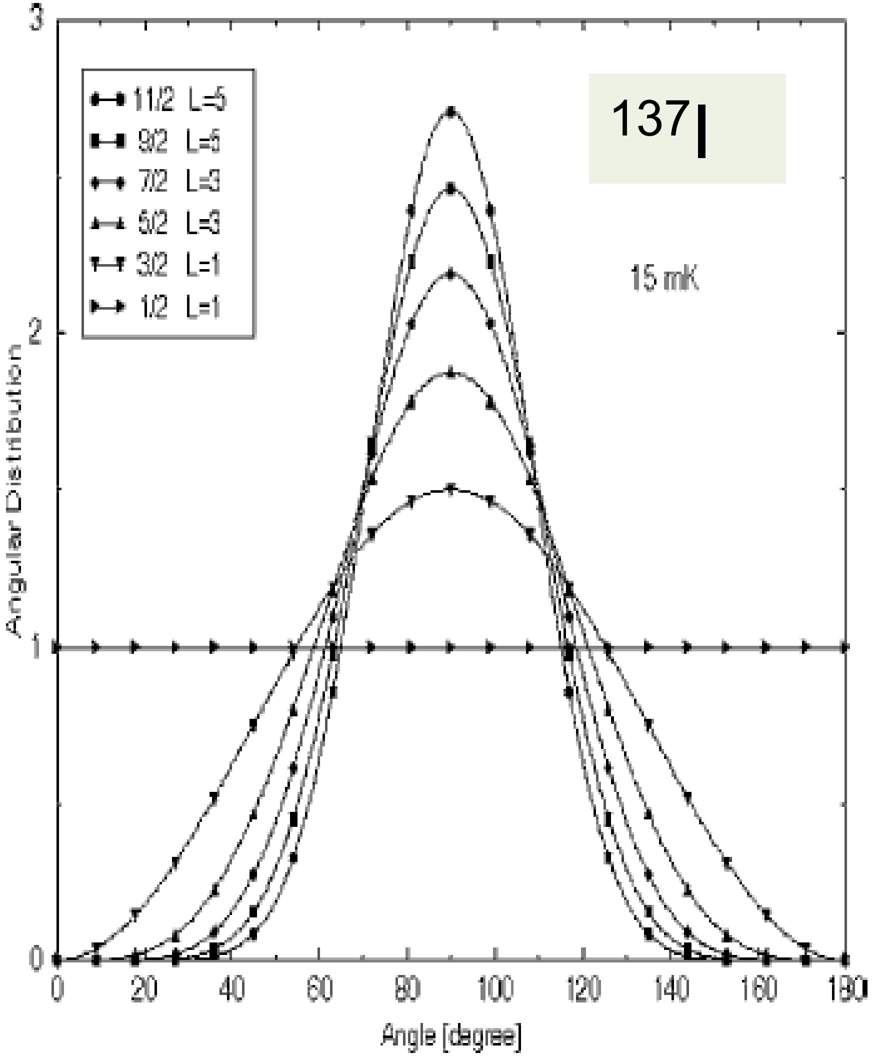


Simulations J. Stone and N. Stone

→ partial waves distribution for different angular momenta

→ example of expected level of anisotropy





Calculated angular distributions for several emitter spins and neutron partial waves

Phase and Interference in Unresolved Spectra

In the study of RESOLVED transitions (alpha, gamma decay) interference of competing partial wave amplitudes is central to the description of the process.
- and is one of the advantages/complications in experimental analysis! E.g the M1/E2 mixing ratio.

When many UNRESOLVED transitions are summed sensitivity to phase and amplitude mixing ratio is completely lost - that is we assume both phases and all 'mixing ratios' equally represented.
In consequence the familiar gamma transition mixing ratio F coefficients reduce to sums with all possible mixing terms equally represented

- the result is the same as an INCOHERENT sum of equal intensities of the competing partial waves.

This is the assumed situation with beta-delayed neutron emission from high density excited states in the emitter.
E.G. level spacing < keV, resolution 10’s keV, continuum spectra
[Ray Satchler: Physics Letters **7** (63) 55]

(N.B. Presence or absence of interference effects do not affect lifetime estimates)

What coincidence and correlation measurements are possible?

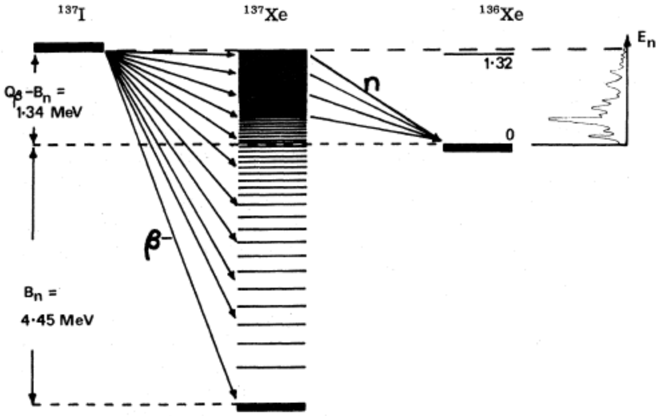


FIG. 2. Energy-level diagram for β-delayed neutron emission from ^{137}Xe.

Beta – gamma [gamma in emitter]

If assumed GT beta and E1 gamma these give spins of emitter states in best cases

Beta spectrum is continuous, gammas line spectra

Beta-gamma [gamma in daughter – neutron unobserved]

May give emitter state spin but complex possibilities. CANNOT reveal interference effects in neutron emission

Beta spectrum continuous, gammas line spectra

Beta – neutron

Can give spin of emitter state and reveal interference effects in neutron emission

Beta spectrum continuous, neutrons complex line spectra

Neutron-gamma [exist only if excited states in the daughter are fed]

Generally gamma well known so measurement gives direct evidence for neutron L values and possible interference.

