Photons in the universe
Photons in the universe

- INFRARED
- UV
- HIGH-ENERGY
- X-RAY
- GAMMA
- MICROWAVE
- RADIO

WAVELENGTH:
- 5,000,000,000 nanometers
- 10,000 nanometers
- 500 nanometers
- 250 nanometers
- 0.5 nanometers
- 0.0005 nanometers

ENERGY:
- 0.000000248 electron volts
- 0.124 electron volts
- 2.48 electron volts
- 4.96 electron volts
- 2480 electron volts
- 2,480,000 electron volts

1 cm = 10,000,000 nanometers

NASA/CXC/SAO/MPE

nasa.gov
Element production on the sun
Spectral lines of hydrogen absorption

Light source

Absorption spectrum

Photographic film

Red

Violet

Hans-Jürgen Wollersheim - 2020
Hydrogen emission spectrum

wave length nm
Spectral analysis

Kirchhoff und Bunsen:
Every element has a characteristic emission band
Nuclear Resonance Fluorescence (NRF) is analogous to atomic resonance fluorescence but depends upon the number of protons AND the number of neutrons in the nucleus.
Low energy photon scattering at S-DALINAC

- "white" photon spectrum
- wide energy region examined

Eγ < 10 MeV

< 10 MeV

e−

Radiator target

Cu

Target

Electrons

Bremsstrahlung

Intensity vs. Energie

Intensity vs. Energie
Absorption processes

Absorption lines only a few eV wide!

- atomic attenuation
  - several processes
  - contributes at each energy
  - independent $d\Gamma_0$

- resonant absorption
  - only at resonance energies
  - depends $d\Gamma_0$

\[
\sigma_a \propto \Gamma_0 \cdot e^{-\left(\frac{E-E_r}{\Delta}\right)^2}
\]
Principle of measurement and self absorption

Use scatterer made of absorber material as „high-resolution detector“.

Self Absorption:
Decrease of Scattered Photons because of Resonant Absorption

\[
R(\Gamma_0) = \frac{N_{\text{woA}} - f \cdot N_{\text{wA}}}{N_{\text{woA}}} \\
f = \frac{N_{\text{std wA}}}{N_{\text{std woA}}}
\]
First $\gamma\gamma$-coincidences in a $\gamma$-beam

First $\gamma\gamma$-coincidences in a $\gamma$-beam

First $\gamma\gamma$-coincidences in a $\gamma$-beam

What is synchrotron radiation?

Electromagnetic radiation is emitted by charged particles when accelerated radially ($v \perp a$) is called synchrotron radiation. It is produced in the synchrotron radiation source using bending magnets, undulators and wigglers.

At the heart of the Crab nebula is a rapidly-spinning neutron star, a pulsar, and it powers the strongly polarized bluish ‘synchrotron’ nebula.
Properties of Synchrotron Radiation: Radiation Spectrum

The Electromagnetic Spectrum
Discovery of X-rays ~100 years ago

- X-ray were discovered (accidentally) in 1895 by Wilhelm Konrad Roentgen.
- Roentgen won the first Nobel Prize in 1901 “for the discovery with which his name is linked for all time: the … so-called Roentgen rays, as he himself called them, X-rays …”

first commercial X-ray tube
Lorentz Force: \[ \vec{F} = q \cdot (\vec{E} + \vec{v} \times \vec{B}) \]

Electromagnetic radiation produced by relativistic charged particles accelerated in circular orbits.
Synchrotron radiation was first observed (accidentally) from a 70 MeV synchrotron in 1947.

On April 24, 1947 Langmuir and I [Herbert Pollack] were running the machine and as usual were trying to push the electron gun and its associated pulse transformer to the limit. Some intermittent sparking had occurred and we asked the technician to observe with a mirror around the protective concrete wall. He immediately signaled to turn off the synchrotron as “he saw an arc in the tube”. The vacuum was still excellent, so Langmuir and I came to the end of the wall and observed. At first we thought it might be due to Cherenkov radiation, but it soon became clear that we were seeing Ivanenko and Pomeranchuk [i.e. synchrotron] radiation.
Radiation from moving charges

Charge at rest: Coulomb field, no radiation

Uniformly moving charge, no radiation (Cherenkov radiation)

