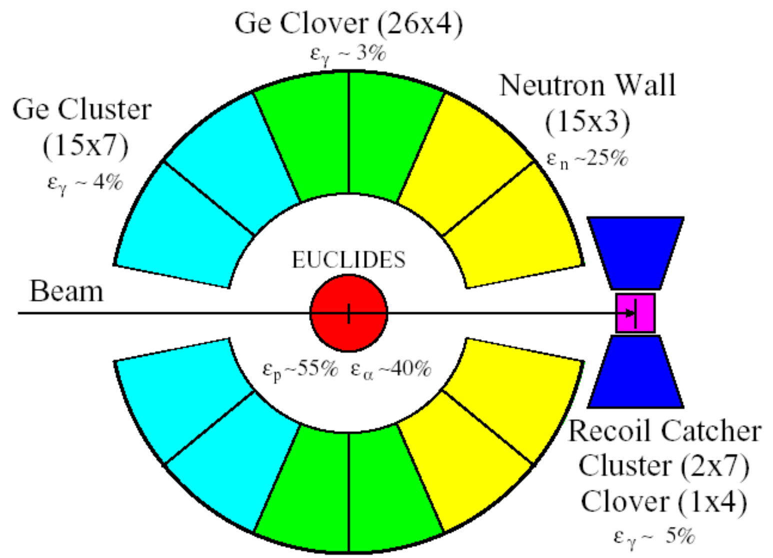
Neutron detectors Arrays

- Low Energy Neutrons: **NWall** (Euroball Ancillary)
  [Low Energy Heavy Ions Reactions: ~ 5-10 MeV/A]
- High Energy Neutrons: **LAND** (GSI)
  [Relativistic Heavy Ions Reactions: up to ~ 1 GeV/A]

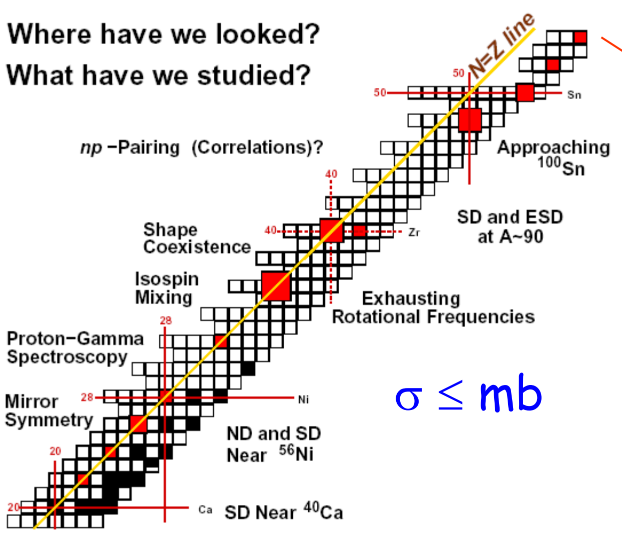
References:

- Skeppstedt et al., NIMA421(1999)531
- Th. Blaich et al., NIMA314(1992)136

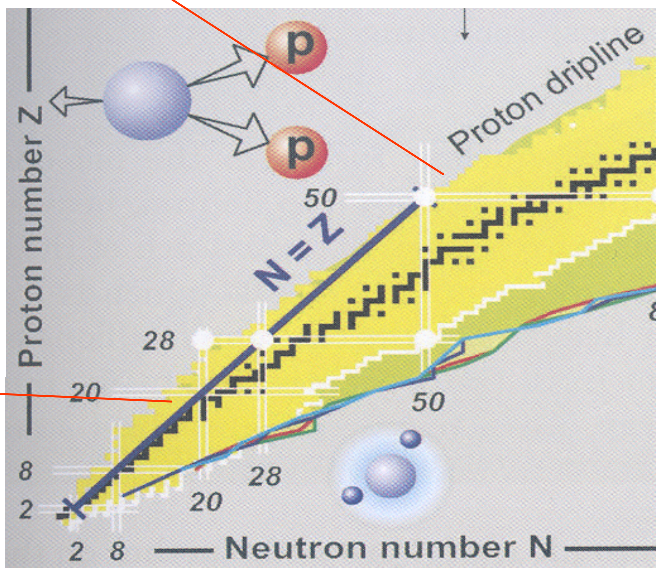
Study of exotic neutron deficient nuclei



the most exotic neutron deficient nuclei are produced by ***fusion evaporation*** reactions involving **1 or more n evaporation**



$\sigma \leq$ mb



Need for *selective devices*:

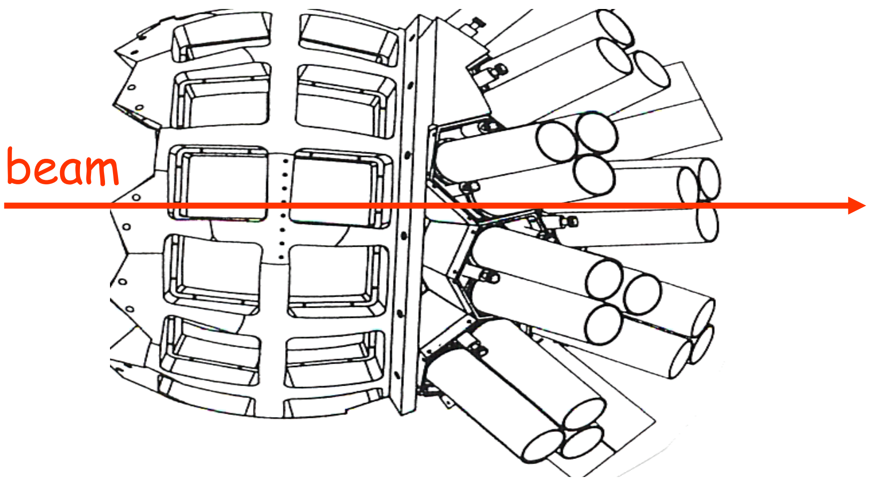
- α and p detectors (Coulomb barrier is low, $\Rightarrow$ α and p are easily emitted)
- n detectors
- isomer detection (~μs)

any *additional neutron evaporation* reduces the cross sections by factor 50 to 100

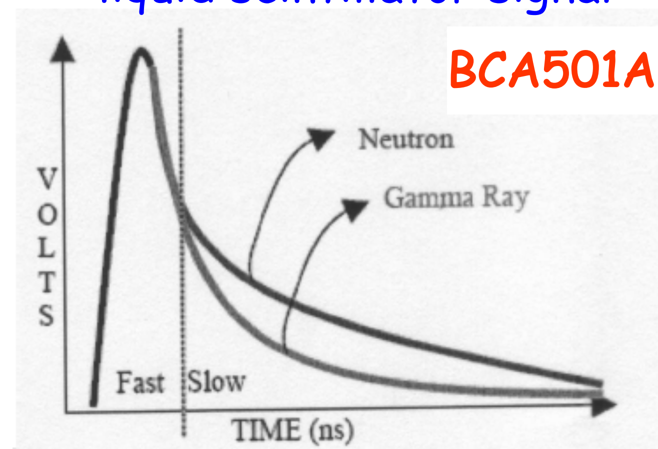
Neutron Wall

Skeppstedt et al., NIMA421(1999)531

(50 detectors ~ 1π)



liquid scintillator signal



τ = 3.16, 32.3 & 270 ns

n & γ vary proportion of first two decay times

- 50 liquid Scintillators BC501A
- total Volume ~ 151 litri
- intrinsic efficiency for n: ε_I ~ 50%
- total efficiency: ε_n ~ 25-30%
- high granularity (to limit count rate/detector)
- minimum cross talk from n scattering
- distance focal point 510 mm
- minimum interference with EUROBALL

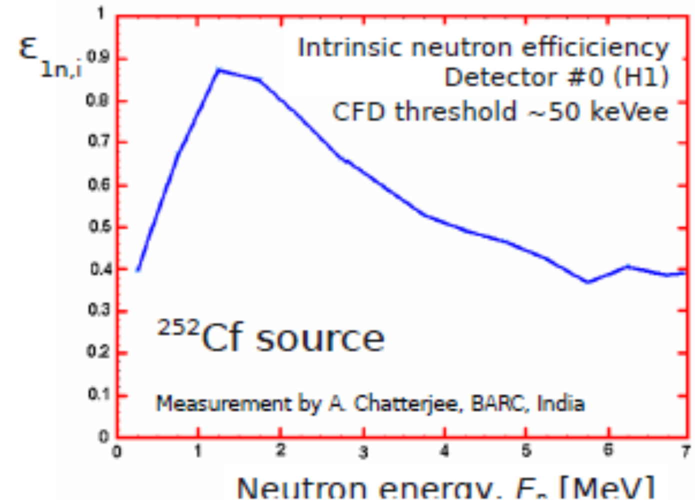
Basic Principle:

- elastic scattering n – p (of the liquid scintillator)
- separation between n and γ with TOF + pulse shape (ZCO time)

Efficiency and energy resolution

Efficiency

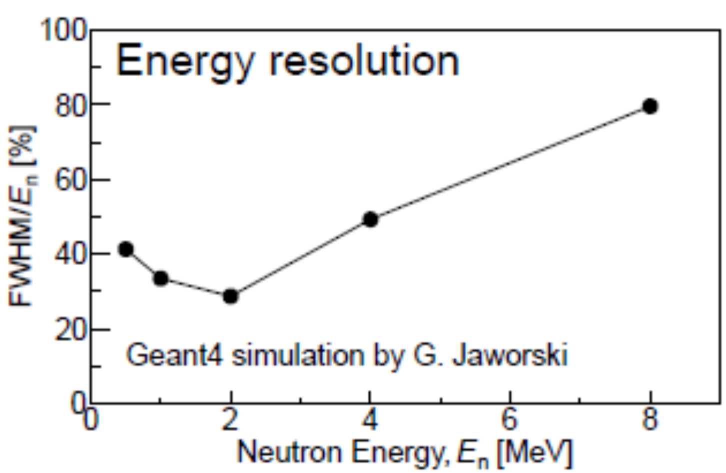
Intrinsic neutron efficiency at $E_n = 2$ MeV: $\varepsilon_{1n,i} \simeq 80\%$



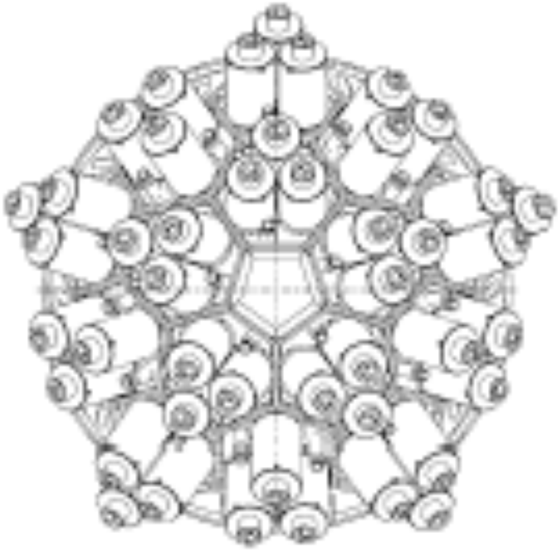
Total Neutron Wall efficiency for symmetric fusion evaporation reactions:

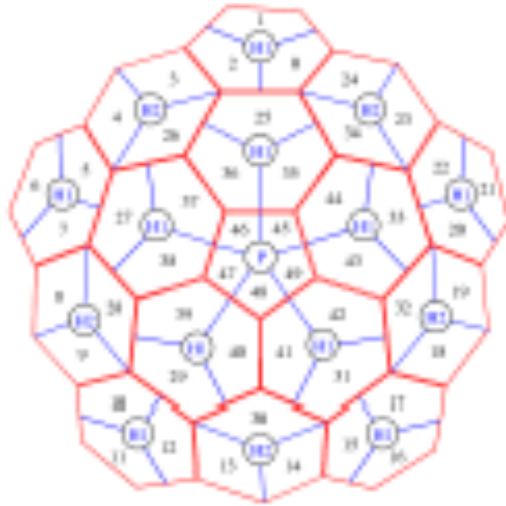
- One-neutron efficiency: $\varepsilon_{1n} = 20\text{-}25\%$
- Two-neutron efficiency: $\varepsilon_{2n} = 1\text{-}3\%$

Energy resolution (Time-of-Flight)



- Distance source to detector front face: 51 cm
- Thickness of detectors: 14.8 cm
- Time resolution of detectors: FWHM = 1.5 ns

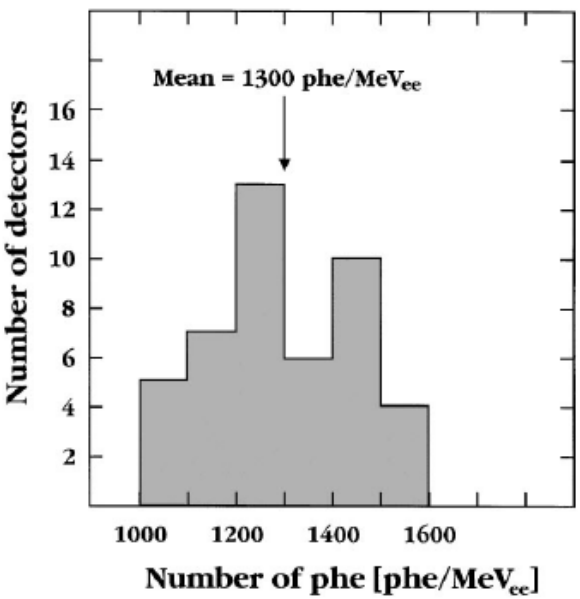




- 3 rings of 15 exagonal units
  + 1 central pentagon

- each segment hermetically separated
- liquid BC501A: best n-γ separation

Photo-electron yields

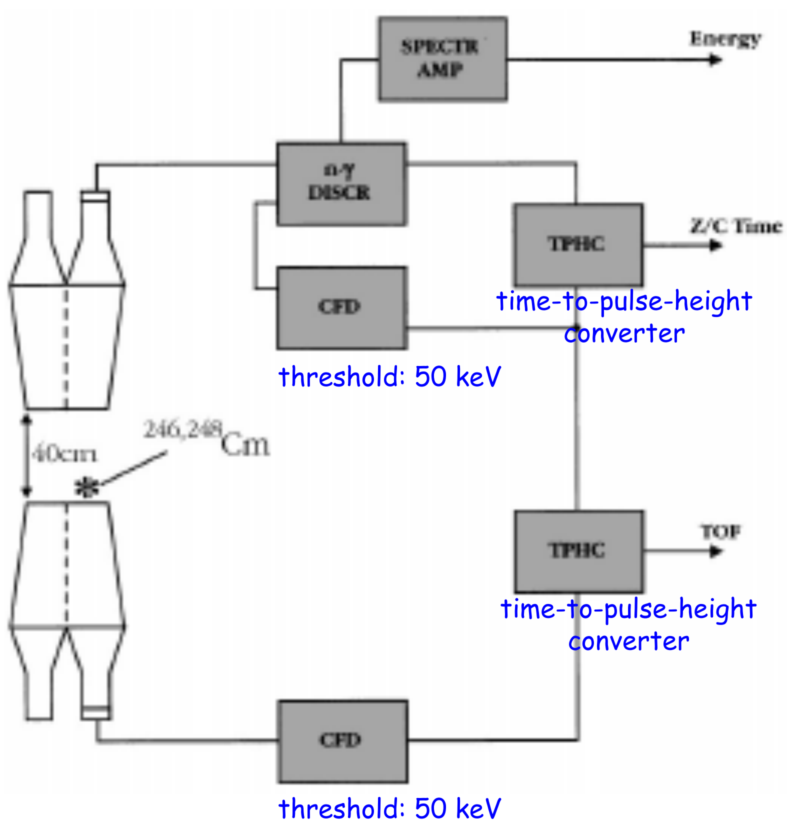


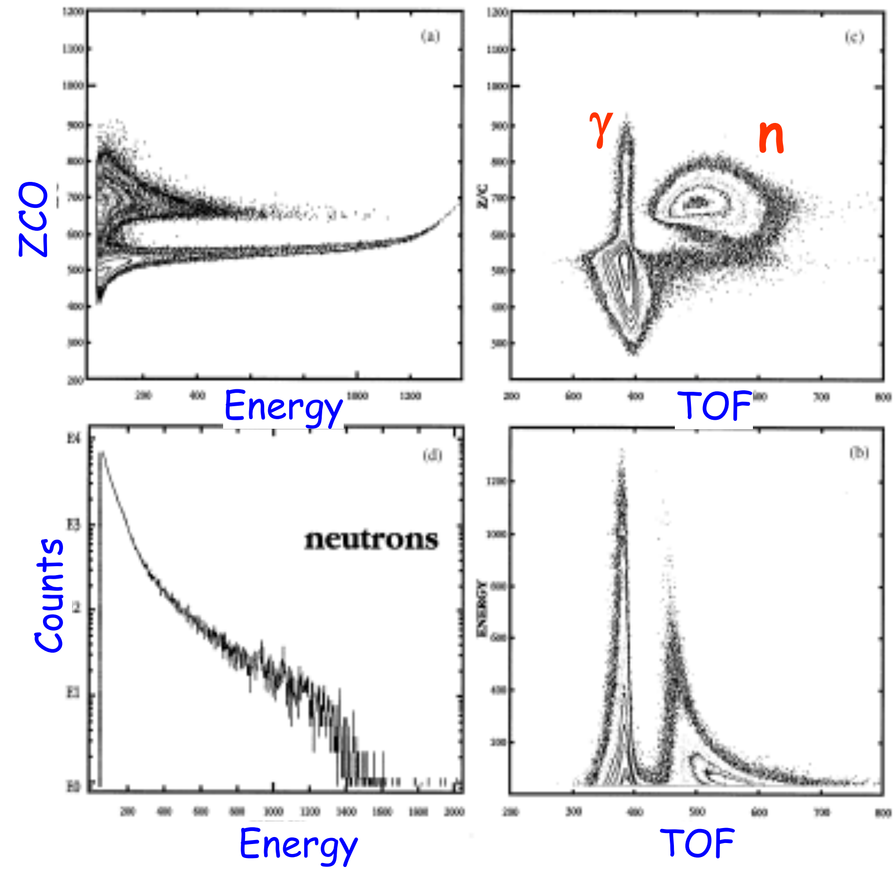
<u>high value</u> depending on:
- pyramidal shape of cells
- rather small cell volume

standard value is
~ 1070 phe/MeV

n-γ discrimination:
TOF + ZCO

<u>*Calibration with ^{246,248}Cm source*</u>:
emission of n with energy similar to n from fusion-evaporation





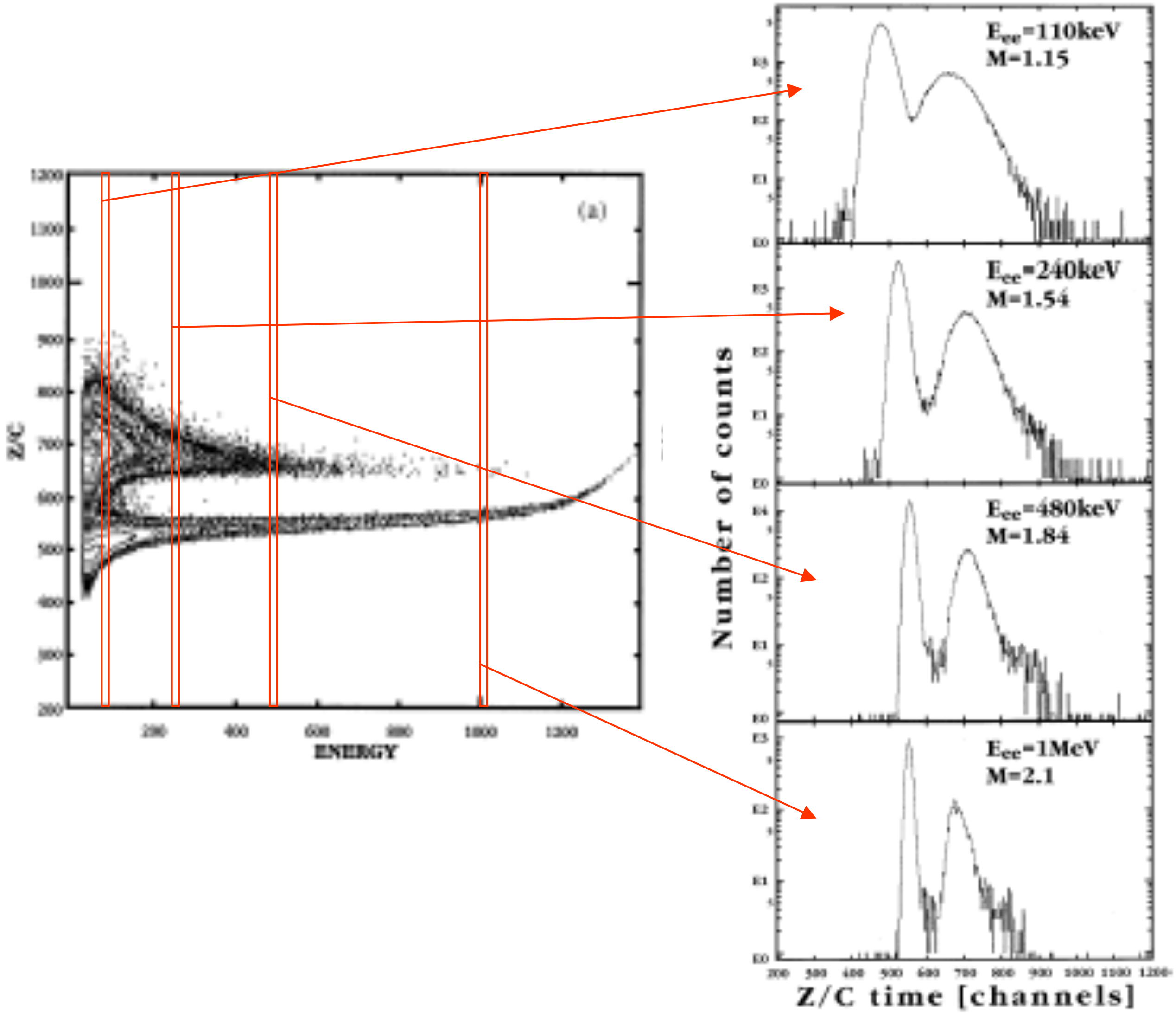
neutrons give a <u>*delayed ZCO*</u> time signal:

