Pheno Seminar this Friday

Friday, November 21st, 2008
Phenomenology Seminar

Methods to Detect the Cosmic Neutrino Background

Time: 2:30 pm
Place: 5280 Chamberlin Hall
Speaker: Bob McElrath, CERN
Course Project

• Please send me your outline **TODAY**

• Course project outline:
  – aim for 18-20 slides (rule of thumb: 1 slide per 1 min)
  – an outline at beginning of talk is useful
  – show tile for each slide
  – show synopsis of topics for each slide
  – add slide with list of all references

• All talks are to be posted by **Friday, December 12, 2008, 5pm CST**
Energy Release in Fission and Self-Fusion

- only nuclei with $40 < A < 95$ are stable against both fission and self-fusion
- $Q_{\text{fis}}$ calculated for symmetric fission
Binding Energies

at $A=120$: 8.5 MeV

at $A=240$: 7.6 MeV
Fission Products
Distribution of Fission Fragments

asymmetric fission into lighter and heavier nuclei
Cesium-137 and strontium-90 are the most dangerous radioisotopes to the environment in terms of their long-term effects. Intermediate half-lives of about 30 years suggests that they are not only highly radioactive but that they have a long enough half-life to be around for hundreds of years.

Iodine-131 is a major concern in any kind of radiation release from a nuclear accident because it is volatile and because it is highly radioactive, having an 8 day half-life.

Iodine is quickly swept up by the thyroid, so that the total intake of iodine becomes concentrated there.
Distribution of Fission Fragments

Mass distributions (or fission-yield curves) for the thermal-neutron fission of uranium-233, uranium-235, and plutonium-239 and the spontaneous fission of californium

The light mass group shifts to higher masses as the mass of the fissioning nucleus increases, while the heavy group remains nearly stationary. The shaded areas show the location of the closed shells of 50 protons, 50 neutrons, and 82 neutrons (see text).
### Energies of Particles in Fission

<table>
<thead>
<tr>
<th>Description</th>
<th>MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic energy of fragments</td>
<td>165 ± 5</td>
</tr>
<tr>
<td>Energy of prompt photons</td>
<td>7 ± 1</td>
</tr>
<tr>
<td>Kinetic energy of neutrons</td>
<td>5 ± 0.5</td>
</tr>
<tr>
<td>Energy of $\beta$ decay electrons</td>
<td>7 ± 1</td>
</tr>
<tr>
<td>Energy of $\beta$ decay antineutrinos</td>
<td>10</td>
</tr>
<tr>
<td>Energy of $\gamma$ decay photons</td>
<td>6 ± 1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>200 ± 6</strong></td>
</tr>
</tbody>
</table>
Nuclear Deformation in Fission

variation of energy as a function of distortion

\[ E_A = \text{fission barrier} \]
Photo-Fission

cross-section for $\gamma^{236}\text{U} \rightarrow \text{fission}$
Mass distribution dependence on the energy excitation in the fission of uranium-235.

At still higher energies, the curve becomes single-humped, with a maximum yield for symmetric mass splits (see text).

At still higher energies, the curve becomes single-humped, with a maximum yield for symmetric mass splits.
**Fission Fragments and Neutron Yields**

*Dependence of neutron yield on initial fragment mass for thermal-neutron fission of uranium-235.*

Average number of neutrons emitted by light and heavy fragments are given the symbols $\nu_L$ and $\nu_H$; the total from both fragments is $\nu$. Also shown are the initial (fission fragment) and final (fission product) mass yields.
Fission Threshold Energies & Neutron Separation Energies

<table>
<thead>
<tr>
<th>Fissioning nucleus $(A, Z)$</th>
<th>$\Delta E_S$ (MeV) $(A, Z)$</th>
<th>$S_n$ (MeV) $(A,Z)$</th>
<th>$T_n$(threshold) (MeV) $(A - 1, Z)$</th>
<th>neutron target $(A - 1, Z)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{234}$U 92</td>
<td>5.4</td>
<td>6.9</td>
<td></td>
<td>$^{233}$U 92</td>
</tr>
<tr>
<td>$^{236}$U 92</td>
<td>5.7</td>
<td>6.3</td>
<td></td>
<td>$^{235}$U 92</td>
</tr>
<tr>
<td>$^{240}$Pu 94</td>
<td>5.5</td>
<td>7.3</td>
<td></td>
<td>$^{239}$Pu 94</td>
</tr>
<tr>
<td>$^{233}$Th 90</td>
<td>6.4</td>
<td>5.1</td>
<td>1.3</td>
<td>$^{232}$Th 90</td>
</tr>
<tr>
<td>$^{235}$U 92</td>
<td>5.8</td>
<td>5.3</td>
<td>0.5</td>
<td>$^{234}$U 92</td>
</tr>
<tr>
<td>$^{239}$U 92</td>
<td>6.0</td>
<td>4.8</td>
<td>1.2</td>
<td>$^{238}$U 92</td>
</tr>
</tbody>
</table>