Accelerating charge
- $v \parallel a \rightarrow \text{Bremsstrahlung}$, antennas
- $v \perp a \rightarrow \text{Synchrotron radiation}$
- Radiation becomes more focused at higher energies
Synchrotron radiation from relativistic electrons

\[ \lambda \approx \lambda' \cdot (1 - \beta \cdot \cos \theta) \]

angle dependent Doppler shift

\[ \lambda = \lambda' \cdot \frac{1 - \beta \cdot \cos \theta}{\sqrt{1 - \beta^2}} \]

\[ E_\gamma = E_{\gamma 0} \cdot \frac{\sqrt{1 - \beta^2}}{1 - \beta \cdot \cos \theta} \]
Synchrotron radiation from relativistic electrons

\[ \frac{d\Omega_{\text{rest}}}{d\Omega_{\text{lab}}} = \left( \frac{E_\gamma}{E_{\gamma 0}} \right)^2 \]

\[ \frac{E_\gamma}{E_{\gamma 0}} = \frac{\sqrt{1 - \beta^2}}{1 - \beta \cdot \cos \theta} \]
Radiation Patterns when $v$ approaches $c$

As $\beta$ approaches 1:

a. The shape of the radiation pattern is changing; it is more forward peaked

b. The size of the radiation pattern is changing; it is getting bigger

So at $\beta \approx 1$, the node at $\theta' = 90^0$ (in the frame of the radiating particle, rest frame) transforms to:

$$\tan \theta_{lab} = \frac{\sin \theta'}{\gamma \cdot (\cos \theta' + \beta)} = \frac{1}{\gamma \cdot \beta} \approx \frac{1}{\gamma}$$

In fact, the opening angle in both the horizontal and vertical directions, is given approximately by:

$$\theta = \frac{1}{\gamma}$$
**Synchrotron Radiation**

Consider a charged particle in homogeneous field $B$

- The acceleration in $B$ is given by

$$\dot{\beta}_\perp = \frac{\beta^2 c}{\rho} \quad \quad m\dot{v} = \frac{mv^2}{\rho}$$

where the bending radius of charged particle, $\rho$, at energy $E_e$ is

$$\frac{1}{\rho[m]} = \frac{e \cdot B \cdot c}{\beta \cdot E_e} = \frac{0.2998}{\beta \cdot E_e[GeV]}$$

Larmor radius

$$\rho = \frac{mv}{e \cdot B} = \frac{mc^2 \cdot v}{e \cdot B \cdot c^2} = \frac{E_e \cdot \beta}{e \cdot \beta \cdot c}$$

Then the instantaneous radiation power becomes

$$P = \frac{2 \cdot c \cdot r_e \cdot m_e c^2}{3} \cdot \frac{\beta^4 \cdot \gamma^4}{\rho^2} = \frac{c \cdot C_\gamma \cdot E_e^4}{2\pi \rho^2}$$

$C_\gamma \equiv \frac{4\pi}{3} \cdot \frac{r_e}{(m_e c^2)^3} = 8.85 \cdot 10^{-5} \left[ \frac{m}{GeV^3} \right]$ classical electron radius

$$r_e = \frac{e}{4\pi \cdot \varepsilon_0 \cdot m_e c^2}$$
Synchrotron Radiation Power and Energy Loss for Electrons

- Instantaneous Synchrotron Radiation Power for a single electron

\[ P_\gamma [GeV/s] = \frac{c \cdot C_\gamma \cdot E^4[GeV^4]}{2\pi \cdot \rho^2[m^2]} \quad \text{with} \quad C_\gamma = 8.8575 \cdot 10^{-5} \frac{m}{GeV^3} \]

- Energy loss per turn for a single particle in an isomagnetic lattice with bending radius \( \rho \) is given by integrating \( P_\gamma \) over the lattice

\[ \Delta E [GeV] = C_\gamma \cdot \frac{E^4[GeV^4]}{\rho [m]} \]

- The average Radiated Power for an entire beam is \( P = \frac{1}{e} \cdot \Delta E \)

\[ P_\gamma [MW] = 8.8575 \cdot 10^{-2} \cdot \frac{E^4[GeV^4]}{\rho [m]} \cdot I [A] \]