- n interact by elastic scattering with p
- p slow down in the liquid producing an intense slow component of scintillator light

γ's produce a <u>*faster ZCO*</u> time signal:

- γ interact in the liquid producing recoiling electrons (less intense slow component)

Zero-Cross-Over



41 volume array

Energy (keV)	EUROBALL	DEMON[a]
100		1.09
110	1.15	
240	1.54	
300		1.65
480	1.84	
1	2.1	2.05

Figure of merit

$$M_{xy} = \frac{|\overline{P}_x - \overline{P}_y|}{w_x + w_y}$$

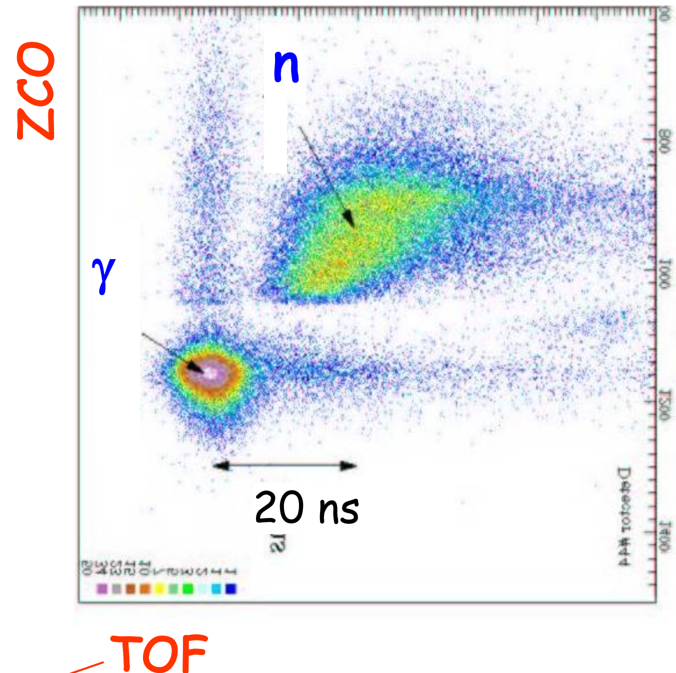
quality of particle identification

good n-γ separation down to at least E_n = 400 keV

Probability of mis-interpreting γ rays as neutrons: $\lesssim 10^{-3}$ (typical value).

in-beam measurements

^{58}Ni (220 MeV) + ^{56}Fe



trigger:

- neutron logic signals from n-detectors are OR-ed together and sent to EUROBALL trigger

⇒ *selection of events with at least 1 n*

external reference:

- Radio Frequency of pulsed beam (~ 3 MHz): $\Delta\tau$ = 5.3 ns
- OR of N-wall CFD signals (self-timing mode): $\Delta\tau$ = 2 ns

[disadvantage: if NO prompt γ are detected the time reference signal is given by a n
⇒ TOF can not be used for n-γ discrimination, ⇒ only ZCO (reduced discrimination)]

N-wall efficiency

intrinsic efficiency for n: $\varepsilon_I \sim 50\%$
total efficiency: $\varepsilon_n \sim 25\text{-}30\%$

$$\varepsilon_n = P_n(\Omega) \times \frac{\Omega}{4\pi} \times \frac{\varepsilon_I}{(1+\varepsilon_{n\gamma})}$$

kinematical focusing:

for typical reaction
$^{58}Ni + ^{50}Cr$ at 230 MeV

$$P_n(\Omega) = 2.54$$

double hit probability:

$$\varepsilon_{n\gamma} = 0.06$$

Array	Number of detectors	Solid angle	Probability of n–γ double hits[1]
OSIRIS [16]	16	2π	0.27
OSIRIS	7	1π	0.36
NORDBALL [10]	15	1π	0.24
EUROBALL	50	1π	0.06

very low due to high granularity

Severe problem:

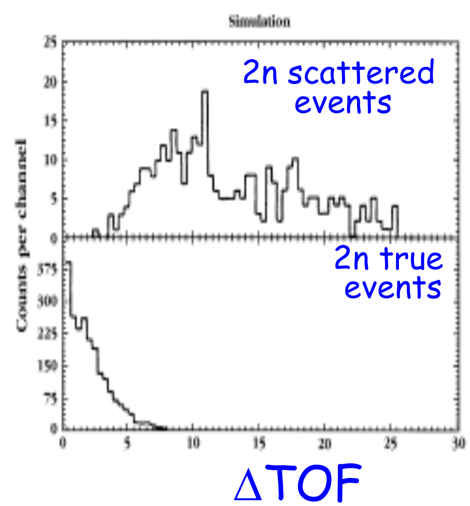
scattering probability $\varepsilon_{2n} \sim 7\%$

⇒ scattered neutrons simulate *higher multiplicity* n-events

⇒ wrong identification of neutron deficient exit channels

2 possible solutions:

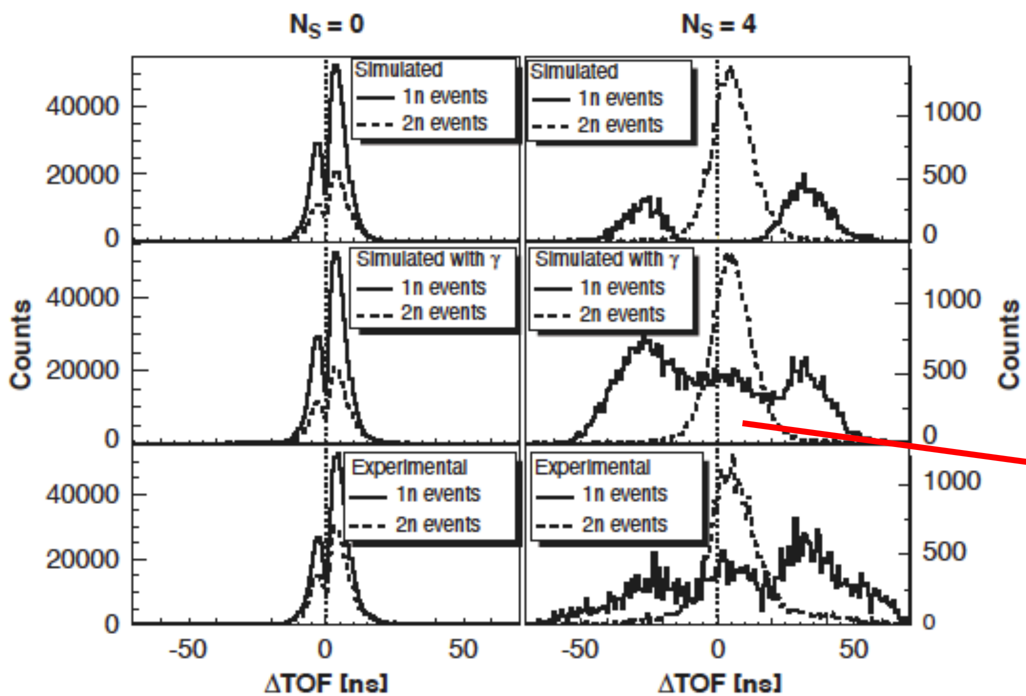
1. rejection of adjacent hits
   ⇒ 17% reduction of ε_{2n}
2. gate on ΔTOF time difference between neutron hits
   ⇒ reduction of ε_{2n} by a factor of 125



Neutron scattering

Probability of 1 neutron giving a signal in 2 or more detectors $\simeq 10\%$.

Serious problem in searches for weakly populated $\geq$ 2n reaction channels: scattered neutrons from much stronger 1n channels are mis-identified as being due to 2n, 3n, . . . channels.



J. Ljungvall et al. NIM A528 (2004) 741

Methods to detect scattered neutrons:

- Neighbor rejection.
- ΔToF. J.Cederkäll et al. NIM A385 (1997) 166.

Small amounts of γ rays mis-identified as neutrons reduces dramatically the quality of the neutron scattering reduction

N_S = n. adjacent detectors

Experimental campaigns and recent results

Experiments performed with EUROBALL at LNL (1998) and at IReS (2001-2003), and with EXOGAM at GANIL (2005-).

Combined with charged particle detector arrays (EUCLIDES, DIAMANT, CUP, . . .).

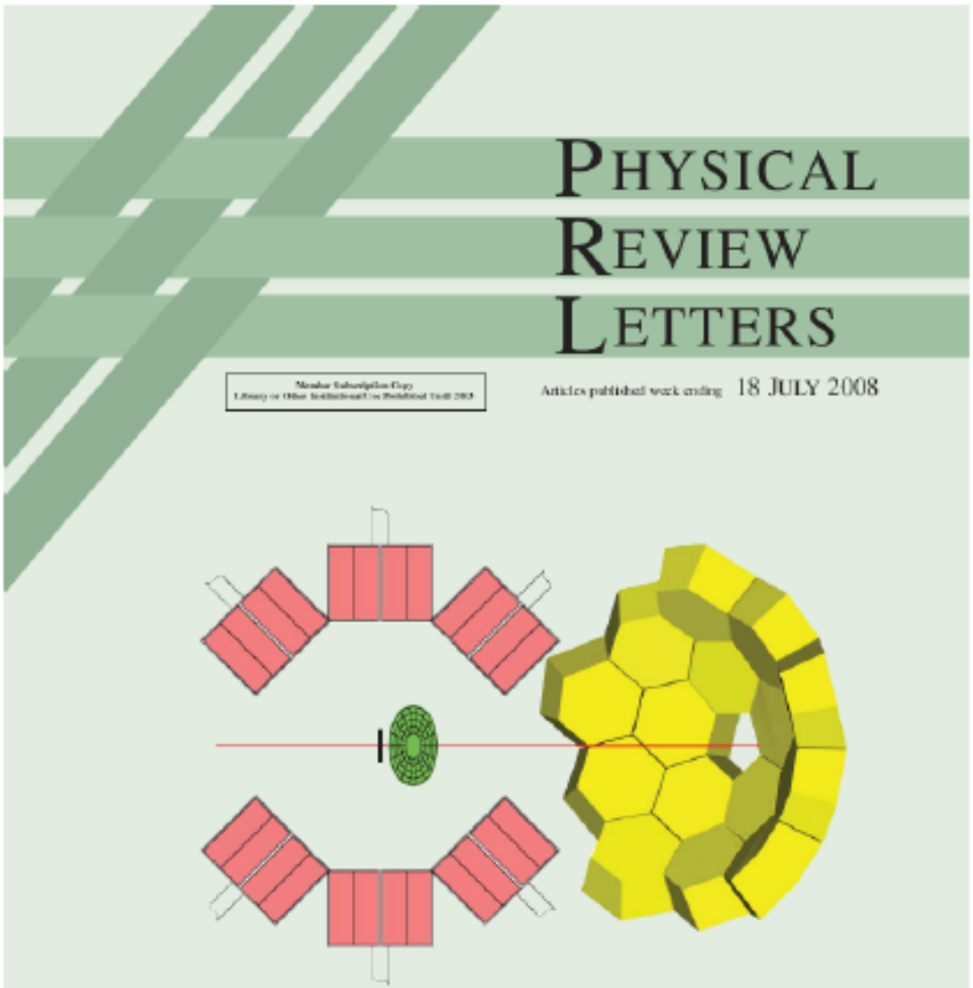
GANIL home base since 2005.