all threshold energies are typically around $\sim 6$ MeV
Experimental Nuclear Physics - PHYS741
Karsten Heeger, Univ. Wisconsin

thermal $n + {}^{235}\text{U}$ can lead to fission of $^{236}\text{U}$

$n + {}^{235}\text{U}$ has higher energy than lowest fissionable state

some nuclei require thermal neutrons for fission, others require fast neutrons

on the other hand:
thermal $n + {}^{238}\text{U}$ does not lead to fission, only radiative capture

fission of $^{239}\text{U}$ requires addition of neutron with kinetic energy $T_n = 6 - 4.8 = 1.2 \text{ MeV}$
Cross-Sections as a Function of Neutron Energy

1.2 MeV threshold for fission
Fissile and Fertile Material

Nuclei which are used most easily as fuel (fission rapidly by thermal neutron capture)

\[ ^{233}\text{U} \]
\[ ^{235}\text{U} \]
\[ ^{239}\text{Pu} \]

\(^{239}\text{Pu}\) and \(^{233}\text{U}\) are produced by neutron capture from fertile materials \(^{238}\text{U}\) and \(^{232}\text{Th}\).

\[ n\, ^{238}\text{U} \rightarrow ^{239}\text{U} \gamma \]

\[ ^{239}\text{U} \rightarrow ^{239}\text{Np} \, e^- \, \bar{\nu}_e \quad t_{1/2} = 23.45 \text{ m} \]

\[ ^{239}\text{Np} \rightarrow ^{239}\text{Pu} \, e^- \, \bar{\nu}_e \quad t_{1/2} = 2.3565 \text{ day} \]

Reactors which burn \(^{239}\text{Pu}\) and which contains \(^{238}\text{U}\) can produce more Pu than it needs -> breeder reactor
## Configurations for Nuclear Reactors

<table>
<thead>
<tr>
<th>$E_n$</th>
<th>fuel</th>
<th>$\sigma_{\text{Ris}}$</th>
<th>$\sigma_{\text{(n,}\gamma\text{)}}$</th>
<th>$\bar{v}$</th>
<th>$\bar{v}'$</th>
<th>$k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sim 2 \text{ MeV}$</td>
<td>$^{235}\text{U}$</td>
<td>1.27</td>
<td>0.10</td>
<td>2.46</td>
<td>2.28</td>
<td>$= \bar{v}'$</td>
</tr>
<tr>
<td></td>
<td>$^{238}\text{U}$</td>
<td>0.52</td>
<td>2.36</td>
<td>2.88</td>
<td>0.52</td>
<td>$= \bar{v}'$</td>
</tr>
<tr>
<td></td>
<td>$^{239}\text{Pu}$</td>
<td>2</td>
<td>0.10</td>
<td>2.88</td>
<td>2.74</td>
<td>$= \bar{v}'$</td>
</tr>
<tr>
<td>$\sim 0.025 \text{ eV}$</td>
<td>$^{233}\text{U}$</td>
<td>524</td>
<td>69</td>
<td>2.51</td>
<td>2.29</td>
<td>1.72 ($^1\text{H}_2\text{O}$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.2 ($^2\text{H}_2\text{O}$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.0 (C)</td>
</tr>
<tr>
<td></td>
<td>$^{235}\text{U}$</td>
<td>582</td>
<td>108</td>
<td>2.47</td>
<td>2.08</td>
<td>1.56 ($^1\text{H}_2\text{O}$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.0 ($^2\text{H}_2\text{O}$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.8 (C)</td>
</tr>
<tr>
<td></td>
<td>$^{238}\text{U}$</td>
<td>0</td>
<td>2.7</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$^{239}\text{Pu}$</td>
<td>750</td>
<td>300</td>
<td>2.91</td>
<td>2.08</td>
<td>1.56 ($^1\text{H}_2\text{O}$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.0 ($^2\text{H}_2\text{O}$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.8 (C)</td>
</tr>
<tr>
<td>0.7% $^{235}\text{U}$</td>
<td>4.07</td>
<td>3.5</td>
<td>2.47</td>
<td>1.33</td>
<td>0.99</td>
<td>0.99 ($^1\text{H}_2\text{O}$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.3 ($^2\text{H}_2\text{O}$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.16 (C)</td>
</tr>
<tr>
<td>2.5% $^{235}\text{U}$</td>
<td>14.5</td>
<td>5.4</td>
<td>2.47</td>
<td>1.8</td>
<td>1.37</td>
<td>1.37 ($^1\text{H}_2\text{O}$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.8 ($^2\text{H}_2\text{O}$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.6 (C)</td>
</tr>
</tbody>
</table>

