# The fission barrier

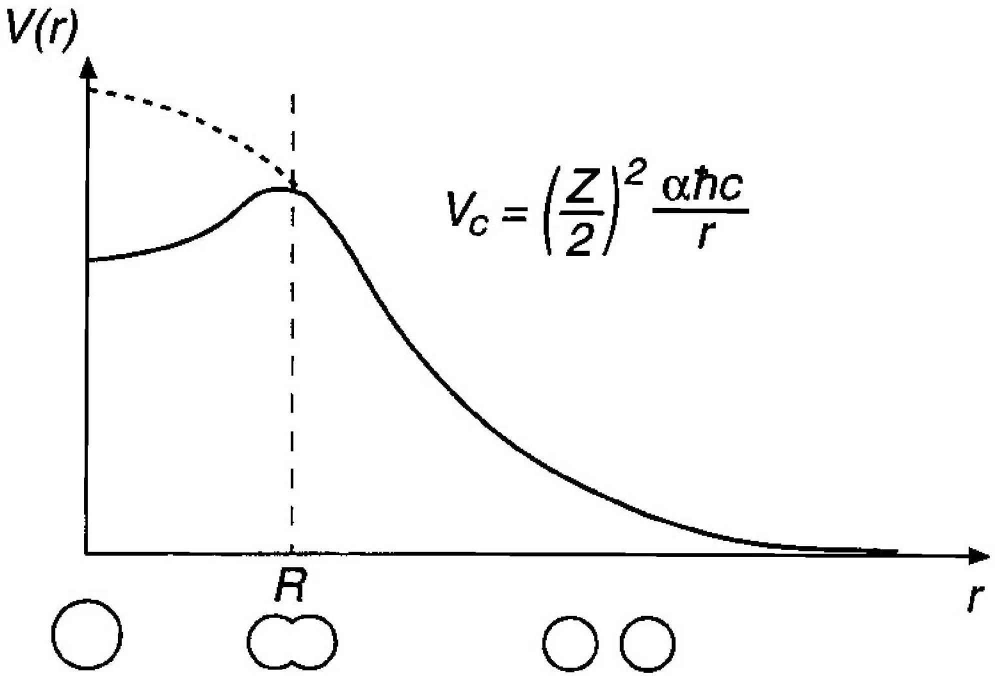


**Fig. 3.8.** Potential energy during different stages of a fission reaction. A nucleus with charge $Z$ decays spontaneously into two daughter nuclei. The solid line corresponds to the shape of the potential in the parent nucleus. The height of the barrier for fission determines the probability of spontaneous fission. The fission barrier disappears for nuclei with $Z^2/A \gtrsim 48$ and the shape of the potential then corresponds to the dashed line.

# Deformation of a heavy nucleus

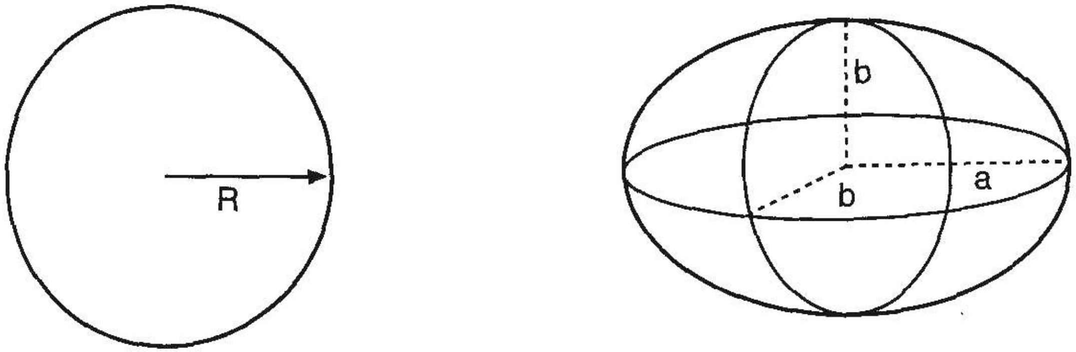


**Fig. 3.9.** Deformation of a heavy nucleus. For a constant volume $V$ ($V = 4\pi R^3/3 = 4\pi ab^2/3$), the surface energy of the nucleus increases and its Coulomb energy decreases.

$$B = a_V A - a_S A^{\frac{2}{3}} - a_C Z(Z-1) A^{-\frac{1}{3}} - a_{sym} \frac{(A-2Z)^2}{A} + \delta$$

$$\frac{4}{3}\pi R^3 = \frac{4}{3}\pi a b^2 \qquad a = R(1+\varepsilon), b = R(1+\varepsilon)^{-1}$$

$$S = 4\pi R^2 (1 + \frac{2}{5}\varepsilon^2 + \ldots)$$

$$E_C = a_C Z^2 A^{-\frac{1}{3}} \left(1 - \frac{1}{2}\varepsilon^2 + \ldots.\right)$$

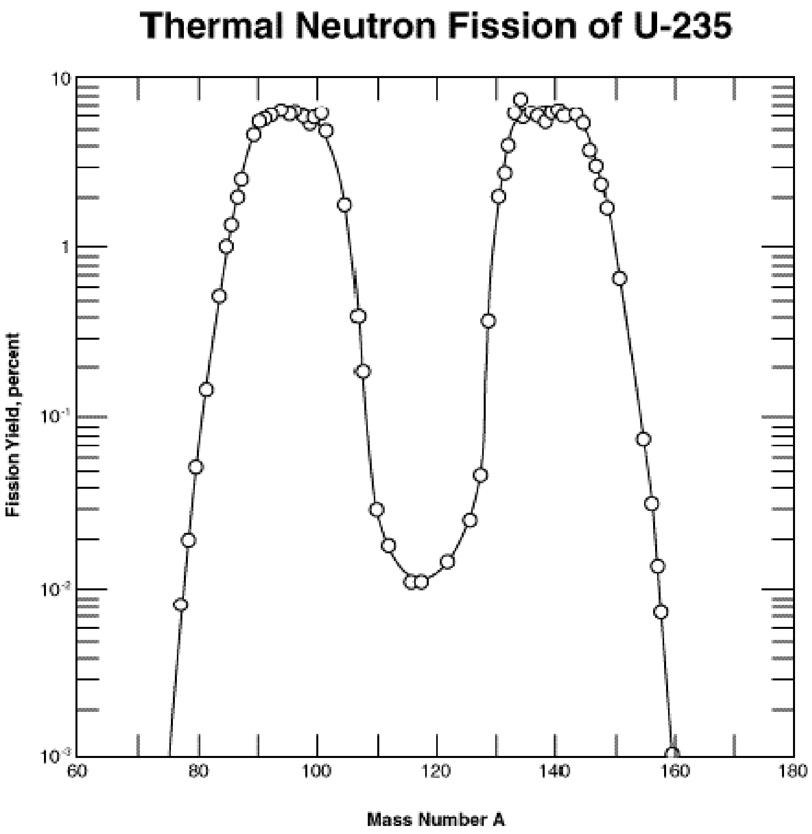
$$E_S = a_S A^{\frac{2}{3}} \left(1 + \frac{2}{5}\varepsilon^2 + \ldots.\right)$$

$$\Delta E = BE(\varepsilon) - BE(0) = \frac{\varepsilon^2}{5}\left(a_C Z^2 A^{-\frac{1}{3}} - 2 a_S A^{\frac{2}{3}}\right)$$