Four experimental campaigns at GANIL with EXOGAM + DIAMANT and other detectors (2005-2009).

Next campaign (two experiments): GANIL 2012.

First experiments with radioactive beams

Two experiments with ^{6}He and ^{8}He beams at SPIRAL 2005-2006



1n and 2n transfer with the Borromean nucleus ^{6}He near the Coulomb barrier,
A. Chatterjee, et al.,
Phys. Rev. Lett. 101 (2008) 032701

Neutron correlations in ^{6}He viewed through nuclear break-up,
M. Assie et al.,
Eur. Phys. J. A 42 (2009) 441

Reactions with the double-Borromean nucleus ^{8}He,
A. Lemasson et al.,
Phys. Rev. C 82 (2010) 044627

Pair and single neutron transfer with Borromean ^{8}He,
A. Lemasson et al.,
Phys. Lett. B 697 (2011) 454

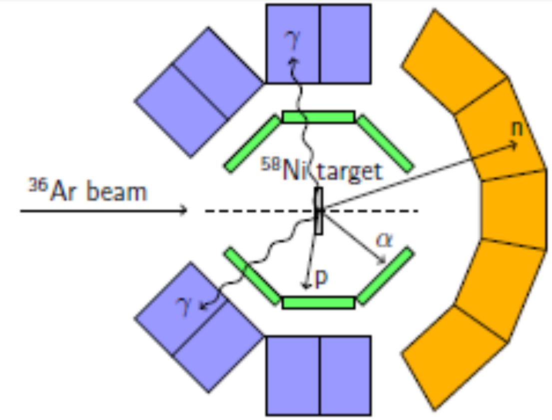
^{92}Pd experiment at GANIL

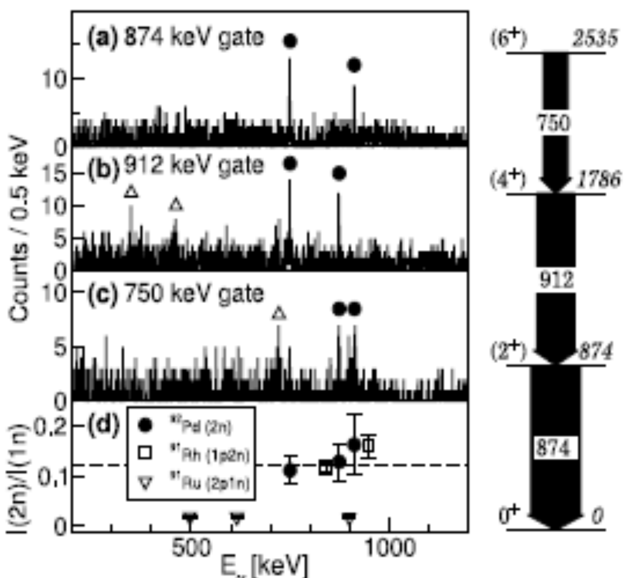
Experiment at GANIL (2009)

EXOGAM + DIAMANT + Neutron Wall

^{36}Ar (111 MeV) + ^{58}Ni $\rightarrow$ ^{92}Pd + 2 n

Cross section: $\sigma(^{92}\text{Pd}) \simeq 1\mu\text{b}$, $\sigma(\text{fusion}) \simeq 0.2$ b,

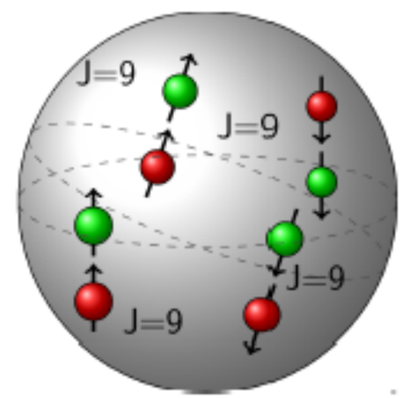




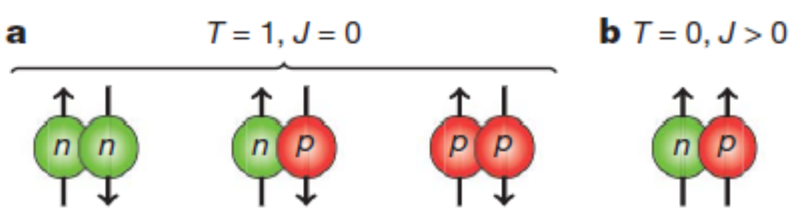
First observation of excited states in ^{92}Pd

Approximately equidistant energy levels

Valence neutrons and protons couple pairwise to $S = 1$, $T = 0$ in the ground and first excited states of ^{92}Pd



B. Cederwall, F. Ghazi Moradi et al., Nature 469 (2011) 68



Nuclear Superfluidity

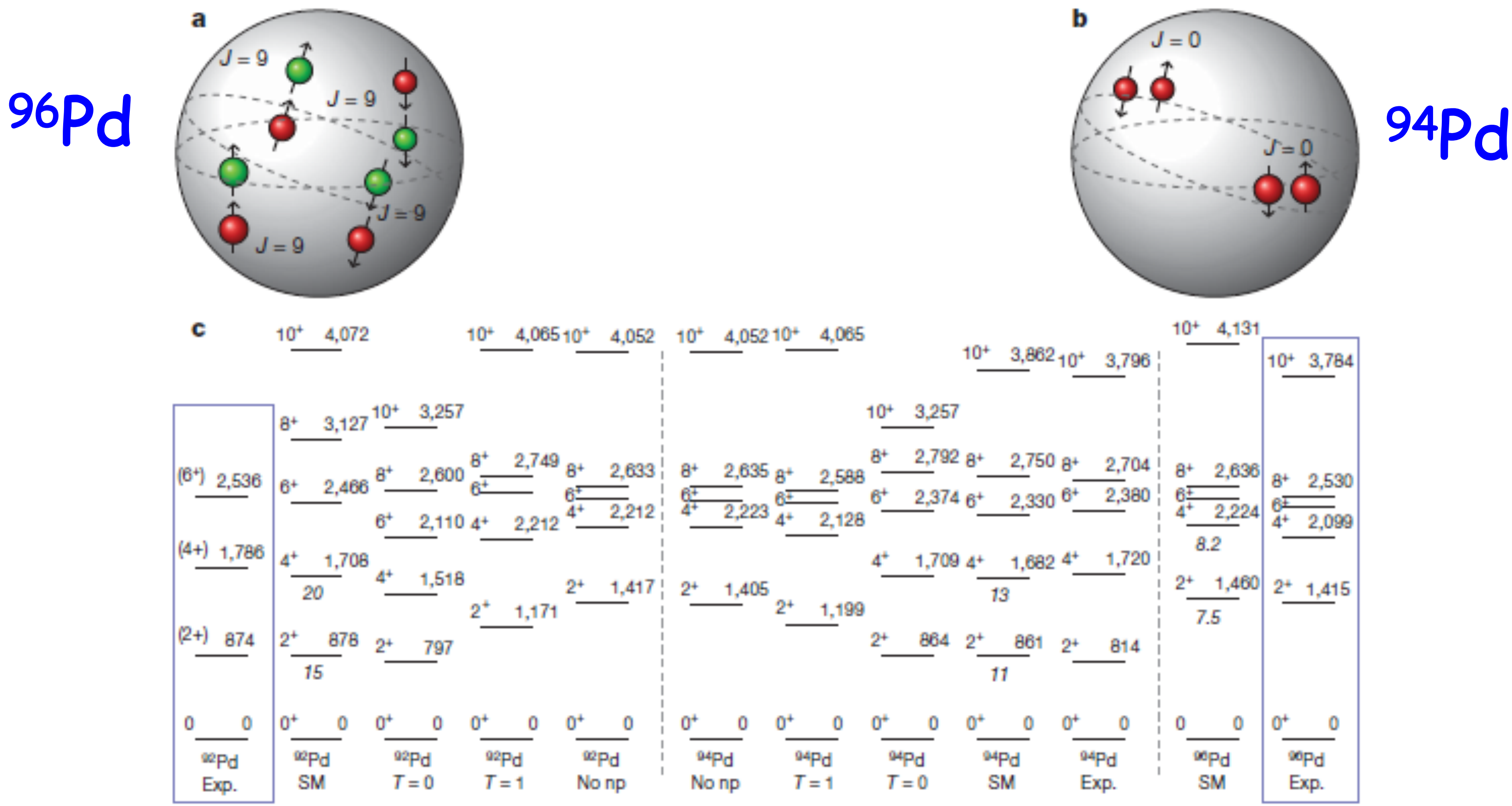


Figure 4 | Illustration of the predicted ground-state wavefunctions of ^{92}Pd and ^{96}Pd, and comparison of calculated and experimental level energies in ^{92}Pd, ^{94}Pd and ^{96}Pd. a, Schematic illustration of the structure of the ground-state wavefunction of ^{92}Pd in the spin-aligned np paired phase (green, neutron hole; red, proton hole). The main component of the wavefunction can be viewed as a system of deuteron-like np hole pairs with respect to the $^{100}_{50}Sn_{50}$ 'core', spinning around the centre of the nucleus. **b**, As **a** but for ^{96}Pd in the normal pairing phase. **c**, Experimental level energies (keV) in the ground-state bands of ^{92}Pd (present work) and ^{94,96}Pd (refs 12, 13) compared with shell model predictions. Calculated $B(E2: 2^+ \rightarrow 0^+)$ and $B(E2: 4^+ \rightarrow 2^+)$ values (Weisskopf units) are also shown in italics below the corresponding initial levels. Text at bottom of each set of levels shows nuclide and gives further details. The calculated spectra for ^{92,94}Pd include, in addition to full neutron–proton interactions (SM), also results for pure $T = 0$ and pure $T = 1$ neutron–proton interactions. The results obtained without residual neutron-proton interactions (no np: that is, normal seniority coupling involving only isovector, $T = 1$, nn and pp pairing), are also shown for ^{92,94}Pd. The vertical dashed lines separate information for different nuclides. Blue boxes highlight the experimental data for ^{92}Pd and ^{96}Pd, emphasizing their different structures.