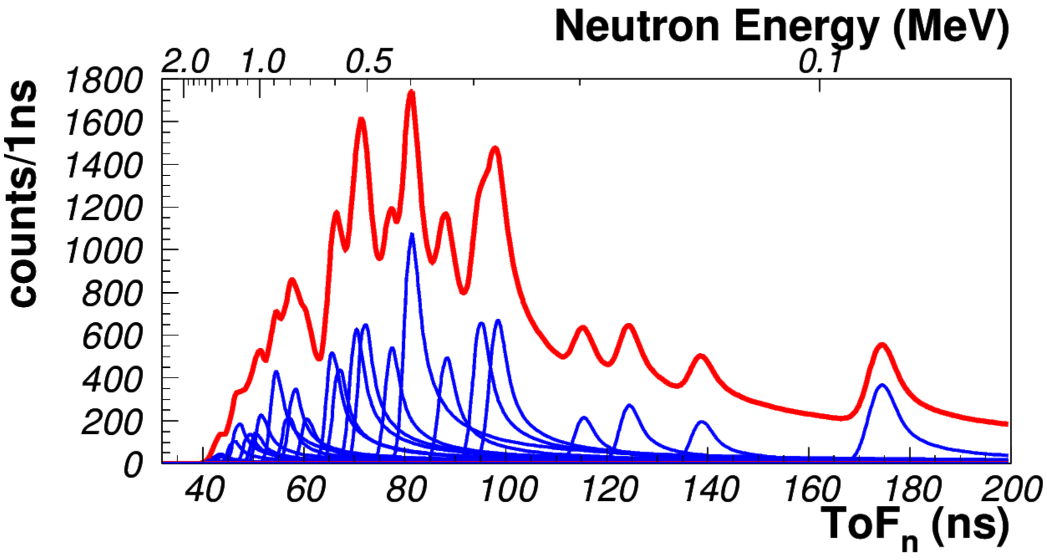
Neutrons complex line spectra, gammas line spectra

Simulations of Vandle spectra At Nicole (based on 75 cm path)