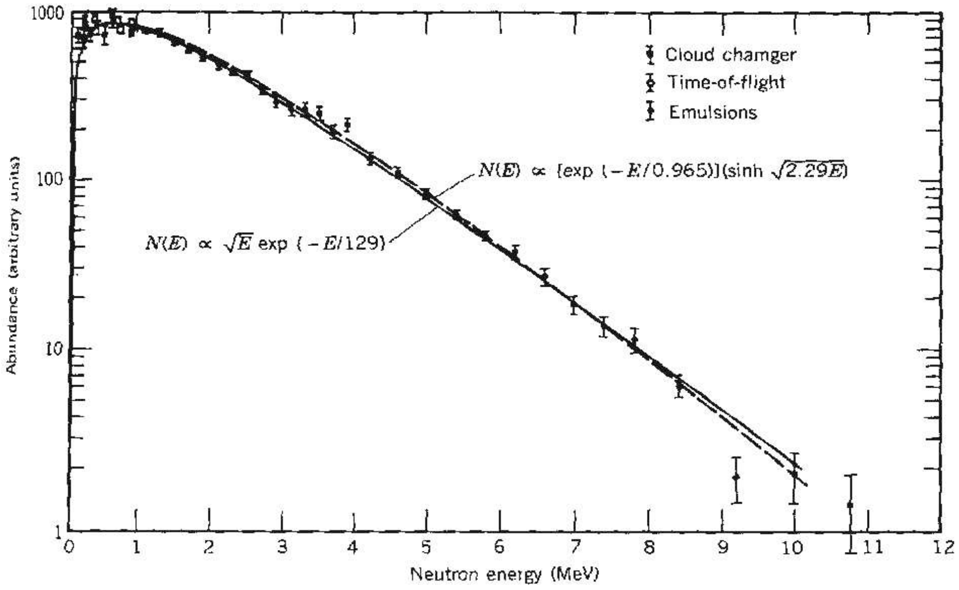
$$\Delta E > 0 \boxed{\Leftrightarrow \frac{Z^2}{A} > 47}$$

# Fission of $^{235}$U

$^{235}U + n \rightarrow ^{93}Rb + ^{141}Cs + 2n$



## Energy spectrum of prompt neutrons in $^{235}$U fission



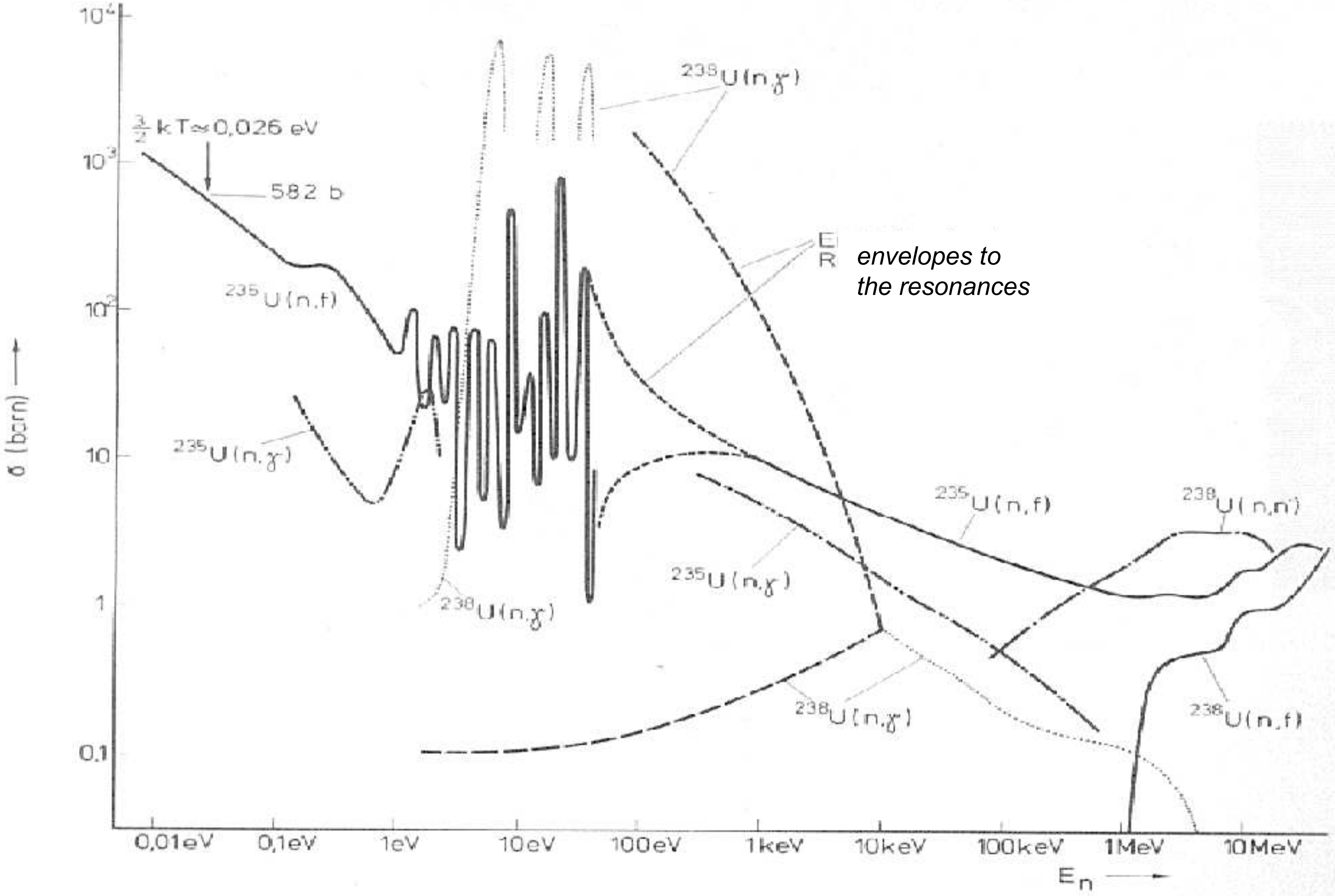
BE($^{235}$U+n) = 6.4 MeV Fission Barrier = 6.3 MeV

--> slow neutrons (E~25 meV)

BE($^{238}$U+n)= 4.8 MeV Fission Barrier= 5.8 MeV

--> fast neutrons (E>1.5MeV)

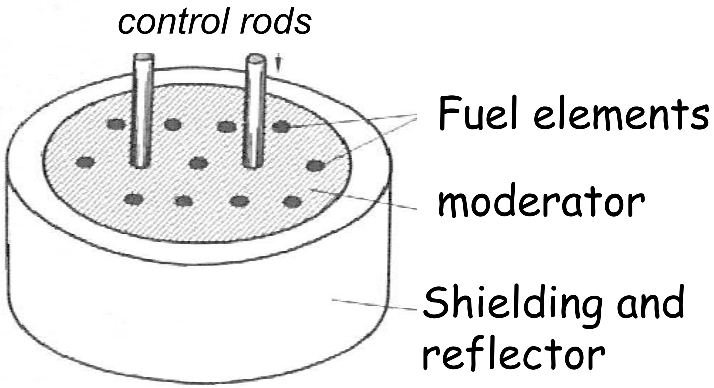
# Neutron cross sections of uranium



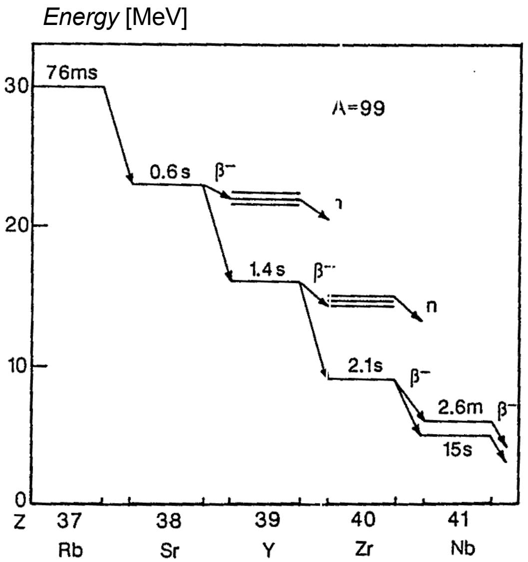
*envelopes to*
*the resonances*

Fig. 124 Übersicht über die Wirkungsquerschnitte bei Reaktionen von Neutronen mit Uran. In den Bereichen dicht liegender Resonanzen können die Strukturen in der Zeichnung nicht wiedergegeben werden. Es ist daher nur die Einhüllende der Resonanzmaxima- und -minima eingezeichnet (gestrichelt). Ein Detail ist in Figur 107 wiedergegeben

# Scheme of a nuclear reactor



Delayed neutron emission



The moderator slows down the neutron from MeV energy to thermal energies. Moreover it absorbs the kinetic energy of the emitted fission fragments.