LAND
(Large Area Neutron Detector)

multilayer structure of
passive counters & active (plastic) scintillators

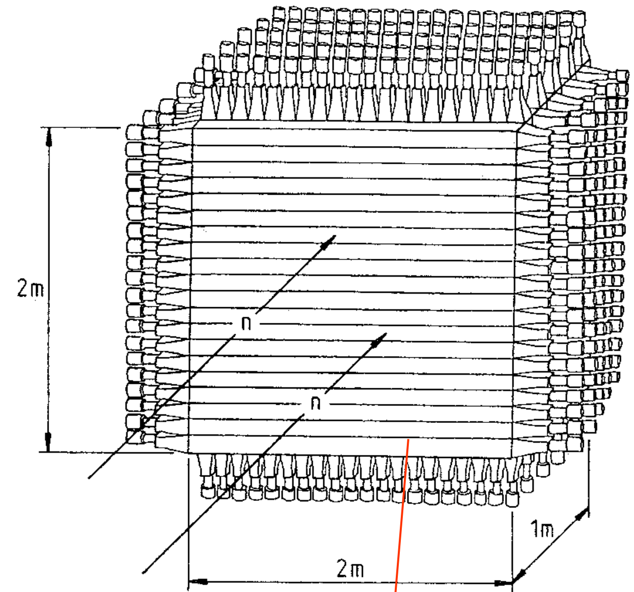
detection of neutrons from near-relativistc heavy ions:

TOF measurements with
good position and time resolution

- neutron energy up to $T_n \sim 1$ GeV
- energy resolution $\Delta T_n / T_n \sim 5.3$ %
- efficiency $\varepsilon \sim 1$

- large front area 2m x 2m
- depth 1 m

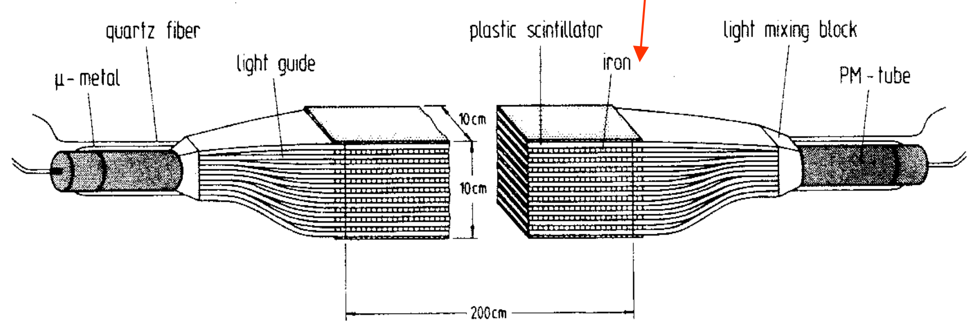
- high ganularity: 200 modules + 40 charged particle vetos



for high energetic neutrons
interaction length in scintillator materials
is large: $\lambda \sim 80$ cm

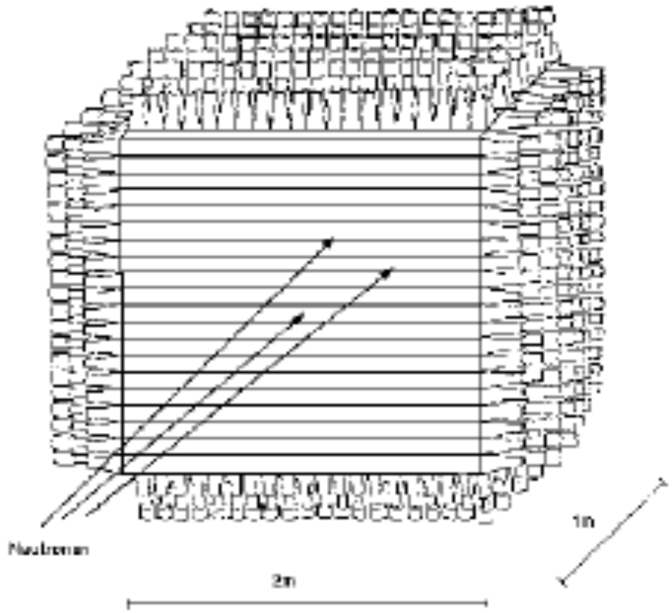
⇒ use of ***iron*** as ***passive converter material***

increses efficiency by factor 2.4



single module (sandwich structure)
5mm iron/5mm scintillator

Neutron Walls



LAND-GSI

NSCL-neutron Wall

Neutron unbound final states

Graded scintillator/radiator .. ~ 4 m^2 x 1m

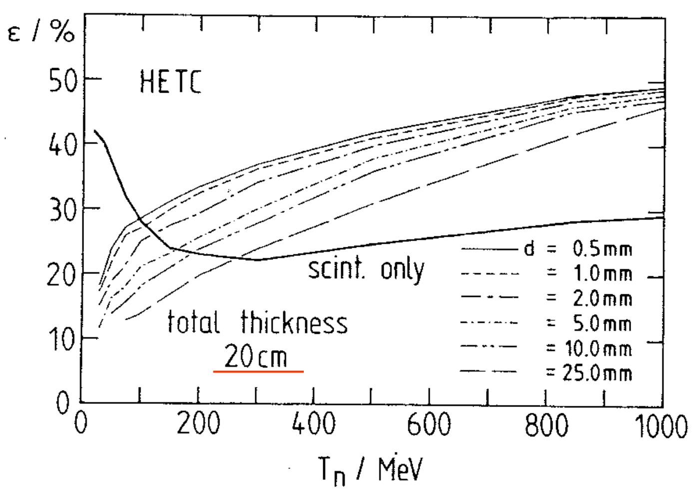
ToF .. E_n ~ 50 – 400 MeV .. Flight path ~50 m

Costs scaled from existing arrays: 2 M$

MonteCarlo simulation for final detector design

- *efficiency versus layer thickness*

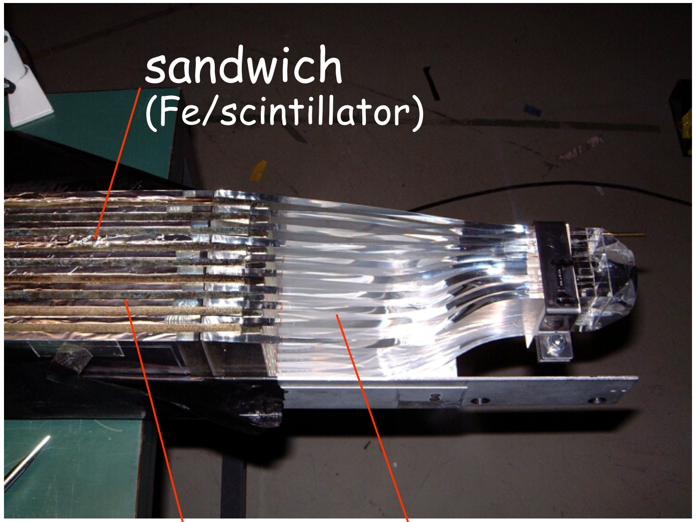
iron/scintillator structure
d(Fe) = d(scintillator)

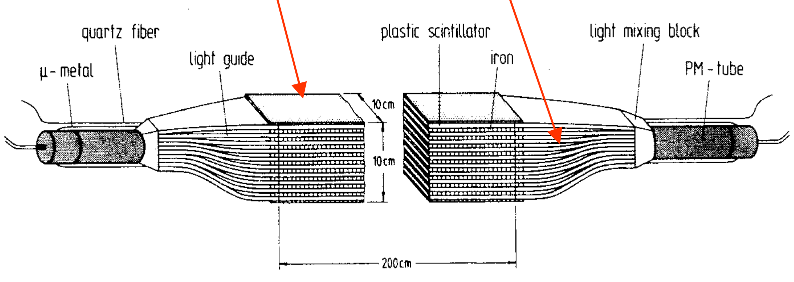


efficiency increases
as the layers becomes thinner

d = 5 mm

good compromise between
thickness, stability and cost





Light produced in a paddle is collected by light guides at *both ends*:

- position of interaction is determined by the difference in arrival time of the two signals;
- mean time gives TOF

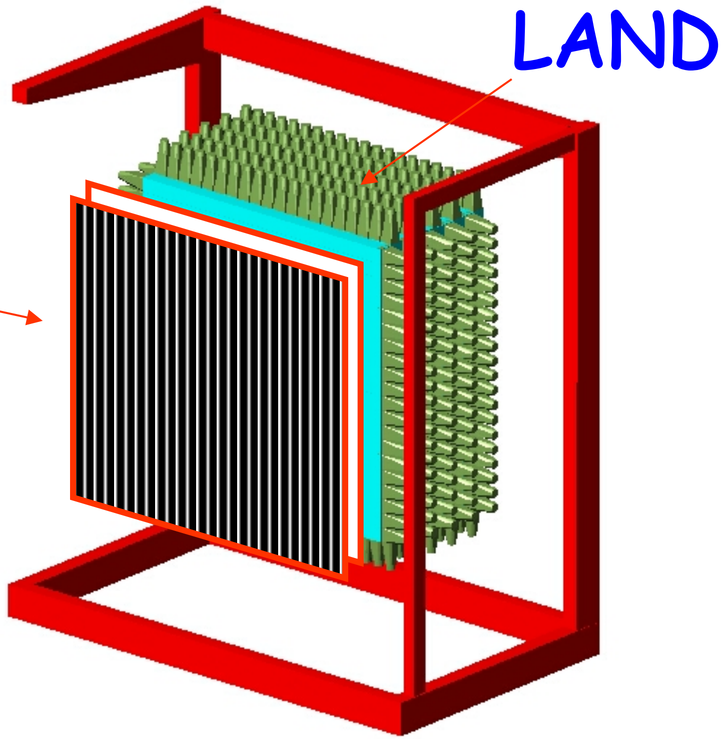
Charged particle VETO detector

is placed in front of LAND:

- 2 crossed layers of 20 scintillator strips matching the neutron paddle size:

  200 cm x 10 cm x 0.5 cm

- light read out at both ends gives position & TOF

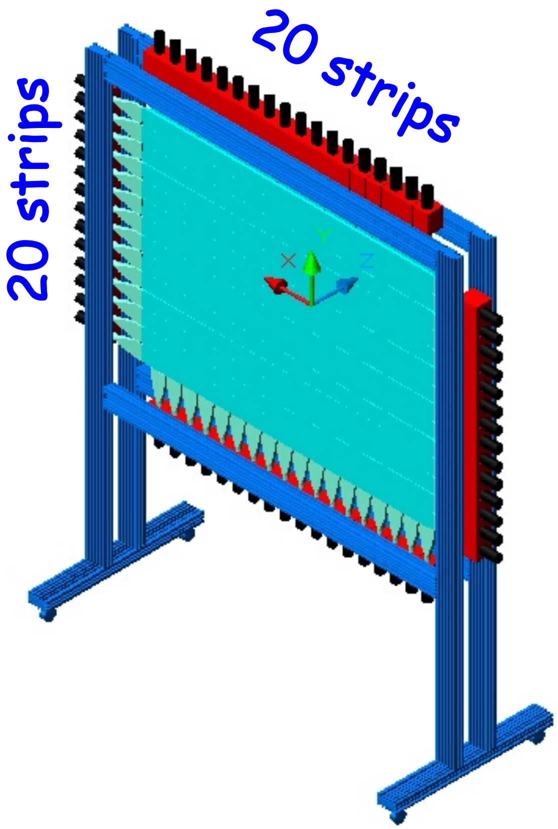


By-product:

VETO detector allows to identify charged particles via ΔE-TOF

⇒ Direct comparison between ***neutrons*** and ***charged particles*** from heavy-ions collisions under same conditions

LAND TOF Veto detectors



2 crossed layers of *20 scintillator strips* matching the neutron paddle size:

200 cm x 10 cm x 0.5 cm

Position & Energy Calibration

1. ***Laser system (pulsed N2 laser):***

   NOT fully reliable

   (problems with light collection)

2. ***Cosmic radiation:***

   - **hard component**

     (97% muons of <E> = 2 GeV)

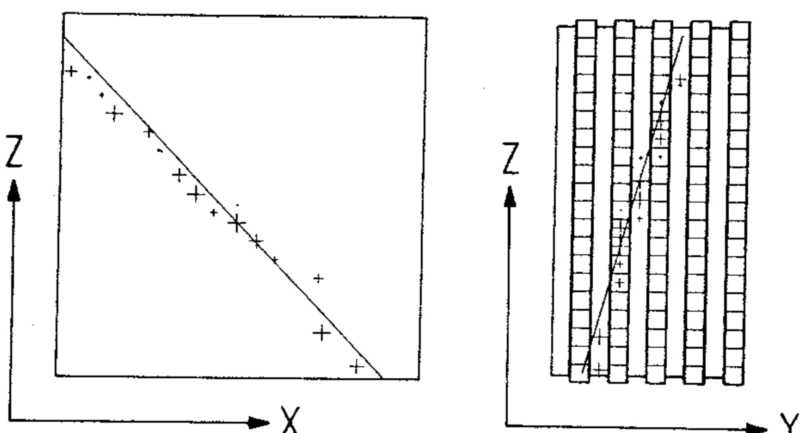
     penetrate concrete ceiling of the cave and traverse LAND detector

   - **incident flux ~ 600 Hz**

     ⇒ in short time LAND is fully scanned

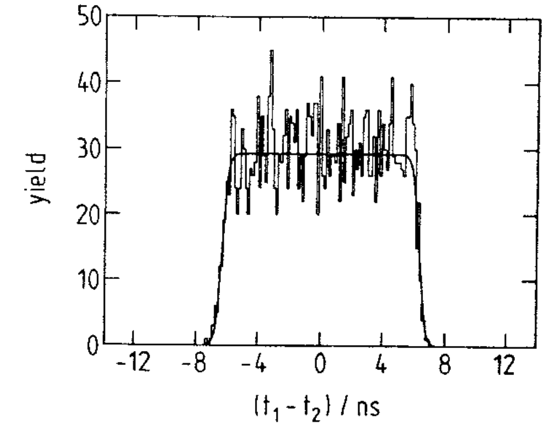
   - **trigger:** ≥ 5 paddles in coincidence

     ($\langle M \rangle = 12$, $M_{max} = 20$)



position calibration (individual paddle)

- **position of light production** from time difference of 2 PMT's signals



spectra show:

- *rectangular shape* folded by Gaussian (due to finite position resolution)
- *width* determined by paddle length & effective velocity of light in scintillator

$$v_{eff} = 15.7 \pm 03 \text{ cm/ns}$$

smaller than **c/n = 19 cm/ns** due to multiple reflections in 0.5 cm plastic sheets

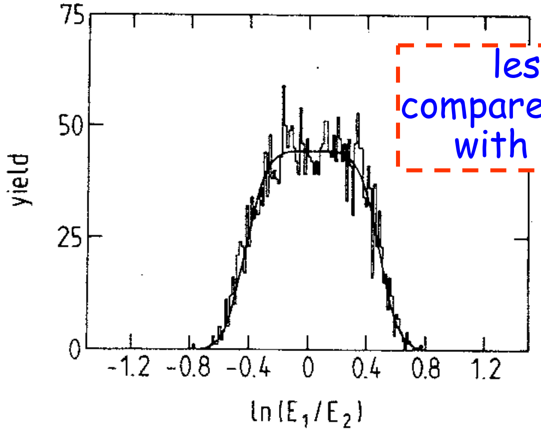
- **adjustment of spectra** to center position

⇓

fitting of tracks by straight line in 3D

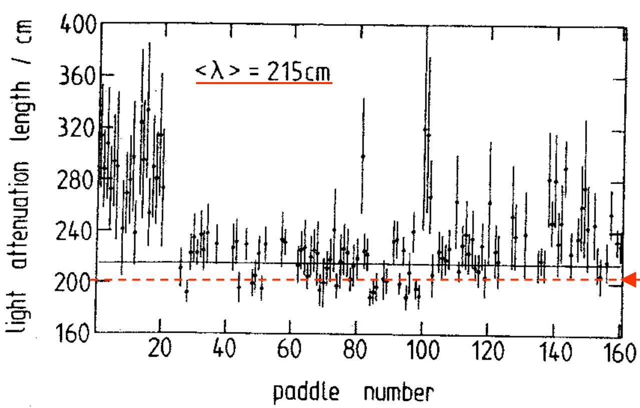
position calibration
from energy signals
(individual paddle)

- **position of light production** from energy signals of 2 PMT
- **rectangular shaped spectra** are shifted to center mean value at 0



less resolution compare to measurement with time signals !!!

- **spectrum width** gives a measure of absorbption length λ



paddle length

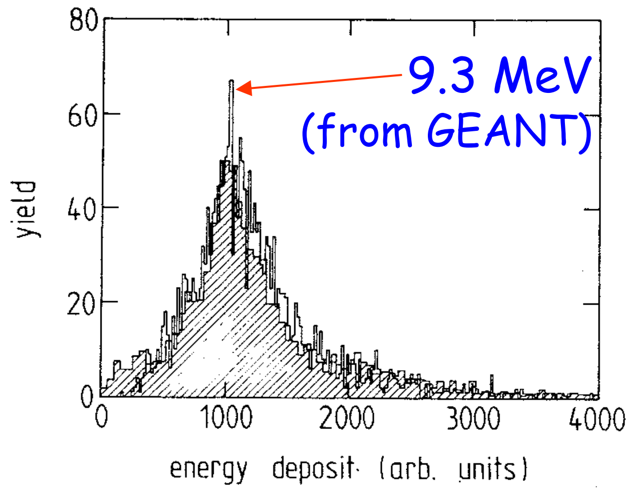
Absolute energy calibration
(full array LAND)

from energy E_0 deposited by a muon

$$E_0 = 2F\sqrt{E_1 E_2}\,\exp(L/2\lambda)$$

E_1, E_2 = energy signals from PMT's
L = paddle length = 2m
λ = absorption length (=2.15 m)
F = correction factor (PMT gains…)

energy deposited per unit length by cosmic radiation



the distribution centroid is the same for all paddles:
muons are minimum ionizing particles

For ***reliable calibration*** of LAND with ***cosmic radiation*** in position, time and energy :

➔ Total of 150000 cosmic events

➔ ~ 80 minutes

Th. Blaich et al., NIMA314(1992)136

Performances of LAND
(test experiment with tagged neutrons)

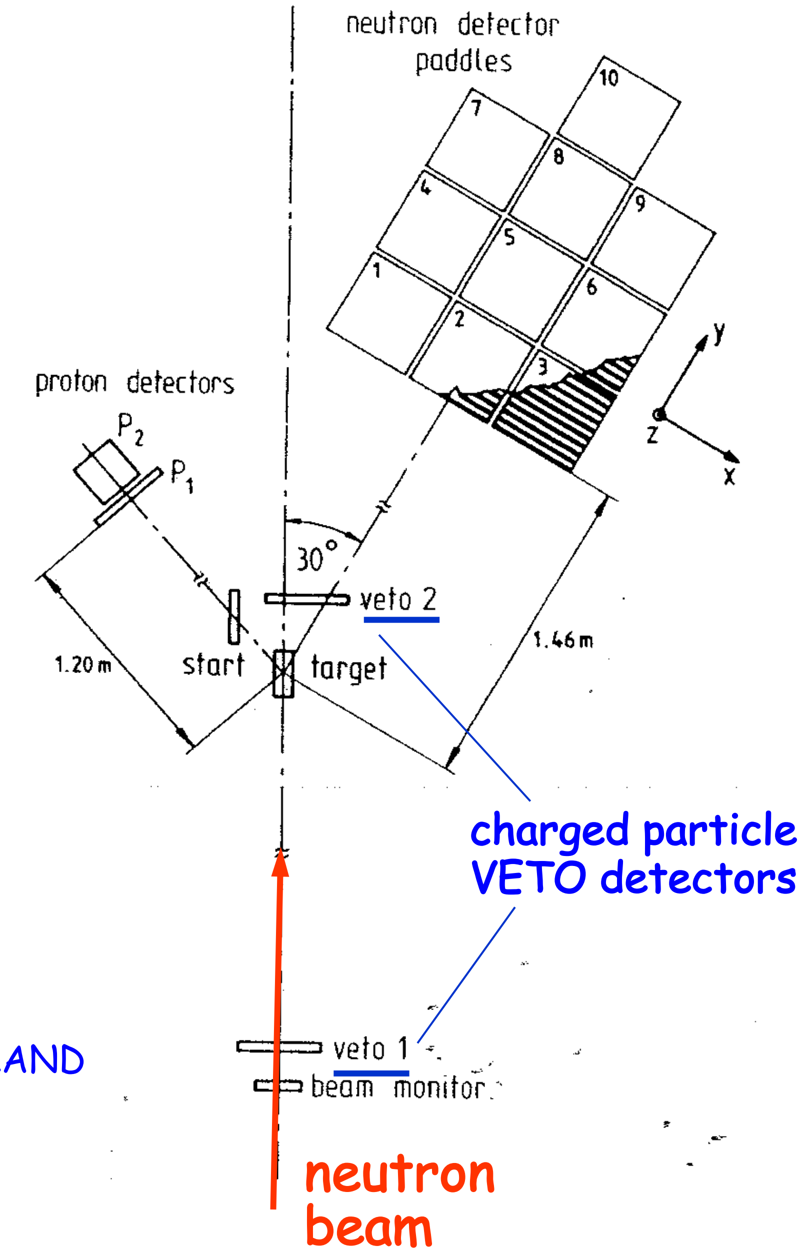
- neutrons from *elastic scattering* on protons:

- n beams from SATURNE accelerator (Saclay) (with energy T_n = 250, 600, 1000 MeV)

- $(CH_2)_n$ target

- *prototype setup* of 10 puddles
  mounted along the z-direction
  Θ = 30° fixed angle