Above

Warm spectrum

Components (blue) and total (red) with scattered background



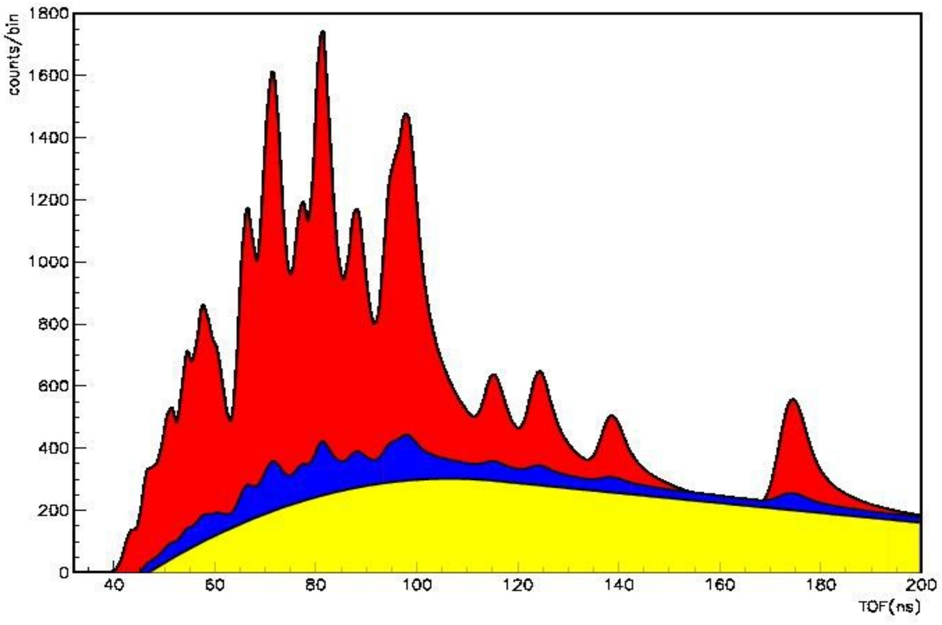
Below

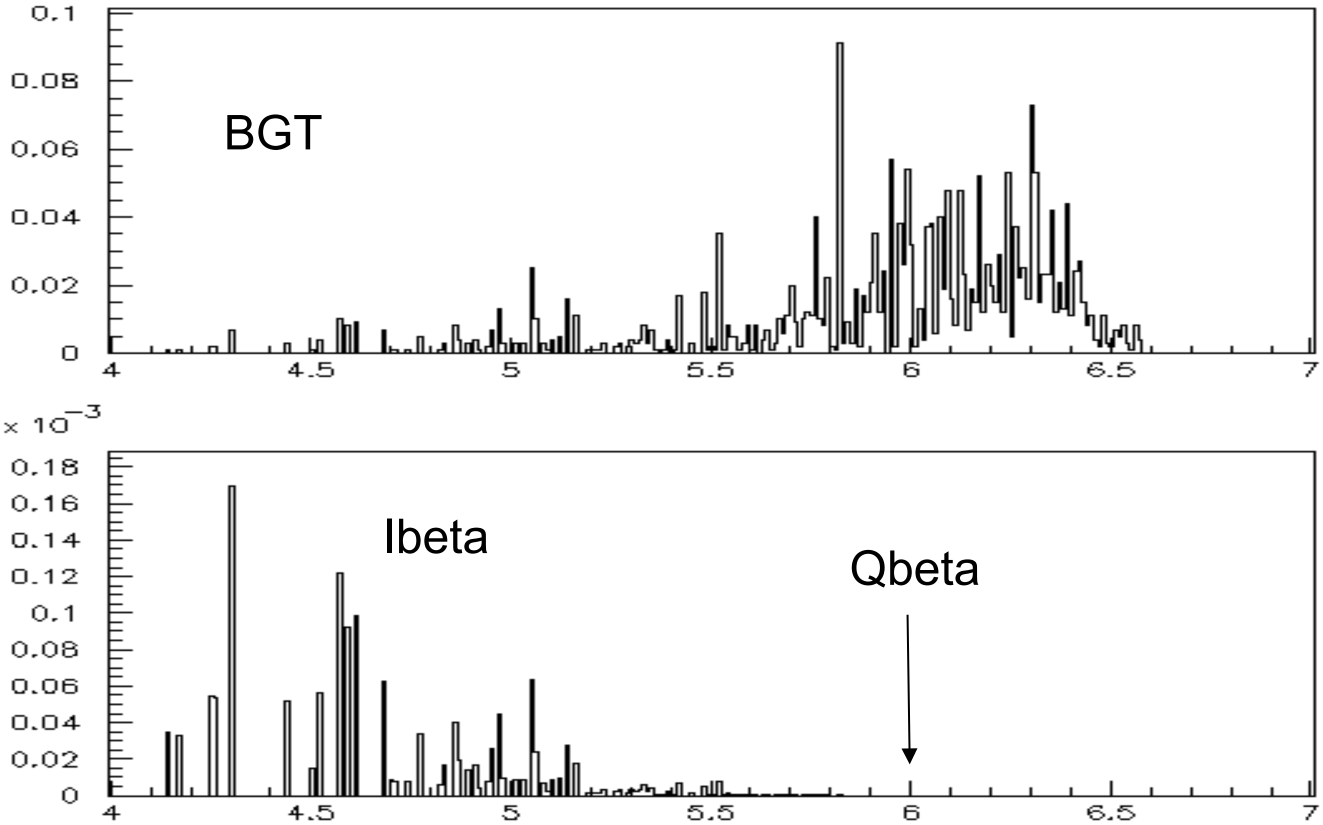
At ~ 15 mK

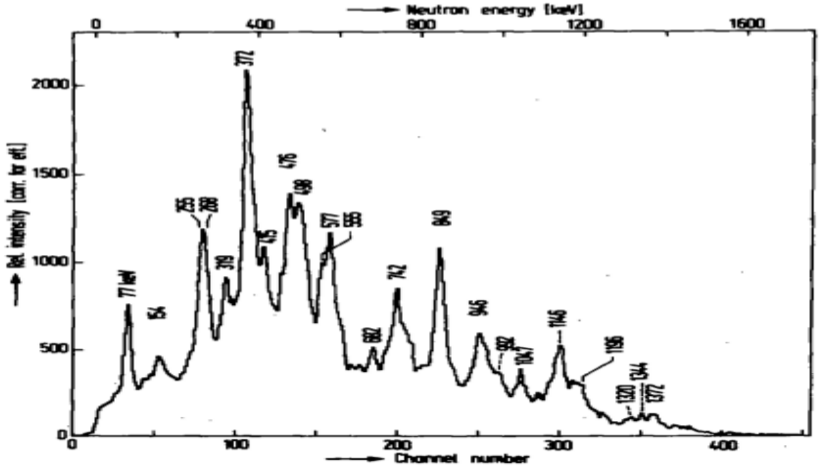
On axis (zero deg) blue

Normal to axis (90 deg) red

Both with scattered (isotropic) Background (yellow)







Extended shell model [new Oxbash] calculation by Robert Grzywacz of GT transitions from 137I compared to observed n spectrum.

Prospective Isotopes for Beta-Delayed Neutron Emission OLNO

Precursor T$_{1/2}$ **%** Bhf I^{p} Mom
Relax Emitter **Emittter**
Z s **neutrons** T nm time (s)
deformation

53 ^{137}I 24.2 **7.5** +114 7/2+ (2.8) < 2 ^{137}Xe
0.24

55 ^{141}Cs 24.9 **4 x 10^{-4}** +41 7/2^{+} (2.8) < 2 ^{141}Ba
0.12

35 ^{87}Br 56.1 **3** +81 3/2- (2.0) < 5 ^{87}Kr
0.06

59 ^{155}Pr (2) **(2)** (+300) (3/2-) (1.0) < 0.5 ^{155}Nd **0**

Objectives in the study of beta - delayed neutron emission angular properties

Basic Questions

1. Are the **average** sign and magnitude of the spatial anisotropy in agreement with
theory ?

Correlation: **multipole content, phase effects, spin assignment**
Orientation: **greater sensitivity to the same: also L dependent transmission**

2. Does the anisotropy of the distribution vary as predicted with emitted particle **energy** ?

Tests: **Density of emitter spin states as function of energy (spin dependence)**
Partial wave make-up of emission (barrier penetration)
Fluctuations may show presence of interference terms, i.e. non-statistical averaging

3. Does anisotropy show additional variation dependent upon emitter **deformation** ?

Sources

LTNO

Iodine implants very well and makes excellent samples for ^{137}I – ^{137}Xe

Bromine implantation is more problematic

(there are other examples - lanthanides and lighter fission fragments)

Correlation

Easier to set up experiments – effects usually weaker and harder to measure

Conclusion:

Several avenues of investigation are open with regard to this increasingly important decay mode