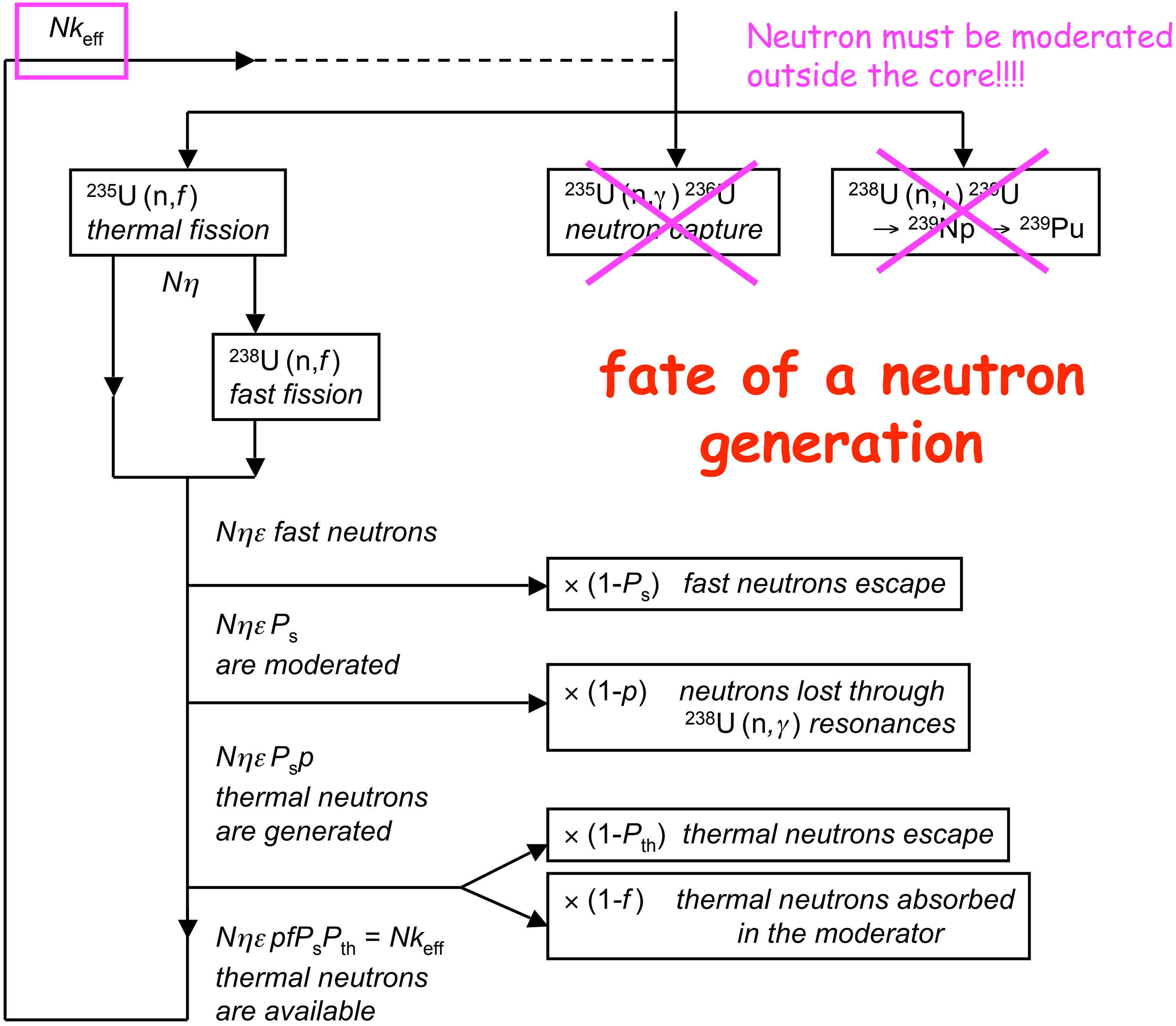
$$\eta = \frac{fission\ neutrons}{absorbed\ neutrons} = \nu \frac{\sigma_f}{\sigma_f + \sigma_r} > 1$$

$\nu = <number> neutrons\ pro\ fission$

$\sigma_f = fission\ cross-\sec tion$

$\sigma_r = neutron\ reaction\ cross-\sec tion$

# fate of a neutron generation



$Nk_{\text{eff}}$

Neutron must be moderated outside the core!!!!

$^{235}$U (n,*f*) *thermal fission*

~~$^{235}$U (n,$\gamma$) $^{236}$U *neutron capture*~~

~~$^{238}$U (n,$\gamma$) $^{239}$U → $^{239}$Np → $^{239}$Pu~~

$N\eta$

$^{238}$U (n,*f*) *fast fission*

$N\eta\varepsilon$ *fast neutrons*

× (1-$P_s$) *fast neutrons escape*

$N\eta\varepsilon P_s$
*are moderated*

× (1-*p*) *neutrons lost through* $^{238}$U (n,$\gamma$) *resonances*

$N\eta\varepsilon P_s p$
*thermal neutrons*
*are generated*

× (1-$P_{th}$) *thermal neutrons escape*

× (1-*f*) *thermal neutrons absorbed in the moderator*

$N\eta\varepsilon pfP_sP_{th} = Nk_{\text{eff}}$
*thermal neutrons*
*are available*

# Reactor Controlling

$K_{eff}$= effective multiplication

$K_{eff}$>1 to start the reactor

$K_{eff}$=1 to keep it stationary

$$\frac{d\rho}{dt} = \frac{k_{eff}\rho - \rho}{t_0}$$

$$\rho = neutron\ number$$

$$t_0 = time\ between\ two\ neutron\ productions$$

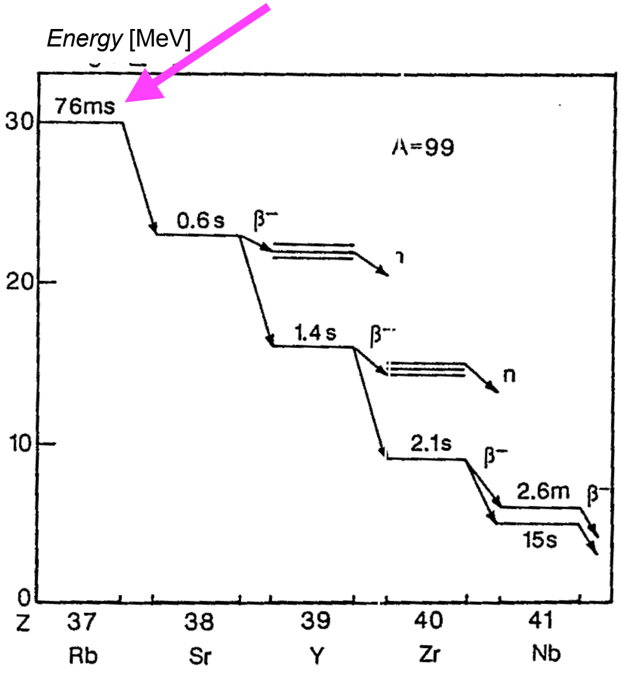
$$\Rightarrow \rho(t) = \rho_0 e^{\frac{t}{\tau}}$$

$$\tau = \frac{t_0}{k_{eff} - 1}$$

$$k_{eff} = 1.007\ t_0 = 1ms \Rightarrow \tau \approx 0.1s$$

Delayed neutron emission

$^{235}U+n \rightarrow ^{93}Rb + ^{141}Cs + 2n$



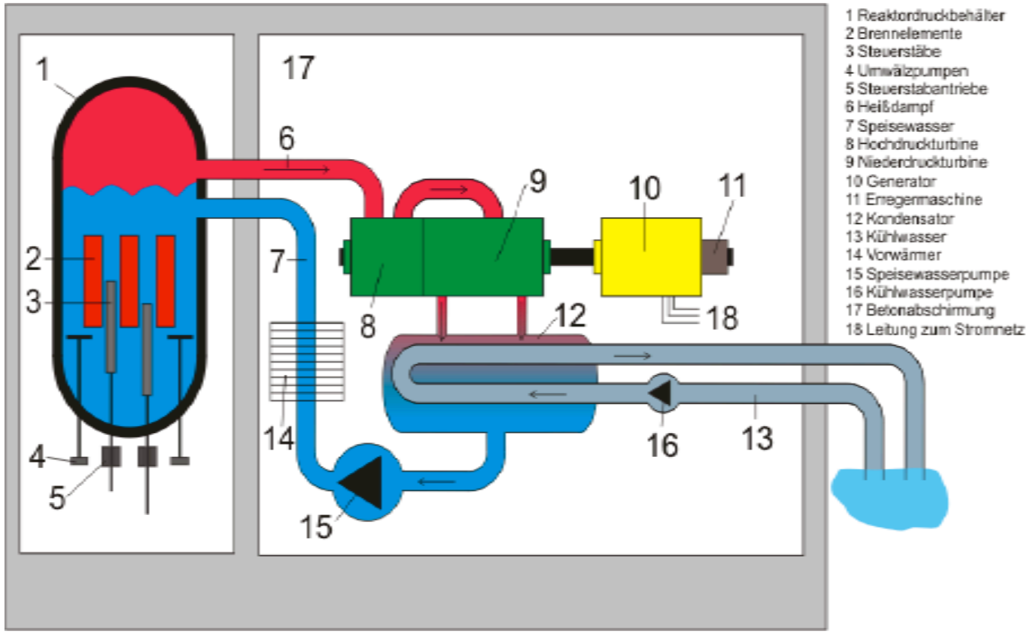
These neutrons slow down the reactor period