- *proton detectors*
  placed at corresponding two-body kinematics:
  Θ = 56.7, 52.7 and 48.5°
  [N.B. kinetic energies of neutrons reaching LAND:
  T_n = 181, 417, 662 MeV]



trigger condition

$$\overline{V}_1 \wedge \overline{V}_2 \wedge S \wedge P_1 \wedge P_2 \wedge N$$

neutron event in LAND

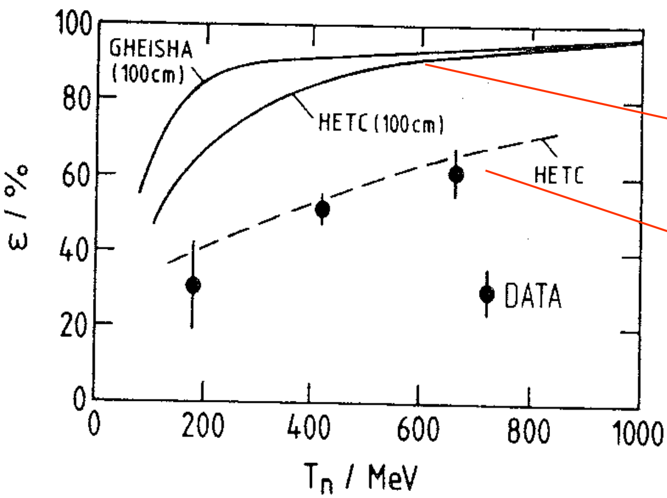
proton event

NO charged particles in beam & from target

reference signal for TOF

neutron array efficiency

$$\varepsilon = \frac{p-n\ coincidence\ rate}{p\ rate\ \ from\ target}$$



extrapolation to full array

test array

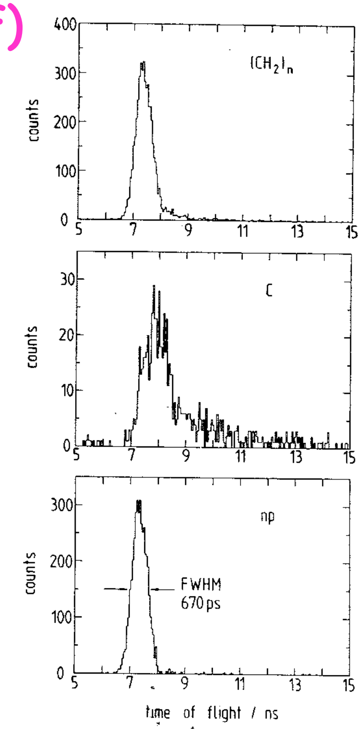
ε > 90 %

for neutrons with

T_n > 550 MeV

time resolution (TOF)

(T_n = 417 MeV)



$(CH_2)_n$ target →

C target →

(for comparison)

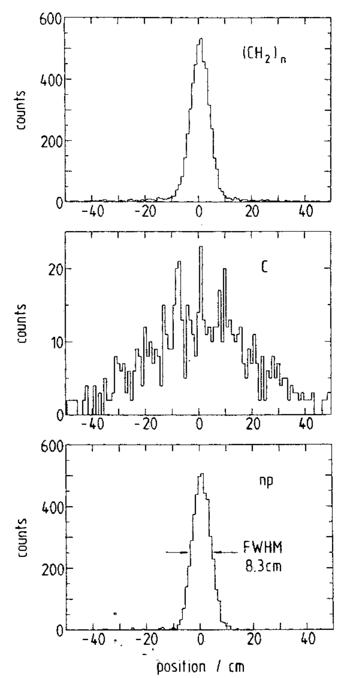
difference spectrum →

⇒ intrinsic resolution

ΔT_{LAND} = 370 ps

position resolution

(T_n = 417 MeV)



← $(CH_2)_n$ target

← C target

(for comparison)

← difference spectrum

⇒ intrinsic resolution

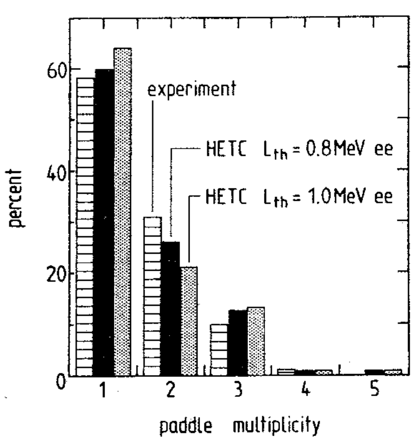
ΔZ_{LAND} = 5.1 cm

properties of adronic showers

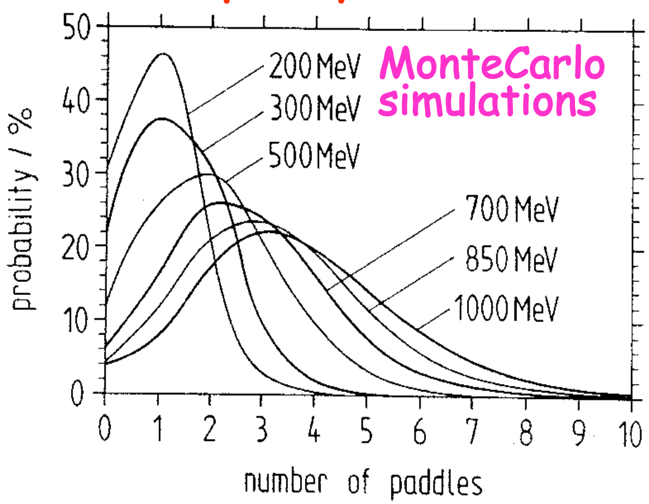
- neutron with *lowest energy*:
  shower is one proton only !
- neutrons with *high energy*:
  production of several charged particles

⇒ *visible energy is produced in more than one paddle*

T_n = 417 MeV

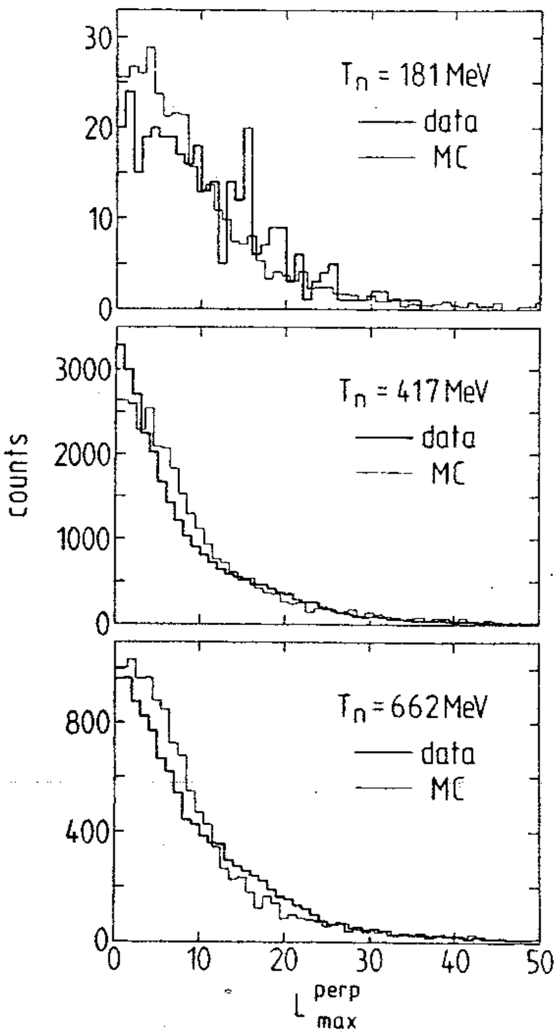


multiplicity distribution



increasing multiplicity & broadening with increasing energy: ⟨M⟩ = 1-4

Shower length in Z-direction



Example of Physics with LAND

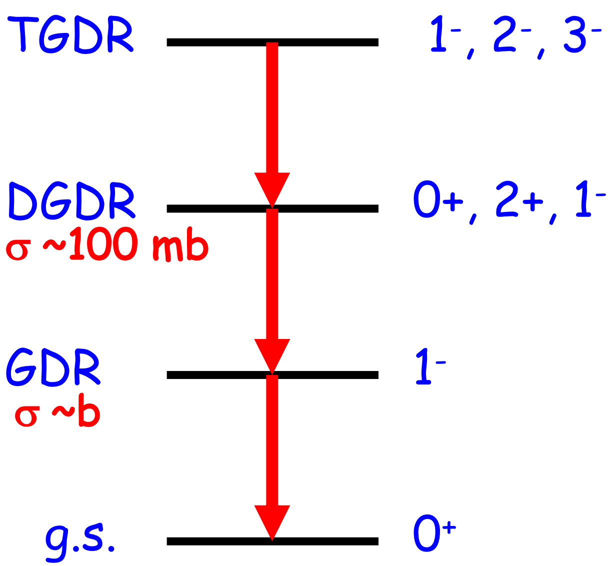
Double Phonon Giant Resonances: ^{136}Xe, ^{208}Pb, ^{238}U

High Energy Heavy-Ion Coulomb excitation: 500-700 MeV/A

Heavy-ions reactions
(very fast)

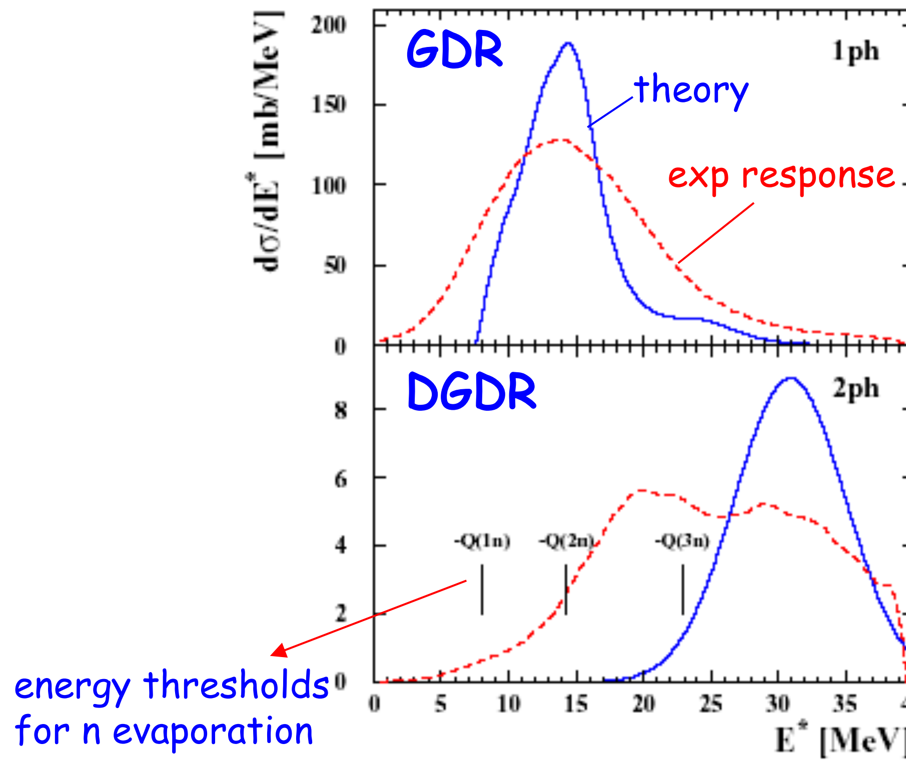
allow the excitation of
multiphonon states