The new initiatives and instrumentation make such investigations timely

Thank you for your attention

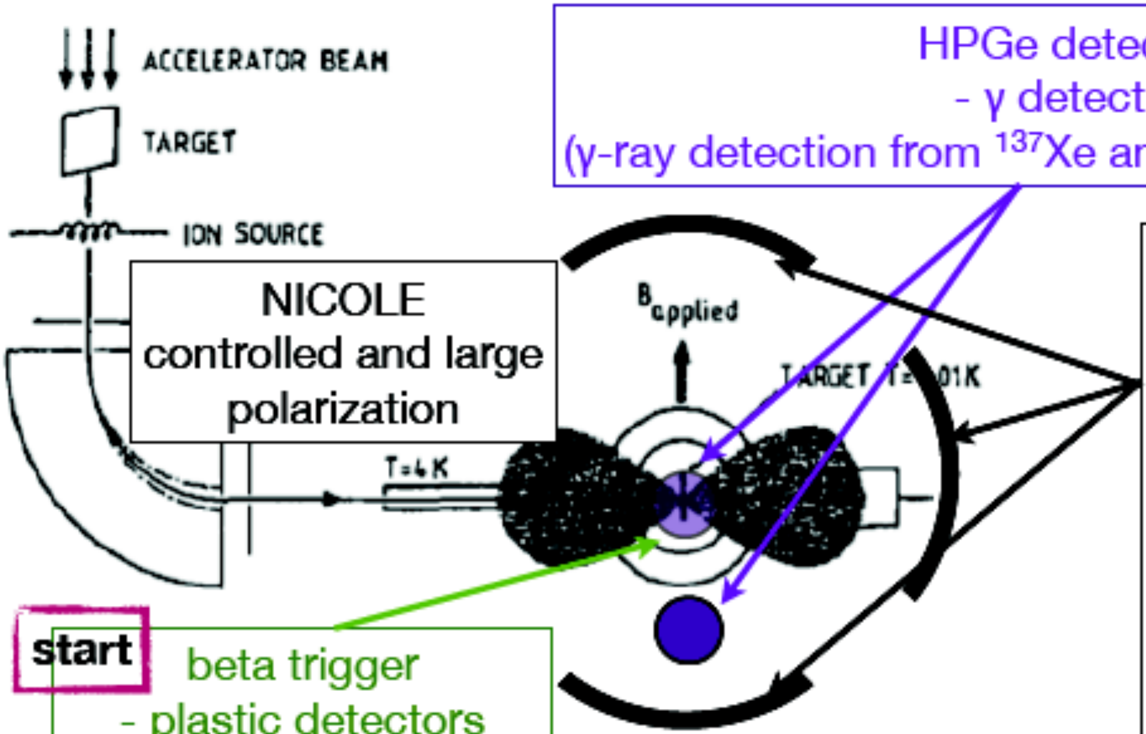
Proposal accepted by the ISOLDE and Neutron Time-of-Flight Committee
September 2013

Beta-delayed neutrons from oriented ^{137,139}I and ^{87,89}Br nuclei.

R.Grzywacz [1,9], J.R.Stone [1,2,3], N.J.Stone [1,2], U. Köster [4], B. Singh[5], C.R.Bingham [1], S. Gaulard [6], K. Kolos [1], M. Madurga[1], J.Nikolov [7], T. Otsubo [8], S. Roccia [6], M. Veskovic [7] , P. M. Walker [10], W. B. Walters [3]

1 University of Tennessee, Knoxville, TN, USA,
2 University of Oxford, Oxford, UK
3 University of Maryland, College Park, MD, USA
4 ILL Grenoble, France,
5 McMaster University, Hamilton, Canada,
6 CSNSM IN2P3 Orsay, France,
7 University of Novi Sad, Novi Sad, Serbia,
8 Niigata University, Japan
9 OaK Ridge National Laboratory

Nuclear orientation experiment with VANDLE at NICOLE



HPGe detectors
- γ detection
(γ-ray detection from ^{137}Xe and ^{60}Co temp. monitor)

NICOLE
controlled and large
polarization

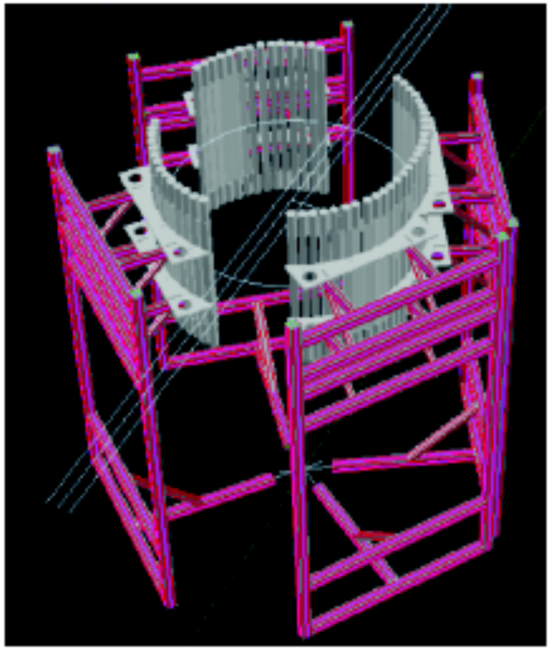
start

beta trigger
- plastic detectors
as trigger from VANDLE

Fig. Schematic on-line nuclear orientation experiment.