# Fission Reactor

Ligth water reactor

P= 71 bar

T= 286°C



Moderator:

$H_2O$: p+n -->d ($\sigma_{absorption}$ = 33.3 mb)

$D_2O$: d+n -->t --> ($\sigma_{absorption}$ = 0.5 mb) lower neutron absorption

Graphite: difficult to stop Overheating (Cernobyl)

To compensate for the n absorption in $H_2O$:

Natural Abundance $^{235}$U:0.7%

Enriched A. $^{235}$U ~ 4%

# Breeding reactions

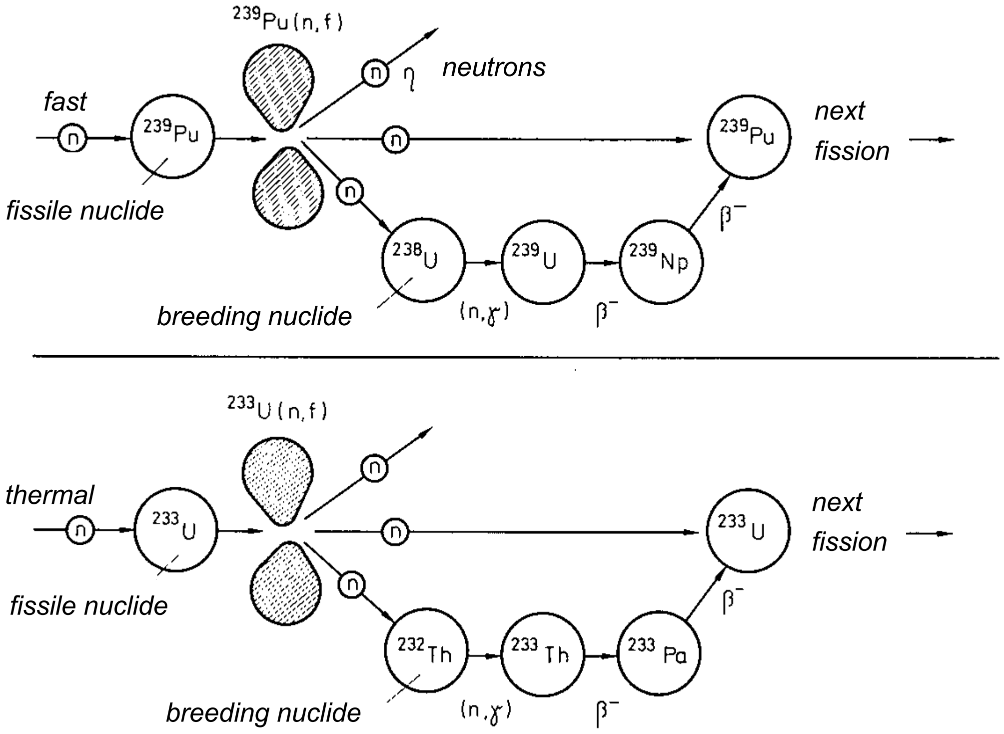
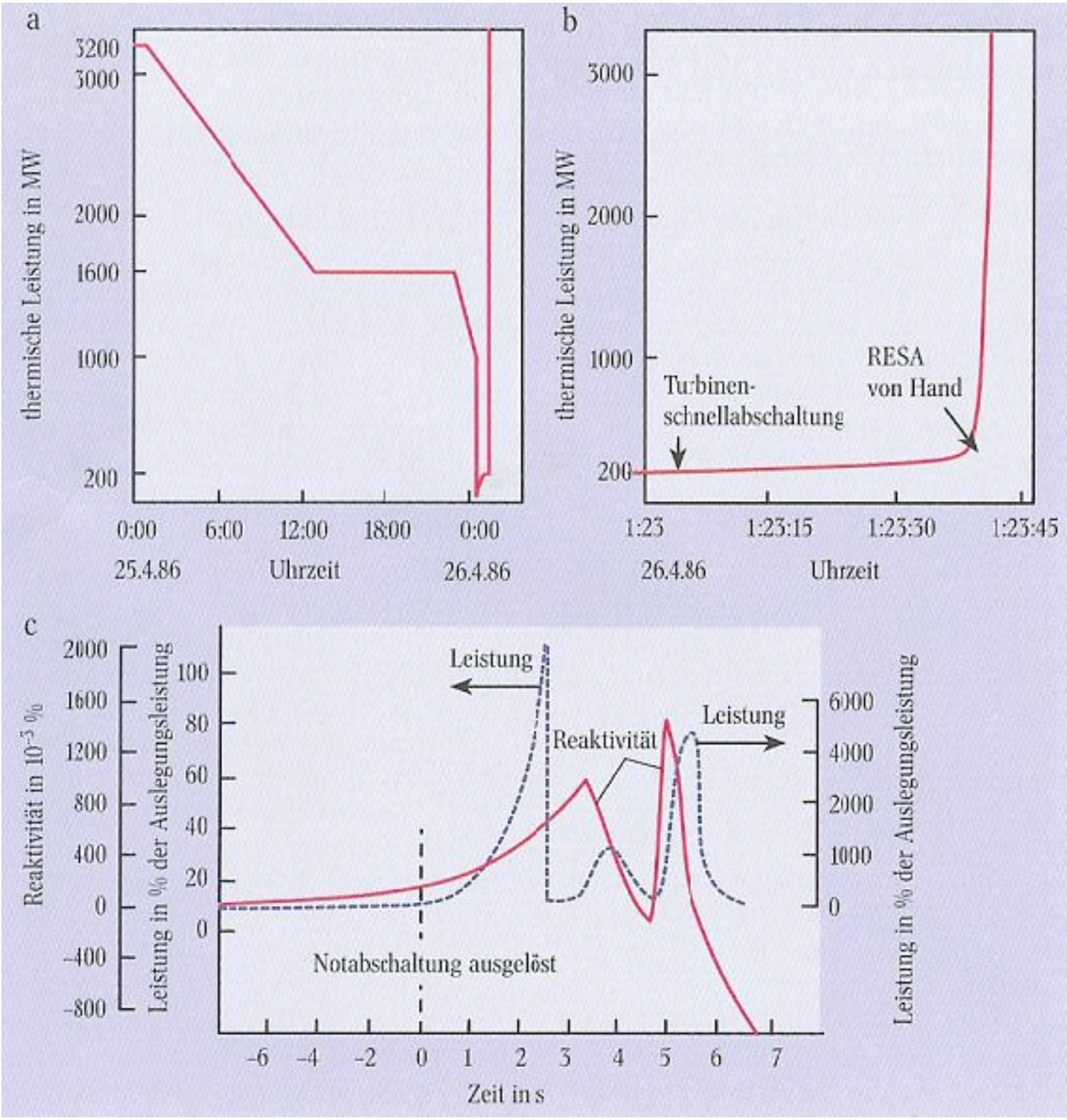