- Radiated Power varies as the inverse fourth power of particle mass. Comparing radiated power from a proton vs. an electron, we have:

\[ \frac{P_e}{P_p} = \left(\frac{m_p}{m_e}\right)^4 = 1836^4 = 1.1367 \cdot 10^{13} \]

\[ P_\gamma [MW] = 2.65 \cdot 10^{-2} \cdot E^3 [GeV]^3 \cdot B [T] \cdot I [A] \]
Total photon numbers

$$\dot{N}_{ph,le} = \frac{15\sqrt{3}\pi}{4} C_\psi I_e E_e$$

$$= 8.08 \times 10^{20} I[A] E_e [\text{GeV}] \quad [\text{photons/s}]$$
Some useful formulas for synchrotron radiation

\[ \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{1}{\sqrt{1 - \beta^2}}; \quad \beta = \frac{v}{c}; \quad (1 - \beta) \approx \frac{1}{2\gamma^2} \]

\[ E_e = \gamma \cdot mc^2; \quad p = \gamma \cdot mv \]

\[ \gamma = \frac{E_e}{mc^2} = 1957 \cdot E_e \text{ [GeV]} \]

\[ \hbar \omega \cdot \lambda = 1239.842 \text{ [eV} \cdot \text{nm]} \]

\[ 1 \text{ Watt} \Rightarrow 5.034 \cdot 10^{15} \cdot \lambda \text{ [nm]} \cdot \frac{\text{photons}}{s} \]

**Bending Magnet:** \[ E_c = \frac{3e \cdot \hbar \cdot B \cdot \gamma^2}{2m}; \quad E_c(\text{keV}) = 0.6650E_e^2 \text{ [GeV]} \cdot B[\text{T}] \]

**Undulator:** \[ \lambda = \frac{\lambda_u}{2\gamma^2} \cdot \left(1 + \frac{K^2}{2} + \gamma^2 \cdot \theta^2\right); \quad E(\text{keV}) = \frac{0.9496 \cdot E_e^2 \text{ (GeV)}}{\lambda_u(\text{cm}) \cdot \left(1 + \frac{K^2}{2} + \gamma^2 \cdot \theta^2\right)} \]

where \[ K \equiv \frac{e \cdot B_0 \cdot \lambda_u}{2\pi \cdot mc} = 0.9337 \cdot B_0(T) \cdot \lambda_u(\text{cm}) \]
Accelerator Synchrotron Sources

- Synchrotron radiation is generated in normal accelerator bending magnets.

- There are also special magnets called wigglers and undulators which are designed for this purpose.
Electrons are generated and accelerated in a **LINAC**, further accelerated to the required energy in a **booster** and injected and stored in a **storage ring**. The circulating electrons emit an intense beam of synchrotron radiation which is sent down the beamlines.
**Synchrotron Radiation Spectrum**

**Bending Magnet Radiation** covers a broad region of the spectrum, including the primary absorption edges of most elements.

\[ E_c = \hbar \omega_c = \frac{3e \cdot \hbar \cdot B \cdot \gamma^2}{2m} \]

\[ E_c(keV) = 0.6650 \cdot E_e^2(GeV) \cdot B(T) = 2.218 \cdot \frac{E_e^3[GeV]^3}{\rho[m]} \]

\[ \frac{d^2F_B}{d\theta \ d\omega/\omega} = 2.46 \cdot 10^{13}E_e(GeV) \cdot I(A) \cdot G_1(E/E_c) \cdot \frac{\text{photons/s}}{mrad \cdot (0.1\%BW)} \]

**Advantages:**
- cover broad spectral range
- least expensive
- most accessible

**Disadvantages:**
- limited coverage of hard X-rays
- not as bright as undulator
**Undulator:** Electron beam is periodically deflected by a weak magnetic field. Particle emits radiation at wavelength of the periodic motion, divided by $\gamma^2$. So period of cm for magnets results in radiation in VUV to X-ray regime.

**Wiggler:** Electron beam is periodically deflected by strong bending magnets. Motion is no longer pure sinusoid and radiation spectrum is continuous up to a critical cut off photon energy ($\varepsilon_{\text{crit}} \sim B \cdot \gamma^2$). Spectrum is infrared to hard X-rays.
Three Forms of Synchrotron Radiation

Bending magnet radiation

Wiggler radiation

Undulator radiation
An Undulator up close

ALS U5 undulator, beamline 7.0, $N = 89$, $\lambda_u = 50 \text{ mm}$
Undulator Radiation

Laboratory Frame of Reference:

\[ E = \gamma mc^2 \]
\[ \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \]
\[ N = \# \text{ periods} \]
\[ \lambda' = \frac{\lambda_u}{\gamma} \]