stop

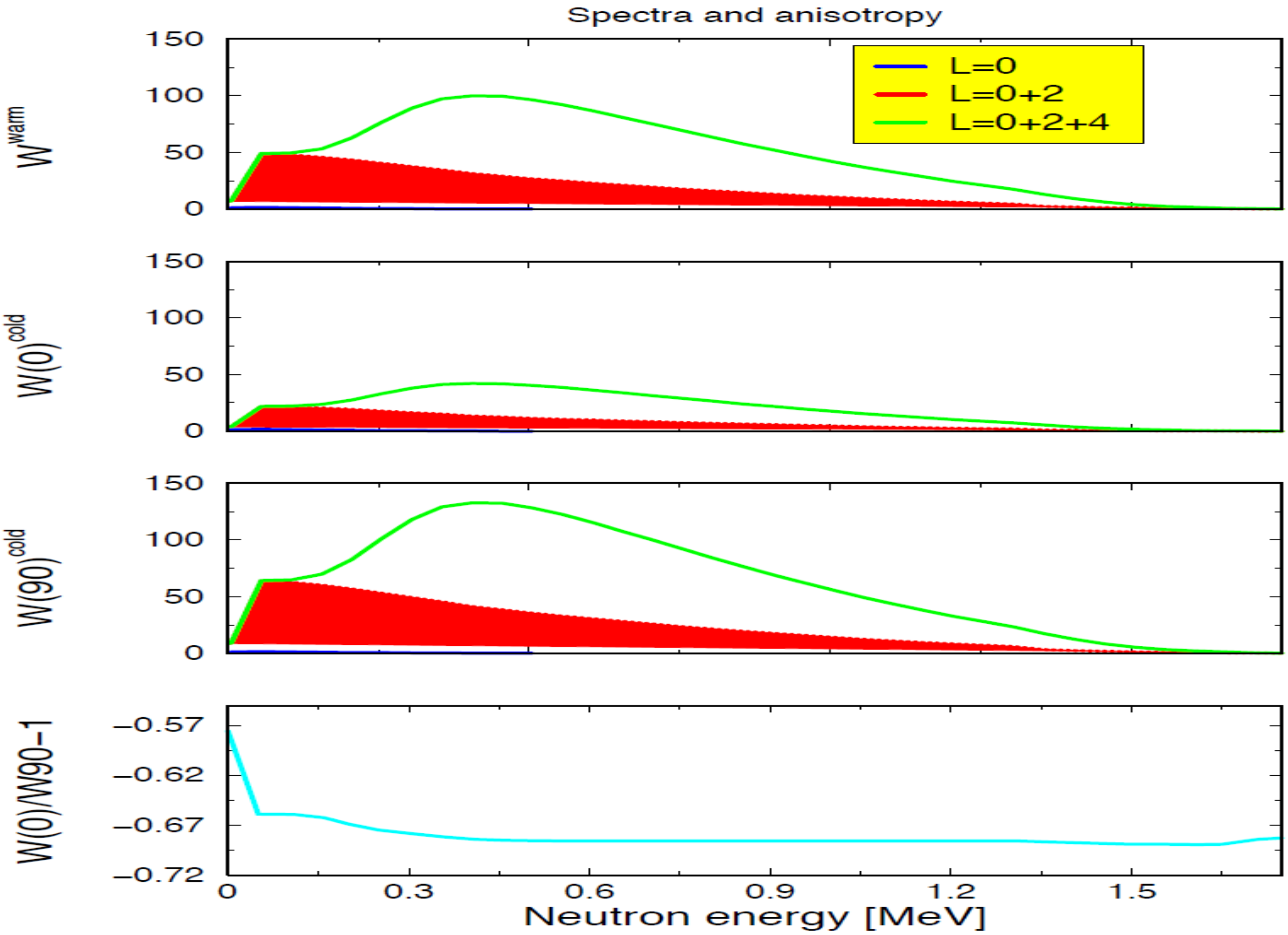
VANDLE
- neutron TOF measurement
placed at the distance of 50cm
3x16 bars 3x3x60cm^3 each
Timing resolution ~1ns



digital electronics
- Pixie16 modules
nano-second time
resolution required for
TOF measurements