(mainly of DGDR type)



cross section calculation
for dipole excitation

^{136}Xe (700MeV/A) on ^{208}Pb target



n emission is the main decay mode

E of projectile is reconstructed*

by kinematical complete measurement of all products of decaying system

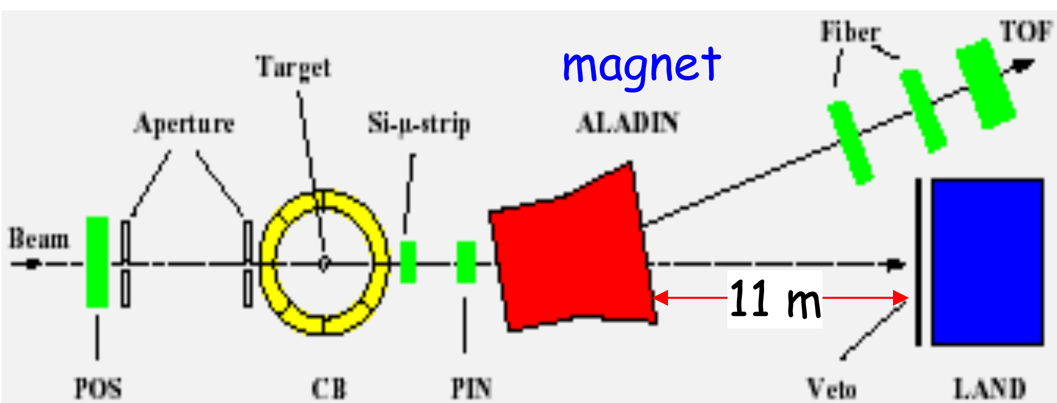
projectile nuclei are:

- ***excited*** by peripheral collision
- ***deexcited*** by emission of neutrons and subsequent γ-decay of heavy residue

E* is calculated event by event by invariant mass analysis

$$M^2 = \left(\sum_i P_i\right)^2 = (M_P + E^*)^2$$

P_i = four-momenta of all dissociation products
M_P = projectile rest mass

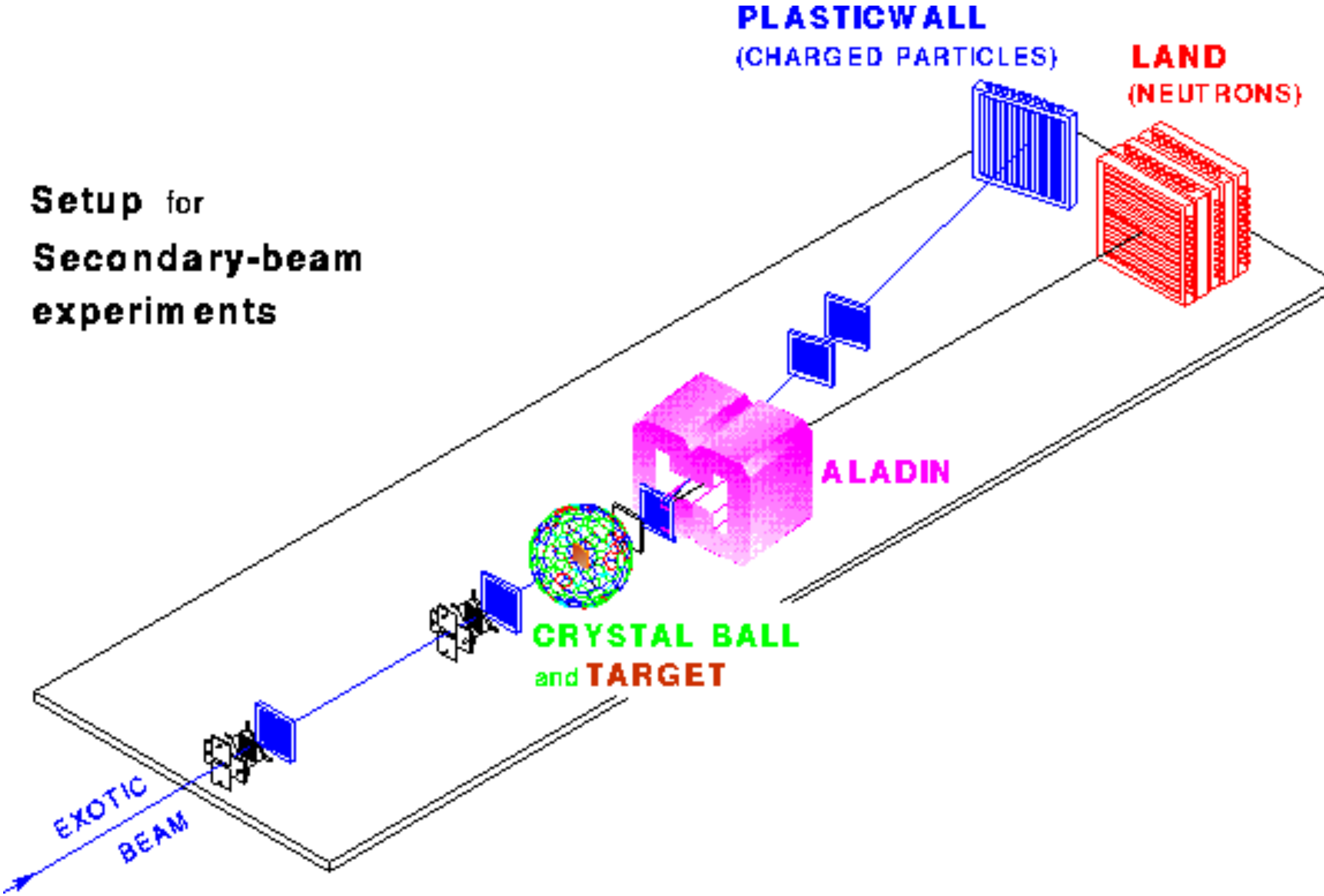


charged particle detector
(trace of projectile and projectile fragments)
Z, B, TOF ⇒ A

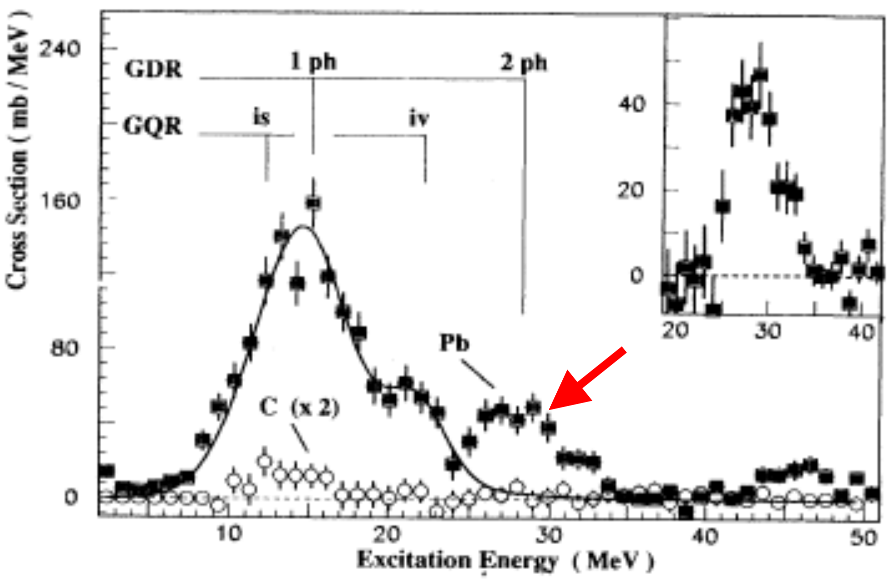
n detector
full coverage of n-solid angle due to kinematical focusing:
$d\Omega_{LAND} \geq$ 200 mrad,
$d\Omega$ = 160 mrad forward n cone

γ-detector (Crystal Ball)
4π array of 162 NaI

Setup for Secondary-beam experiments



^{136}Xe projectile excitation

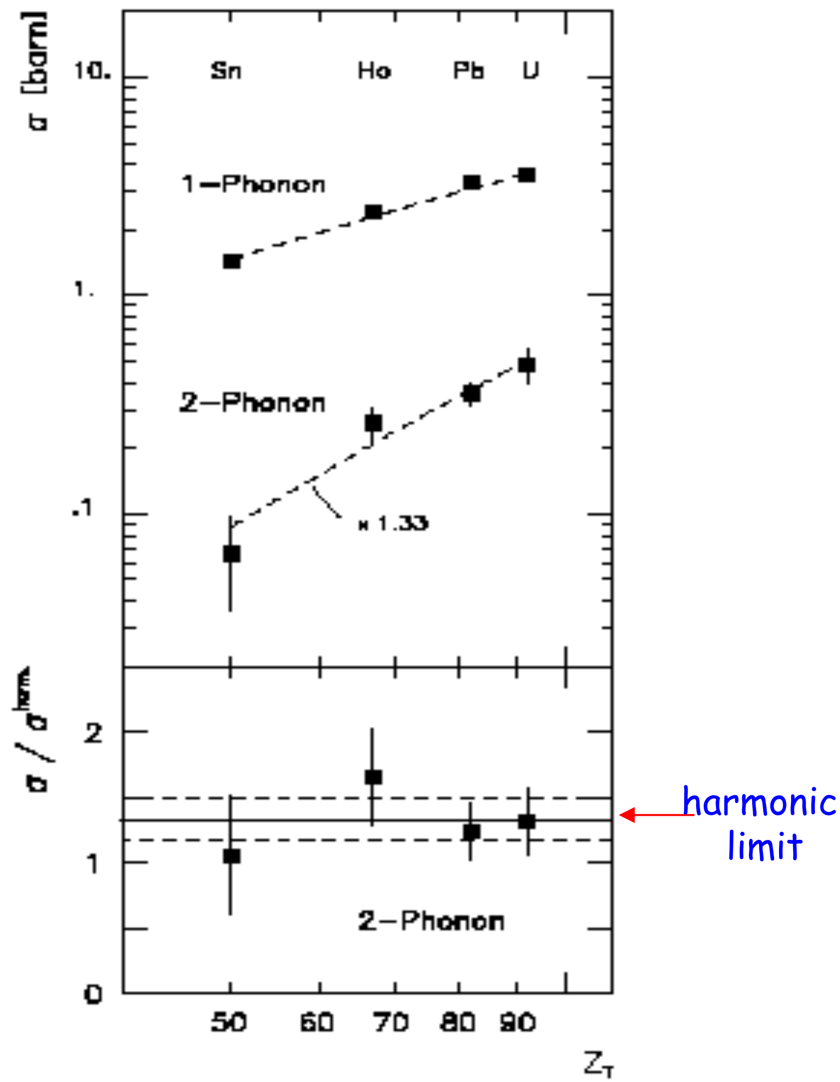


	Mean energy	Width (FWHM)	Cross section
DGDR	28.3 ± 0.7 MeV	6.3 ± 1.6 MeV	215 ± 50 mb
DGDR/GDR	1.86 ± 0.05	1.3 ± 0.4	0.21 ± 0.05

The structure is NOT visible with C target

⇒ ***it is not due to nuclear interactions***

^{136}Xe dipole cross sections (with different targets)



Schmidt et al., PRL70(1993)1767

Boretzky et al., PRC68(2003)024317