- natural
- typical enrichment
## Moderators

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{el}$</th>
<th>$\sigma_{(n,\gamma)}$</th>
<th>$p = \frac{\sigma_{(n,\gamma)}}{\sigma_{tot}}$</th>
<th>$N_{col}$</th>
<th>$\delta = (1 - p)^{N_{col}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1$H$_2$O</td>
<td>44.8</td>
<td>0.664</td>
<td>$1.5 \times 10^{-2}$</td>
<td>18</td>
<td>0.76</td>
</tr>
<tr>
<td>$^2$H$_2$O</td>
<td>10.4</td>
<td>$10^{-3}$</td>
<td>$9.6 \times 10^{-5}$</td>
<td>25</td>
<td>0.998</td>
</tr>
<tr>
<td>C</td>
<td>4.7</td>
<td>$4.5 \times 10^{-3}$</td>
<td>$9.6 \times 10^{-4}$</td>
<td>115</td>
<td>0.895</td>
</tr>
</tbody>
</table>

$p = \text{probability for absorption}$
Nuclear Reactors

control rods  fissile material
moderator

cold leg  hot leg
heat transfer  radiation protection

Containment Structure
Pressurizer  Steam Generator
Control Rods  Reactor Vessel

Generator  Turbine  Condenser

cooling tower
Fuel Element for a PWR Reactor

In the diagram, the fuel element for a PWR reactor is shown. The diagram includes components such as fuel rods, control rods, guide thimbles, grid assemblies, and nozzle assemblies. The fuel rods are stacked and interspersed with control rods, which are essential for regulating the reactor's power output. The bottom nozzle assembly and the top nozzle assembly are also depicted, indicating the entry and exit points for coolant and fuel. The control cluster control assembly is highlighted as a crucial component for the reactor's safe operation.
Build-Up of Fission Products

single n capture on 238-U, at large times balanced by destruction from fission and n capture

requires 2 n captures on 235-U, varies quadratically with time
Production of Trans-Uranium Elements

\[ ^{258}\text{Fm} \rightarrow ^{3.4}\text{Fm} \]

\[ ^{1.6}\text{Es} \rightarrow ^{3.2}\text{Es} \]

\[ ^{2.4}\text{Cf} \rightarrow ^{3.7}\text{Cf} \]

\[ ^{4.0}\text{Bk} \rightarrow ^{3.5}\text{Bk} \]

\[ ^{5.2}\text{Cm} \rightarrow ^{3.0}\text{Cm} \]

\[ ^{6.4}\text{Am} \rightarrow ^{3.0}\text{Am} \]

\[ ^{7.1}\text{Pu} \rightarrow ^{5.3}\text{Pu} \]

\[ ^{8.8}\text{Np} \rightarrow ^{4.7}\text{Np} \]

\[ ^{11.4}\text{U} \rightarrow ^{4.7}\text{U} \]

n-capture and beta-decays
Radioactivity in Spent Fuel

assume 99.5% of U and Pu was removed for reprocessing
Oklo Natural Nuclear Reactor
Oklo Natural Nuclear Reactor

Composition of Uranium Deposit

U-235/U-238 (%)

transverse position (meters)

dashed line=
Uranium abundance profile

solid line=
$^{235}$U abundance highly depleted

$^{235}$U is depleted to 0.42% from natural 0.72%
Abundances of Nd Isotopes at Oklo

Fission products $^{143-150}$Nd all have larger than normal abundances compared to $^{142}$Nd.
Radiative Neutron Capture Cross-Section on $^{149}\text{Sm}$

The first resonant state can absorb thermal neutrons

$(3kT = 0.078 \text{ eV}, T = 300\text{K})$