Example of oriented source experiments: ^{137}I

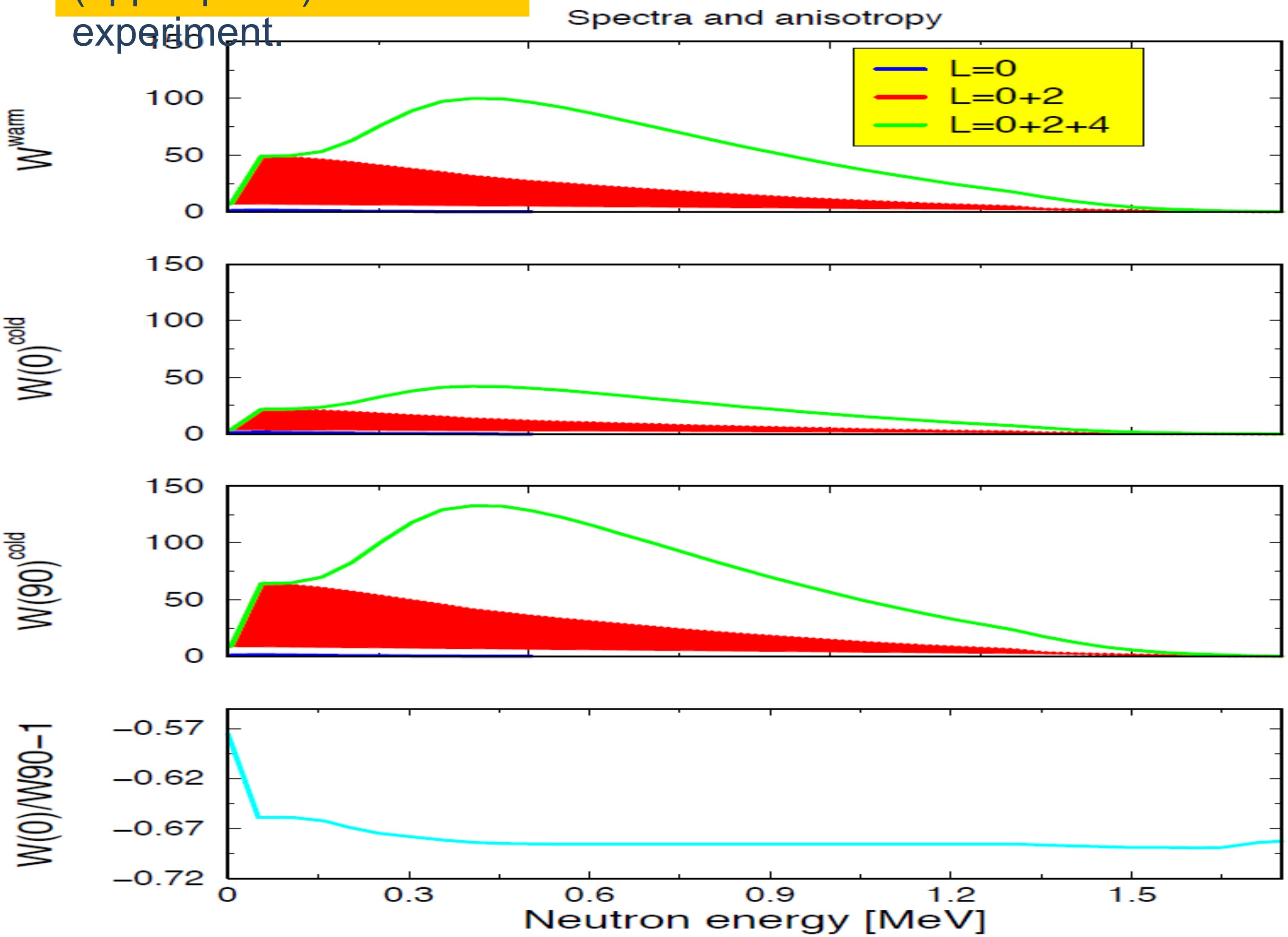
^{137}I



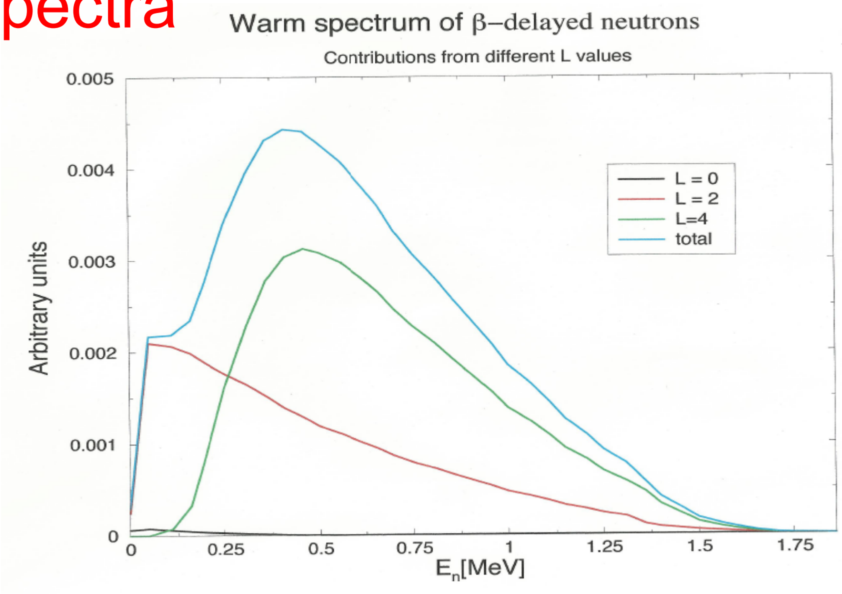
Compare predicted neutron spectrum (upper panel) with experiment.