Frame of Moving e⁻:

\[ \theta = \sin^2 \Theta \]
\[ \lambda = \lambda' \gamma (1 - \beta \cos \theta) \]

Frame of Observer:

Doppler shortened wavelength on axis:
\[ \lambda = \frac{\lambda_u}{2\gamma^2} \left(1 + \gamma^2 \theta^2 \right) \]
\[ \theta_{cen} \approx \frac{1}{\gamma \sqrt{N}} \]

Following Monochromator:

For \[ \frac{\Delta \lambda}{\lambda} \approx \frac{1}{N} \]
\[ \theta_{cen} \approx 40 \text{ rad} \]

Accounting for transverse motion due to the periodic magnetic field:
\[ \lambda = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2} + \gamma^2 \theta^2 \right) \]

where \( K = \frac{eB_0 \lambda_u}{2\pi mc} \)
How to characterize the properties of a synchrotron radiation source?

Total flux \( \equiv \frac{\text{Photons}}{s} \)

Spectral flux \( \equiv \frac{\text{Photons/s}}{0.1\% \text{ bandwidth}} \)

Brightness \( \equiv \frac{\text{Photons/s}}{\text{mrad}^2 \cdot 0.1\% \text{ bandwidth}} \)

Brilliance \( \equiv \frac{\text{Photons/s}}{\text{mrad}^2 \cdot \text{mm}^2 \cdot 0.1\% \text{ bandwidth}} \)

Brilliance is the figure of merit for the design of a new synchrotron source.
Brilliance takes into account:

1. Number of photons produced per second
2. The angular divergence of the photons, or how fast the beam spreads out
3. The cross-section area of the beam
4. the photons falling within a bandwidth of 0.1% of the central wavelength or frequency

SRS = Synchrotron Radiation Source
Electrons are generated and accelerated in a **LINAC**, further accelerated to the required energy in a **booster** and injected and stored in a **storage ring**. The circulating electrons emit an intense beam of synchrotron radiation which is sent down the beamlines.

*Soleil, France*
Applications

Medicine, Biology, Chemistry, Material Science, Environmental Science and more

**Biology**
Reconstruction of the 3D structure of a nucleosome with a resolution of 0.2 nm

**Archeology**
A synchrotron X-ray beam at the SSRL facility illuminated an obscured work erased, written over and even painted over of the ancient mathematical genius Archimedes $287\,\text{B.C.}$

The collection of precise information on the molecular structure of chromosomes and their components can improve the knowledge of how the genetic code of DNA is maintained and reproduced

X-ray fluorescence imaging revealed the hidden text by revealing the iron contained in the ink used by a 10th century scribe. This X-ray image shows the lower left corner of the page.
Protein Crystallography

Protein crystal

X-rays

Diffraction pattern
Bragg Scattering in Crystals

- Regular structure (crystal)
- Monochromatic light

⇒ Diffractive Pattern
Imaging of magnetic domains

Circularly polarized SR, $E = 778$ eV

Co/Pt multilayer
Microstructure of bones: Development during Osteoporosis disease

Microstructure of ice crystals in snow

Structure of wet snow
Future experiments with Synchrotron Radiation

**Improvement of:**

* Spatial resolution
* Energy resolution
* Time resolution

Most of present-day experiments are dealing with equilibrium properties of condensed matter. In the future, non-equilibrium properties will be of great interest:

Dynamics of phase transitions, magnetic switching phenomena, chemical reactions etc.

Reveal the underlying mechanisms by taking snapshots on ultrashort time scales!
Future experiments with Synchrotron Radiation

Time Scales in Magnetism

- Domain Propagation
- Spin-Lattice Relaxation
- Spin Precession
- Spin-Orbital Exchange
New radiation sources

**Limits of Storage – Ring Based Sources**

Beam properties reflect the equilibrium Dynamics of particle in the ring, resulting from averaging over all revolutions

Particles are re-cycled

**Development of New Radiation Sources**

Radiation is generated by single bunches passing through an undulator

Energy – Recovery Linear Accelerator (ERL)
Sub-Picosecond Pulsed Sources (SPPS)
X-ray Free Electron Laser (XFEL)
New radiation sources

*Limits of Storage – Ring Based Sources*

Beam properties reflect the equilibrium Dynamics of particle in the ring, resulting from averaging over all revolutions