Fig. 127 Spalt-Brut-Ketten für den schnellen Brüter und den Thorium-Brüter


a
3200
3000
2000
1600
1000
200
thermische Leistung in MW
0:00
6:00
12:00
18:00
0:00
25.4.86
Uhrzeit
26.4.86
b
3000
2000
1000
200
thermische Leistung in MW
Turbinen-
schnellabschaltung
RESA
von Hand
1:23
1:23:15
1:23:30
1:23:45
26.4.86
Uhrzeit
c
Reaktivität in $10^{-5}$ %
2000
1600
1200
800
400
0
-400
-800
Leistung in % der Auslegungsleistung
100
80
60
40
20
0
Leistung
Reaktivität
Leistung
6000
4000
2000
1000
0
Leistung in % der Auslegungsleistung
Notabschaltung ausgelöst
-6
-4
-2
0
1
2
3
4
5
6
7
Zeit in s

# Weizsäcker parabola for even-odd isobars

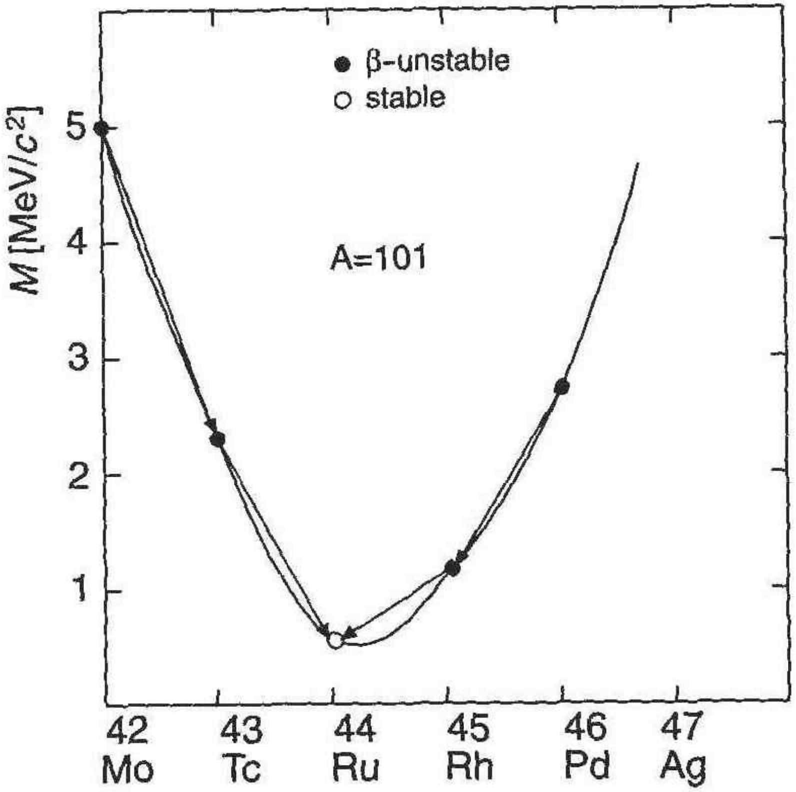


**Fig. 3.2.** Mass parabola of the $A = 101$ isobars (from [Se77]). Possible $\beta$-decays are shown by arrows. The abscissa co-ordinate is the atomic number, $Z$. The zero point of the mass scale was chosen arbitrarily.

# Weizsäcker parabolas for even-even and odd-odd isobars

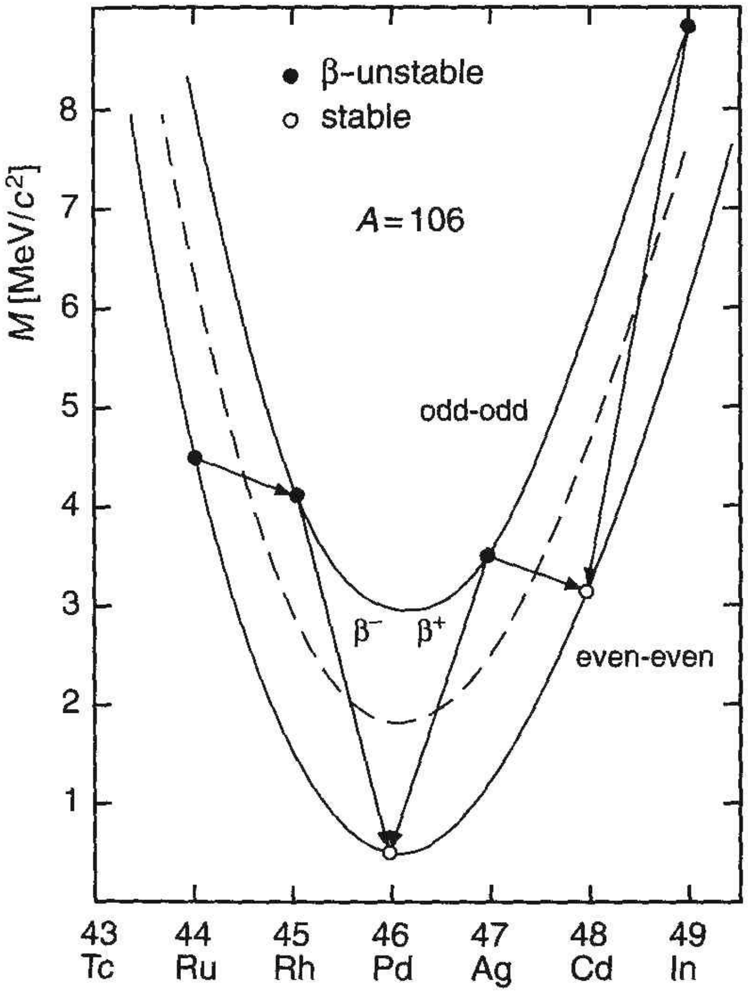
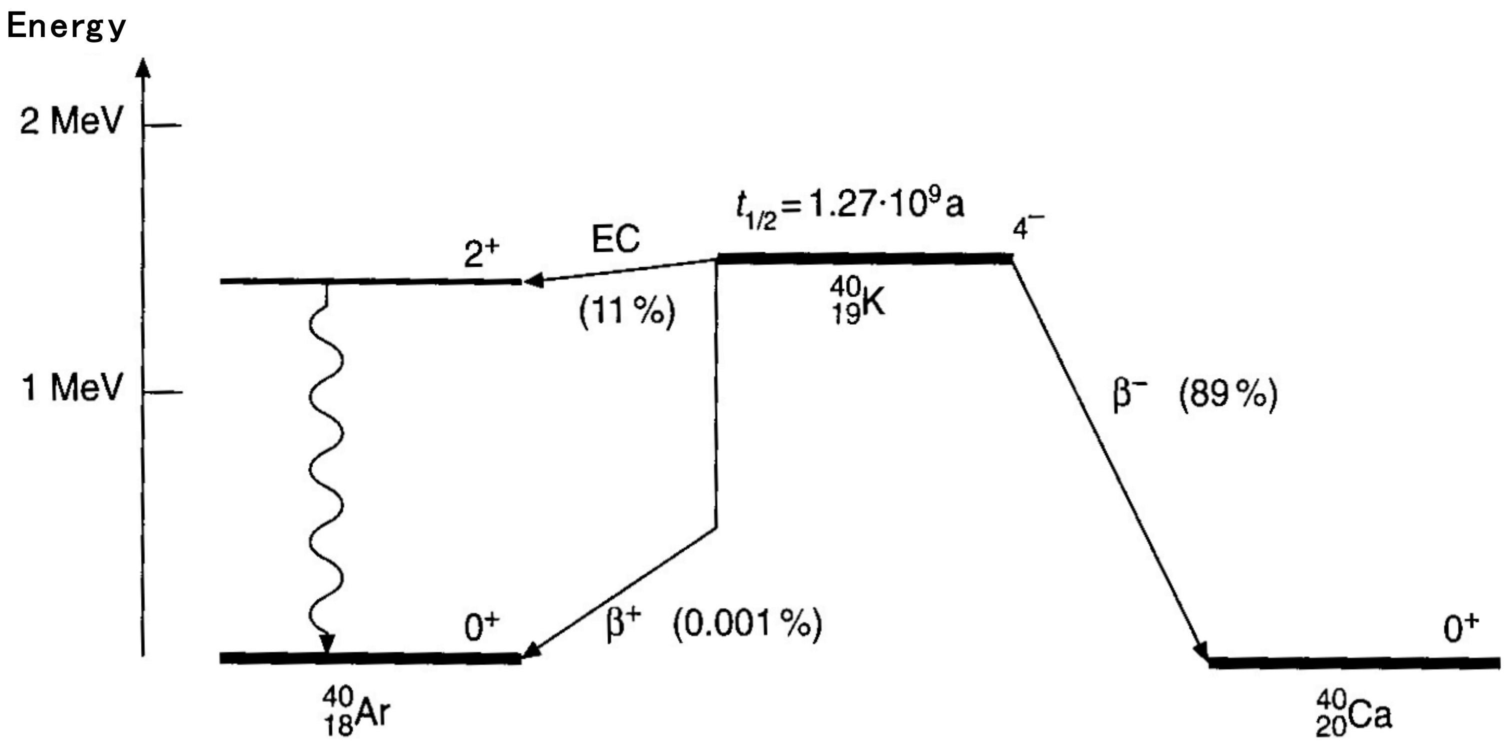


**Fig. 3.3.** Mass parabolas of the $A = 106$-isobars (from [Se77]). Possible $\beta$-decays are indicated by arrows. The abscissa coordinate is the charge number $Z$. The zero point of the mass scale was chosen arbitrarily.