^{137}I

L
A
T
E
R

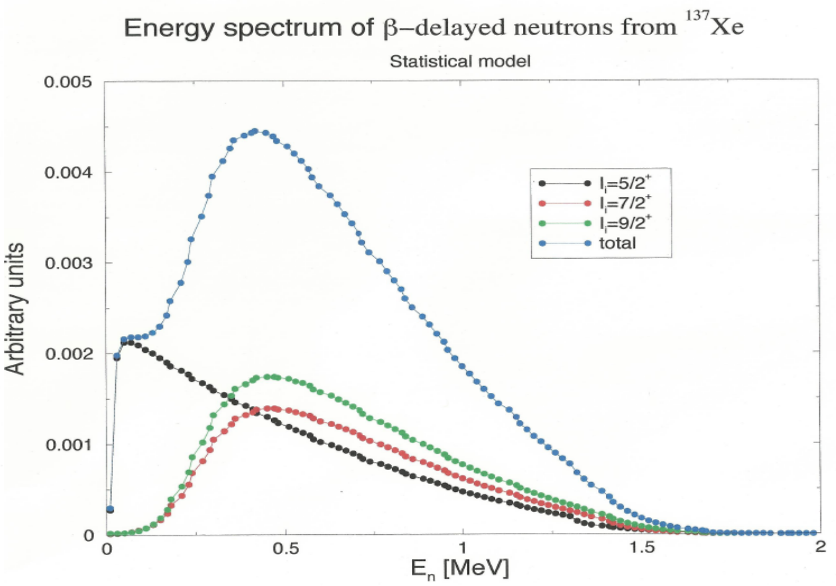


Warm and Cold 137I neutron model spectra



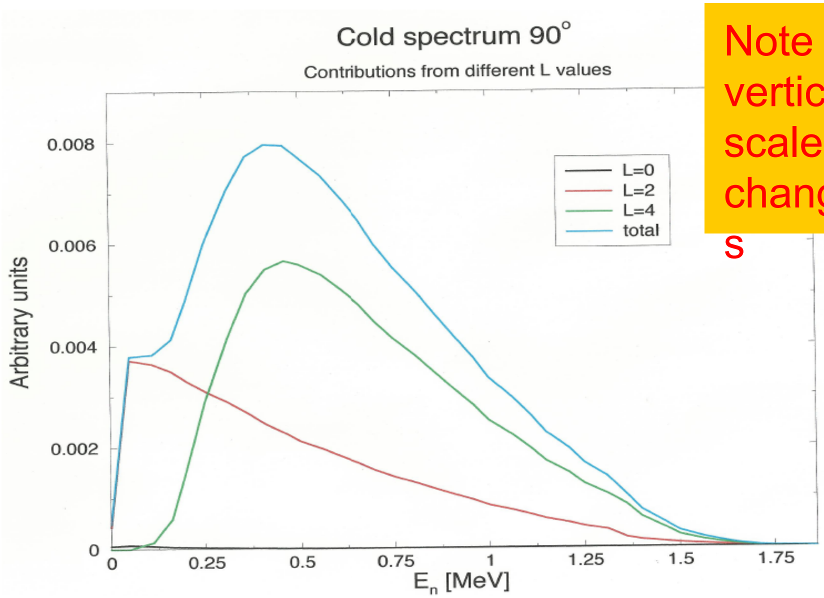
Warm spectrum of β–delayed neutrons

Contributions from different L values



Energy spectrum of β–delayed neutrons from ^{137}Xe

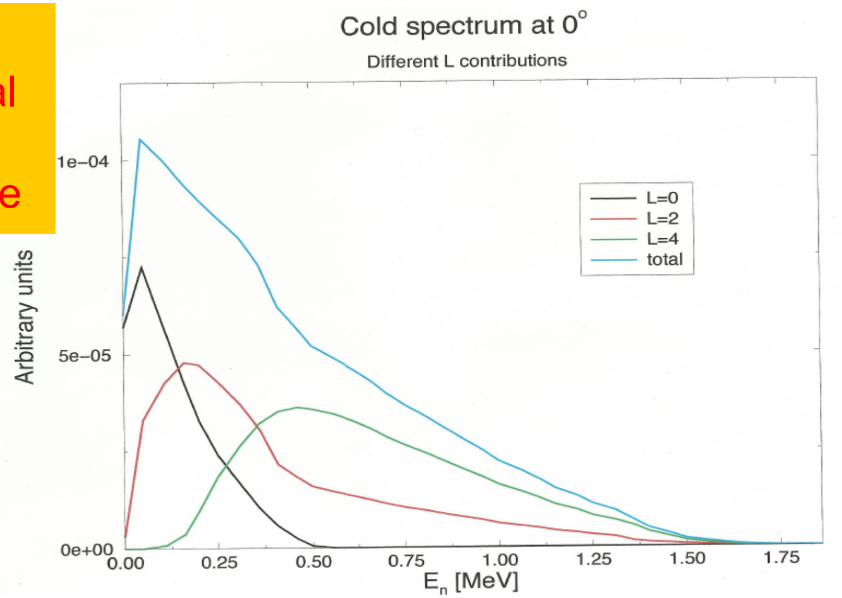
Statistical model



Cold spectrum 90°

Contributions from different L values

Note vertical scale changes



Cold spectrum at 0°

Different L contributions

An On-Line Nuclear Orientation Experiment.

Implant parent activity

Suitable implantation energy and beam strength.

Good lattice sites and tolerable radioactive heating.

Orient parent activity

Adequate hyperfine interaction, long enough life-time to cool.

Observe emissions

Primary implant, accumulated daughter activities, all emissions potentially useful. Simultaneous observation of e.g particles, gammas and (beta's).

Vary sample temperature and change axis of polarisation

Check symmetry and detector response, explore degree of orientation and quality of implantation

Delayed Neutron Emission from ^{137}I

S. Shalev* and G. Rudstam
The Swedish Research Council's Laboratory, Studsvik, Nyköping, Sweden
(Received 17 January 1972)

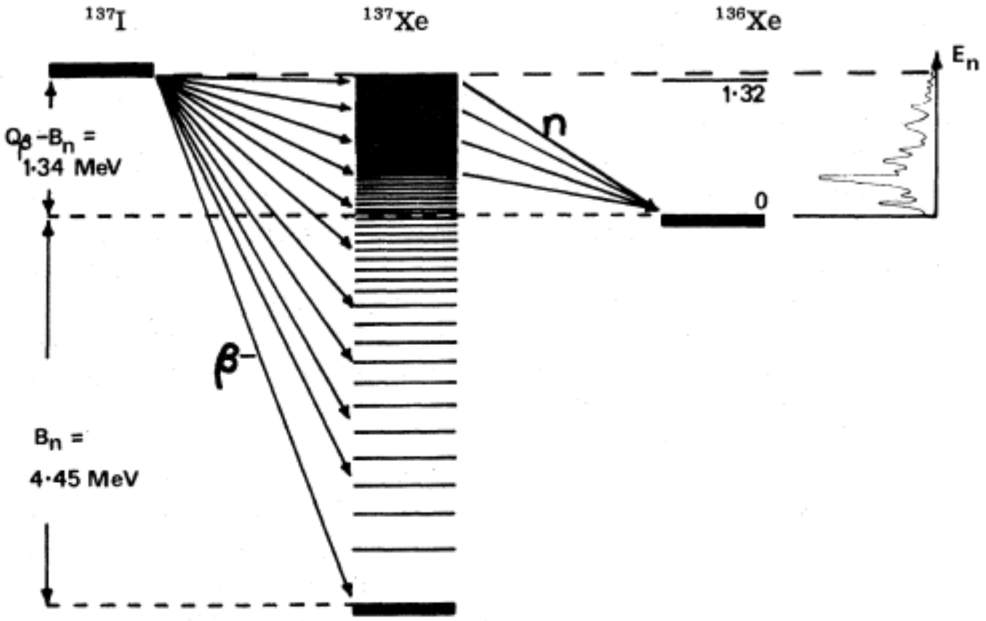
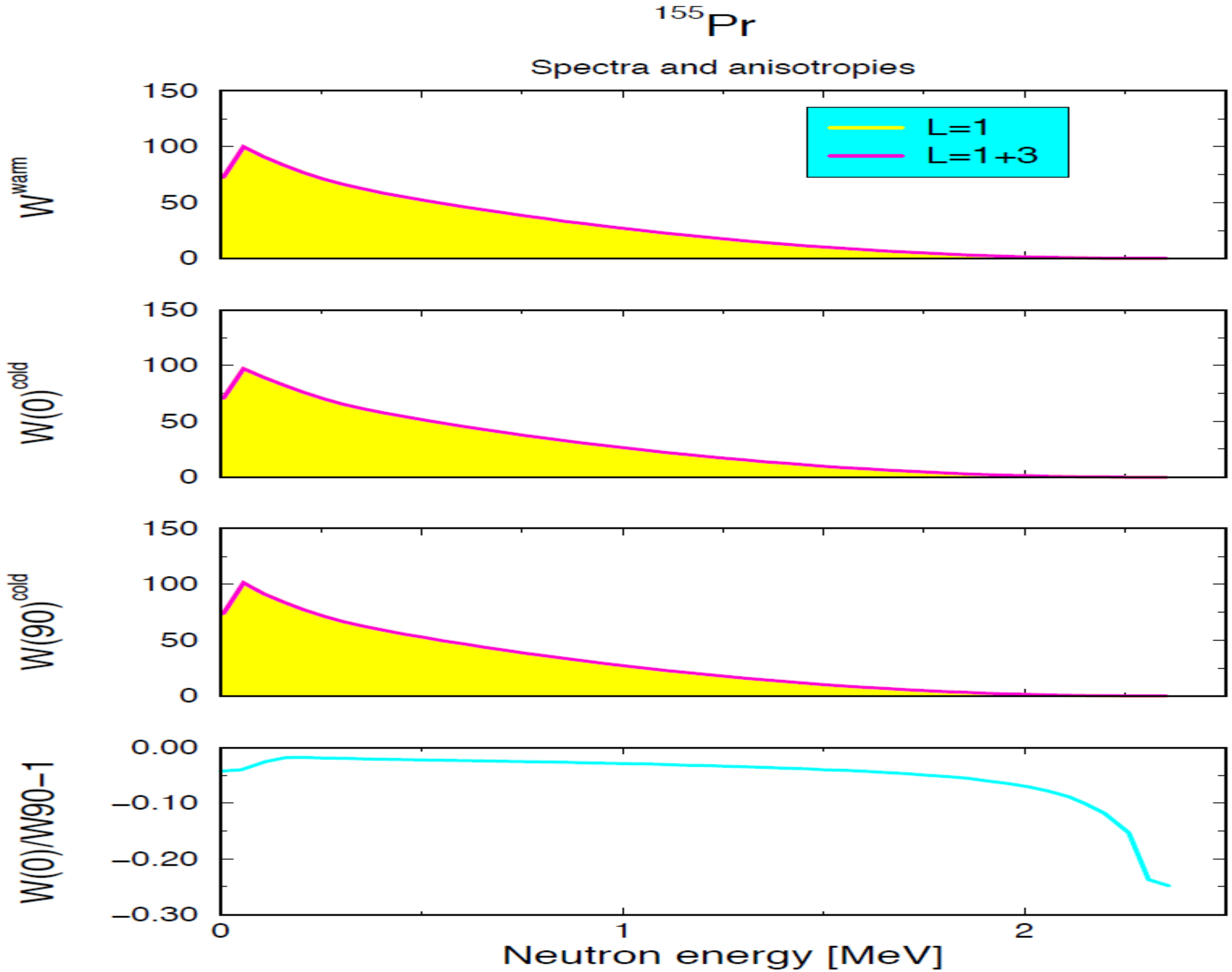