Particles are re-cycled

*Development of New Radiation Sources*

Radiation is generated by single bunches passing through an undulator

Energy – Recovery Linear Accelerator (ERL)
Sub-Picosecond Pulsed Sources (SPPS)
X-ray Free Electron Laser (XFEL)
X-ray free electron laser

self-amplified spontaneous emission

Explosion of a biomolecule (T4 lysozyme) after exposure to a 2-fs XFEL pulse (E=12 keV)

Desy XFEL
Total power received by Earth from the Sun

174 Peta ($10^{15}$) Watt

89 PW absorbed by land and oceans

extreme light infrastructure, Europe
Compton scattering and inverse Compton scattering

Compton scattering:
- Elastic scattering of a high-energy $\gamma$-ray on a free electron.
- A fraction of the $\gamma$-ray energy is transferred to the electron.
- The wave length of the scattered $\gamma$-ray is increased: $\lambda' > \lambda$.

$$h\nu \geq m_e c^2$$

$$\lambda' - \lambda = \frac{h}{m_e c} \cdot (1 - \cos \theta_\gamma)$$

$$E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2} \cdot (1 - \cos \theta)}$$

Inverse Compton scattering:
- Scattering of low energy photons on ultra-relativistic electrons.
- Kinetic energy is transferred from the electron to the photon.
- The wave length of the scattered $\gamma$-ray is decreased: $\lambda' < \lambda$.

$$\lambda' \approx \lambda \cdot \frac{1 - \beta \cdot \cos \theta_\gamma}{1 + \beta \cdot \cos \theta_L}$$
Inverse Compton scattering

- Electron is moving at relativistic velocity
- Transformation from laboratory frame to reference frame of e⁻ (rest frame):
  
  \[ E' = \frac{E \gamma}{1 + \frac{E \gamma}{m_e c^2} \cdot (1 - \cos \phi)} \]

  Doppler shift

  \[ E' = \gamma \cdot E' \left( 1 + \frac{\nu}{c} \cos \theta_{e^{-}-\gamma'} \right) \]

  Compton scattering in rest frame of e⁻

  transformation into the laboratory frame

- Limit \( E \gamma \ll m_e c^2 \)
  
  \[ E' \approx \gamma^2 \cdot E \left( 1 - \frac{\nu}{c} \cos \theta_{e^{-}-\gamma} \right) \left( 1 + \frac{\nu}{c} \cos \theta_{e^{-}-\gamma'} \right) \]

  \[ E' \approx 4 \gamma^2 \cdot E \gamma \]

  electron and γ interaction \( \theta_{e^{-}-\gamma} \sim 180^0 \)  
  γ⁺ emission relative to electron \( \theta_{e^{-}-\gamma'} \sim 0^0 \)
Laser Compton backscattering

Energy – momentum conservation yields $\sim 4\gamma^2$ Doppler upshift.

Thomson's scattering cross section is very small ($6 \cdot 10^{-25} \text{ cm}^2$).

High photon and electron density are required.
Gamma rays resulting after inverse Compton scattering

photon scattering on relativistic electrons ($\gamma >> 1$)

\[ h\nu = 2.3 \text{ eV} \ (\equiv 515 \text{ nm}) \]
\[ T_{e}^{\text{lab}} = 720 \text{ MeV} \rightarrow \gamma_e = 1 + \frac{T_{e}^{\text{lab}}[\text{MeV}]}{931.5 \cdot A_{e}[u]} = 1410 \]

\[ E_\gamma = 2\gamma_e^2 \frac{1 + \cos\theta_L}{1 + (\gamma_e \theta_\gamma)^2 + a_0^2 + \frac{4\gamma_e E_L}{mc^2}} \cdot E_L \]

\[ \frac{4\gamma_e E_L}{mc^2} = \text{recoil parameter} \]
\[ a_L = \frac{eE}{m\omega_L c} = \text{normalized potential vector of the laser field} \]
\[ E = \text{laser electric field strength} \ E_L = \hbar \omega_L \]
\[ \gamma_e = \frac{E_e}{mc^2} = \frac{1}{\sqrt{1-\beta^2}} = \text{Lorentz factor} \]