# Beta decay of $^{40}K$



# Modification of the beta spectrum by Coulomb interaction of β± and daughter nucleus

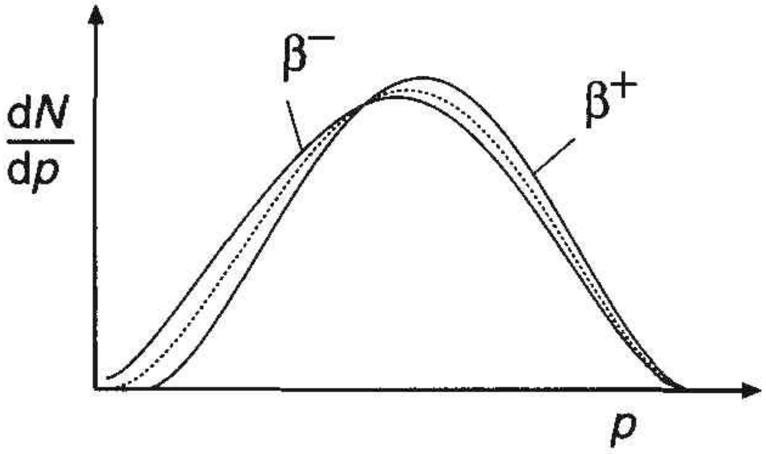


**Fig. 17.17.** Schematic appearance of the electron spectrum in $\beta$-decay. The phase space factor from (15.45) produces a spectrum with a parabolic fall off at both ends (*dotted line*). This is modified by the interaction of the electron/positron with the Coulomb field of the final state nucleus (*continuous lines*). These latter curves were calculated from (17.49) for $Z' = 20$ and $E_0 = 1\,\mathrm{MeV}$.

# Neutrino Detection

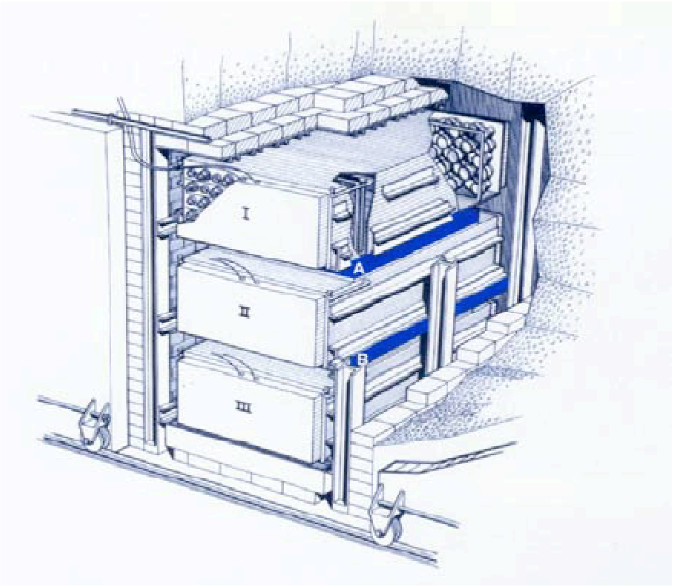
Indirect method: EC in $^{37}$Ar:

$^{37}Ar+e^{-}\text{-->}{}^{37}Cl+\nu_e+\Delta m(=0.814\ MeV/c^2)$

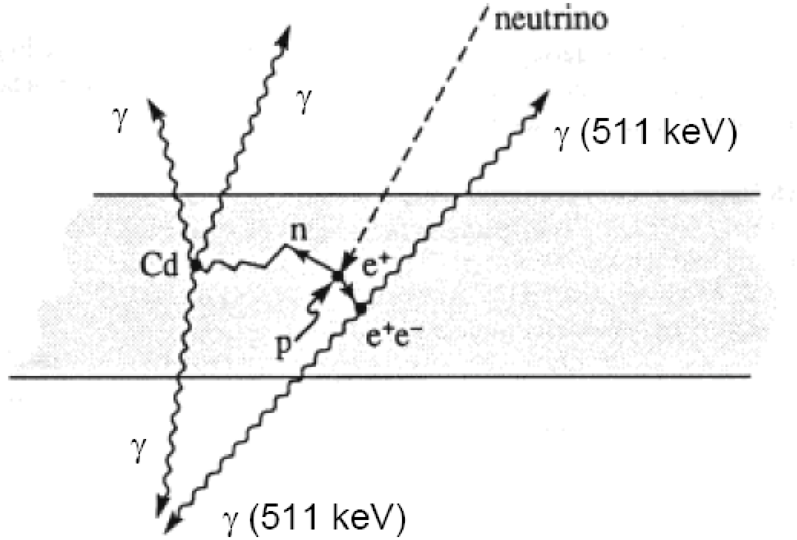
Monoenergetic neutrino and hence a fixed recoil momentum for $^{37}$Cl that one can measure

Direct method: 1) neutrino source? (Reactor)  1953: $\bar{\nu}+p\text{-->}e^{+}+n$

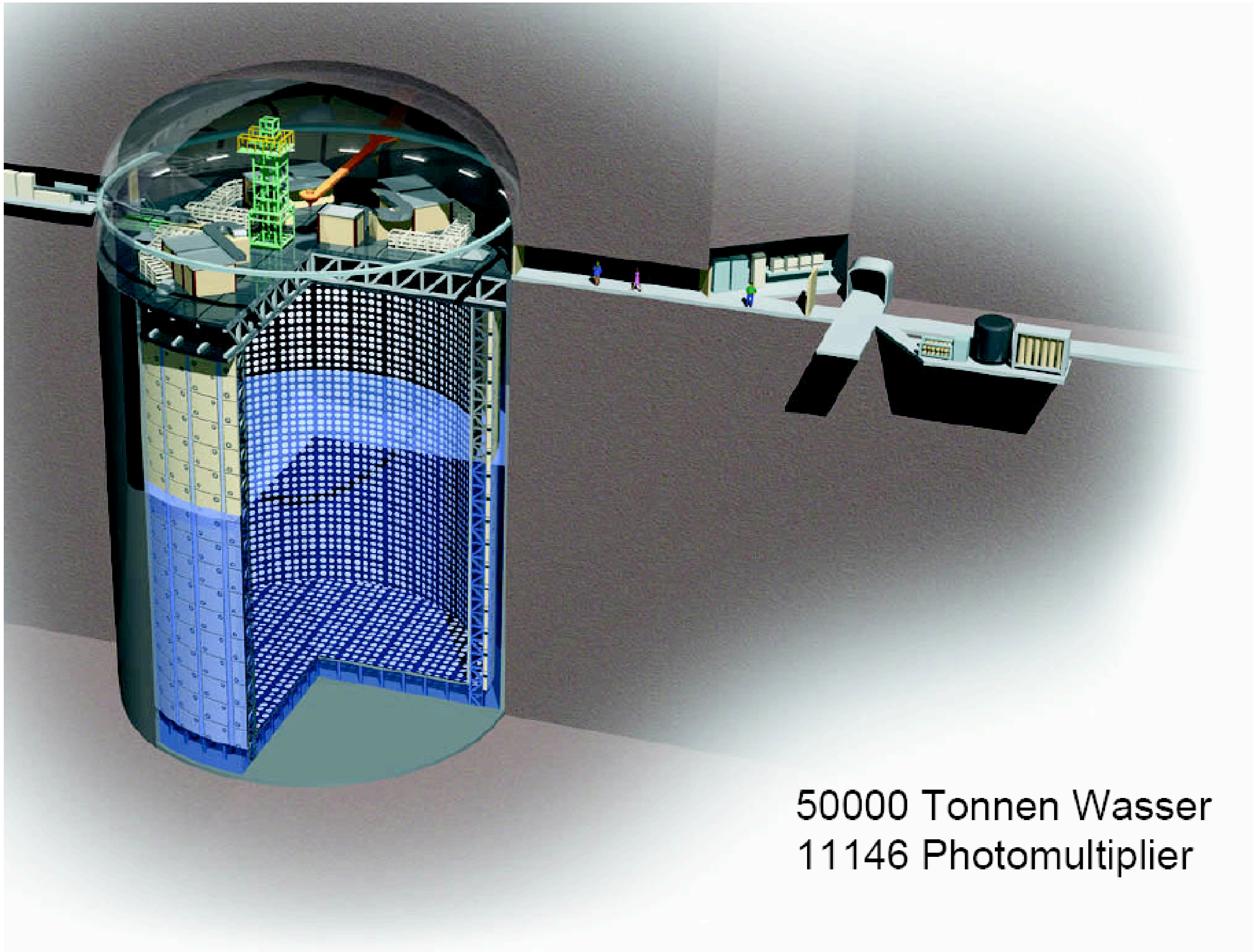
2) how to detect? 200l water with Cadminucloride, g detected by Scintillation Detector