FIG. 2. Energy-level diagram for β-delayed neutron emission from ^{137}Xe.

Particle energies and excitation energy ranges

Beta-delayed neutrons

Precursor	Emitter	E* range MeV	Particle E range MeV	% n emission
^{87}Br	^{87}Kr	5.0 - 6.8	0 - 1.8	2.6 %
^{137}I	^{137}Xe	4.0 - 5.9	0 - 1.9	7. 0 %
^{138}I	^{138}Xe	3.9 - 7.8	0 - 3.9	5.5 %
^{139}I	^{139}Xe	3.6 - 6.8	0 - 3.2	9.9 %
^{141}Cs	^{141}Ba	3.6 - 5.2	0 - 1.6	0.044%


^{155}Pr
Spectra and anisotropies
L=1
L=1+3
W^{warm}
$W(0)^{cold}$
$W(90)^{cold}$
W(0)/W90−1
150
100
50
0
0.00
−0.10
−0.20
−0.30
0
1
2
Neutron energy [MeV]

Further ideas:

For the present experiments:

Coincidence with Daughter Gammas

The b-delayed measurements would clearly benefit from adding a coincidence condition with the gamma from excited states in the daughter.

Especially for b-delayed proton study it should be possible to add this condition without too drastic loss of count rate, given the high efficiency of proton detection.

For the broader future

Give serious consideration to the introduction of a millikelvin cryogenic target in an array set up.

Whilst this is clearly an engineering project of some magnitude, the potential for study of processes with samples having strong and calculable polarisation adds serious opportunities to the physics we can attempt.

Conclusions

These ideas constitute **a new range of experiments**

Angular Distribution studies from oriented samples

of

1. beta-delayed p- and n-emission

open a new window on

3 Dimensional Quantum Tunnelling

and

its dependence upon angular momentum and nuclear deformation.

Density of states as a function of energy, spin and deformation.

Angular distribution experiment sensitive to *differential population* of the possible spin states fed by beta decay.

What determines this?

A. Beta strength function - GT allowed J = J’ +/- 1,J’

B. Density of states $\rho(E,J)$ in emitter

Fermi back-shifted model:

break pairs of nucleons

treat these as an unpaired fermion ‘gas’

spin of excitation subject to gaussian distribution.

Parameters: δ, pairing strength parameter and

a, a parameter of the gaussian width subject to shell corrections.

Spin of level: model gives projection $J_z = M_J$, $\rho(E,M)$

$\rho(E,J) = \rho(E,M = J) - \rho(E,M = J-1)$

IMPORTANCE OF BETA DELAYED NEUTRON EMITTERS

Nuclear power safety:

Some fission products undergo Beta Delayed Neutron Emission which is essential to control the reaction.

Nuclear Energy Agency (NEA) highlights the importance of experimental measurements and data evaluation of delayed neutron emission in its working group 6 “Delayed neutron data” [WPEC-SG6].

Rapid neutron-capture process of stellar nucleosynthesis:

Stellar abundances: delayed neutron emission probability (P_n) of r-process isobaric nuclei define the decay path towards stability during freeze-out, and provide a source of late time neutrons.

Nuclear Structure:

Additionally the measured half-lives ($T_{1/2}$) and β-delayed neutron-emission probabilities (P_n) can be used as first probes of the structure of the β-decay daughter nuclei in this mass region.

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Example of oriented source experiments: ^{87}Br