Nobel Price for Reines in 1995

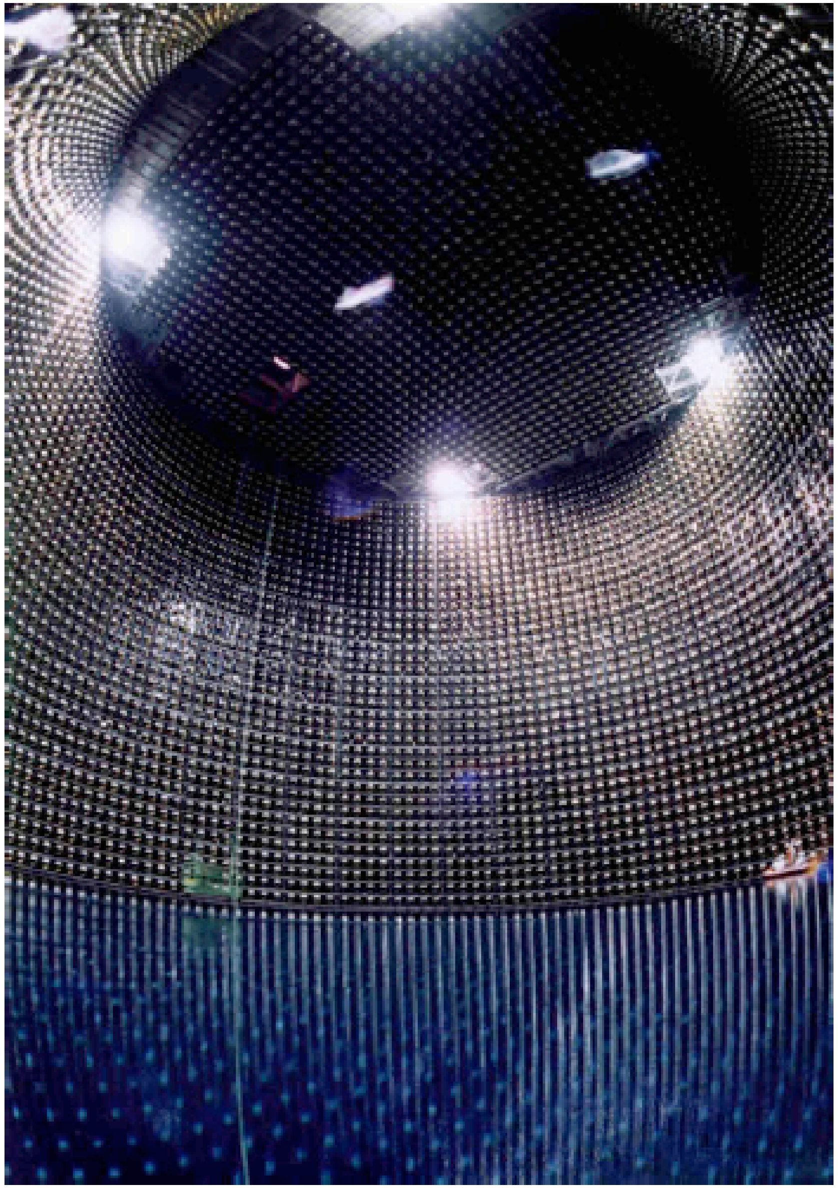


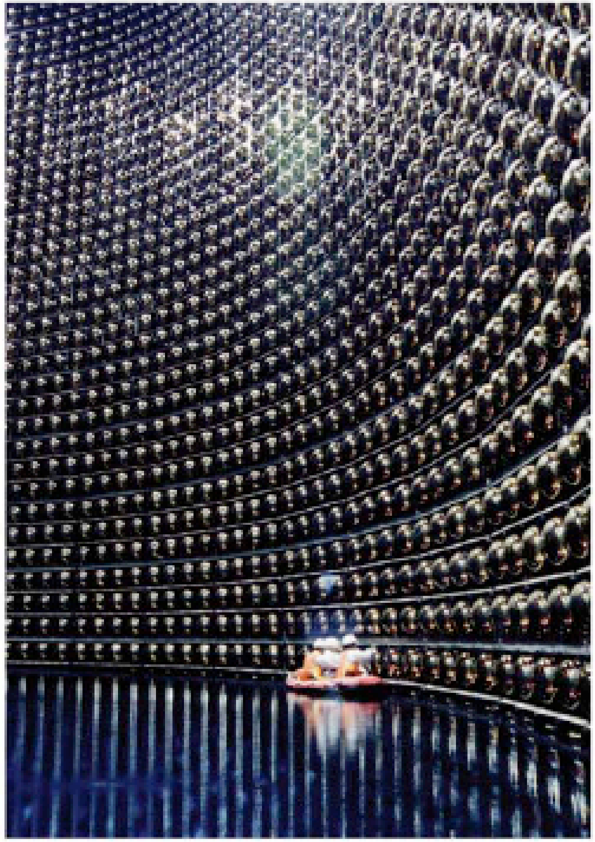
# SuperKamiokande

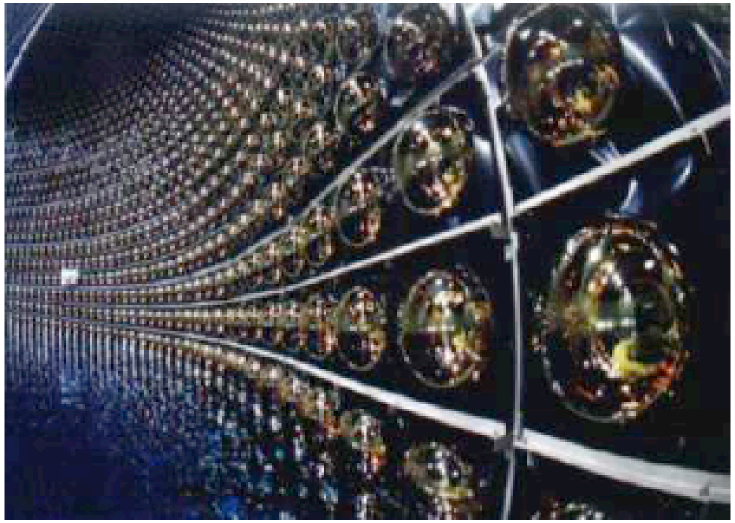


50000 Tonnen Wasser
11146 Photomultiplier

# SuperKamiokande







The interaction of the neutrino with the proton in the water generates either a myon or an electron and these will be detected and distinguished via their Cerenkov-Radiaton

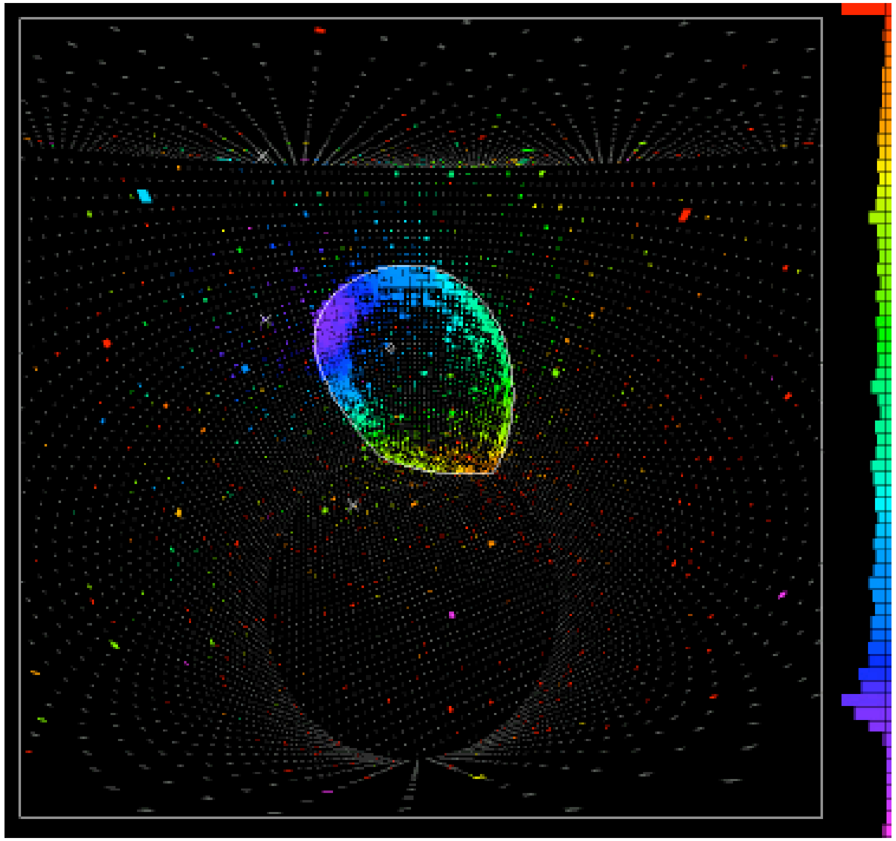
$$\cos\vartheta = \frac{1}{\beta n}$$

Mass$\mu$=105,658 MeV/$c^2$

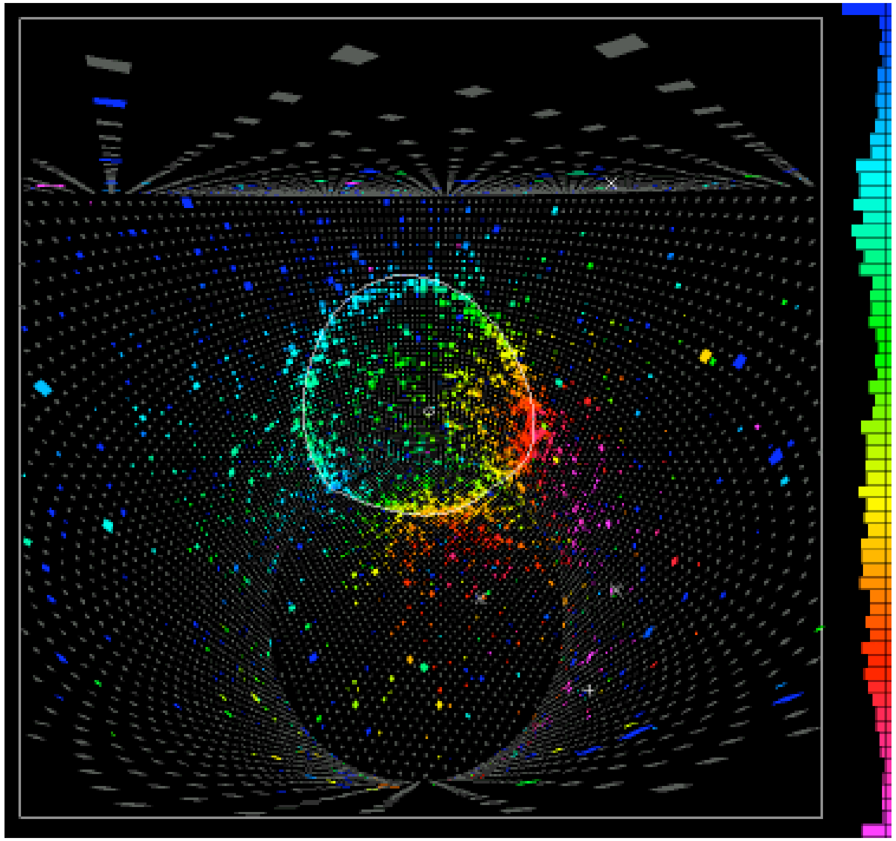
$$\beta = \frac{p}{E}$$

Mass $e^-$=0.511MeV/$c^2$

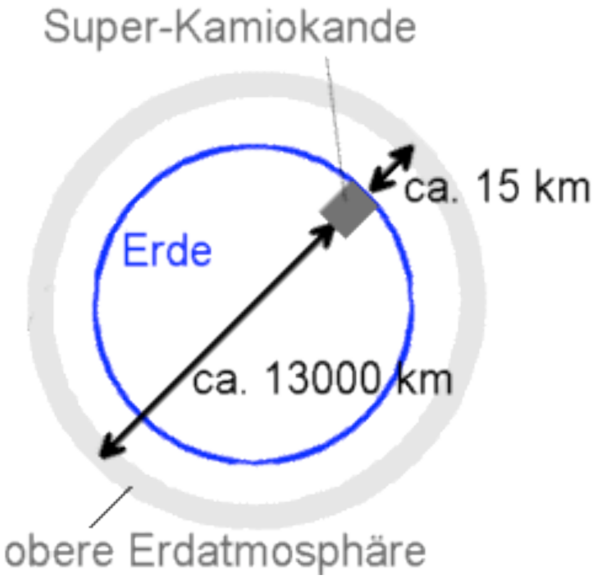
**Myon**



**Elektron**



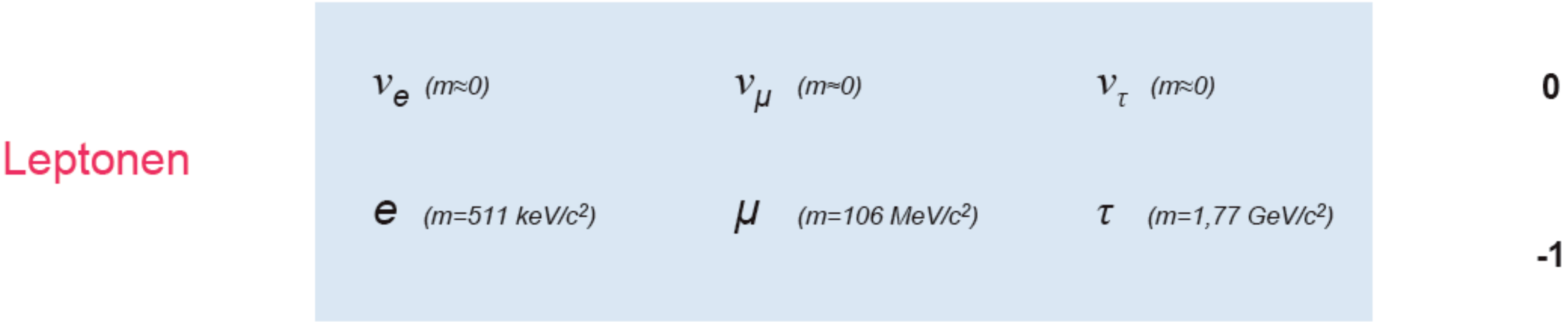
# Neutrino Oscillations



The basics idea is to find out if the atmospherical neutrinos do change their flavours on the their way to the earth (about 13000 km)

$\nu_e$+p-->$e^+$+n

$\nu_\mu$+p-->$\mu^+$+n



| | | | | |
|---|---|---|---|---|
| Leptonen | $\nu_e$ (m≈0) | $\nu_\mu$ (m≈0) | $\nu_\tau$ (m≈0) | 0 |
| | $e$ (m=511 keV/c²) | $\mu$ (m=106 MeV/c²) | $\tau$ (m=1,77 GeV/c²) | -1 |

# Munich reactor