**maximum frequency amplification:**
head-on collision ($\theta_L = 0^0$) & backscattering ($\theta_\gamma = 0^0$)

\[ E_\gamma \sim 4\gamma_e^2 \cdot E_L \approx 18.3 \text{ MeV} \]
Scattered photons in collision

\[ Q = 1[nC] \quad U_L = 0.5[J] \quad h\nu_L = 2.4[eV] = 3.86 \cdot 10^{-19}[J] \equiv 515[nm] \]

\[ \Rightarrow N_e = 6.25 \cdot 10^9 \quad \Rightarrow N_L = 1.3 \cdot 10^{18} \]

\[ \text{Luminosity: } L = \frac{N_L \cdot N_e}{4\pi \cdot \sigma_R^2} \cdot f \equiv 2.9 \cdot 10^{32} \cdot f \text{ [cm}^{-2}\text{s}^{-1}] \quad \sigma_R = 15[\mu m] \]

\[ \gamma\text{-ray rate: } N_\gamma = L \cdot \sigma_{Thomson} \equiv 2 \cdot 10^8 \cdot f \text{ [s}^{-1}] \quad \sigma_T = 0.67 \cdot 10^{-24}[cm^2] \]

(repetition rate: \( f = 3.2 \text{ kHz} \))
Thomson scattering = elastic scattering of electromagnetic radiation by an electron at rest
- the electric and magnetic components of the incident wave act on the electron
- the electron acceleration is mainly due to the electric field
  → the electron will move in the direction of the oscillating electric field
  → the moving electron will radiate electromagnetic dipole radiation
  → the radiation is emitted mostly in a direction perpendicular to the motion of the electron
  → the radiation will be polarized in a direction along the electron motion
Thomson Scattering

J. J. Thomson
Nobel prize 1906

\[
\frac{d\sigma_T(\theta)}{d\Omega} = \frac{1}{2} r_0^2 \cdot (1 + \cos^2 \theta)
\]
differential cross section

\[
r_0 = \frac{e^2}{4\pi\varepsilon_0 m_e c^2} = 2.818 \cdot 10^{-15} \ [m]
\]
classical electron radius

\[
\sigma_T = \int \frac{d\sigma_T(\theta)}{d\Omega} d\Omega = \frac{2\pi r_0^2}{2} \int_0^\pi (1 + \cos^2 \theta) d\theta = \frac{8\pi}{3} r_0^2 = 6.65 \cdot 10^{-29} \ [m^2] = 0.665 \ [b]
\]
Scattered photons in collision

\[ E_\gamma = 2\gamma_e^2 \frac{1 + \cos \theta_L}{1 + (\gamma_e \theta_y)^2 + a_0^2 + \frac{4\gamma_e E_L}{mc^2}} \cdot E_L \]

\( \theta = \pi \)

\( \theta = 0 \)

\( \sin \theta = 1/\gamma \)

Energy spectrum

Gammas energy vs angles

Photon extraction line

- Collimator 1: \( d=11 \text{ m} \ r=0.3 \text{ cm}, t=5 \text{ cm (W)} \)
- Collimator 2: \( d=15 \text{ m} \ r=0.1 \text{ cm}, t=5 \text{ cm (W)} \)
Inverse Compton scattering of laser light
Extreme Light Infrastructure – Nuclear Physics

- High Energy IP
- Low Energy IP
- e⁻ beam dump
- Photogun multibunch
- γ beam coll&diag
- Photogun multibunch
- Interaction Laser High Energy
- e⁻ RF LINAC High Energy 750 MeV
- Interaction Laser Low Energy
- e⁻ RF LINAC Low Energy 350 MeV
- Photo-drive Laser e⁻ source
• Widths of particle-bound states: $\Gamma \leq 10\text{eV}$

• Breit-Wigner absorption resonance curve for isolated resonance:

$$
\sigma_a(E) = \pi \bar{\lambda}^2 \frac{2J + 1}{2} \frac{\Gamma_0 \Gamma}{(E - E_r)^2 + (\Gamma/2)^2} \sim \Gamma_0 / \Gamma
$$

• Resonance cross section can be very large: $\sigma_0 \approx 200 \ [b]$ (for $\Gamma_0 = \Gamma$, 5 MeV)

• Example: 10 mg, A~200 $\rightarrow N_{\text{target}} = 3 \cdot 10^{19}$, $N_\gamma = 100$, event rate = 0.6 [s$^{-1}$]
Count rate estimate

- $10^4 \gamma/(s \ eV)$ in 100 macro pulses
- 100 $\gamma/(s \ eV)$ per macro pulse
- example: 10 mg, $A \sim 200$ target
- resonance width $\Gamma = 1$ eV
- 2 excitations per macro pulse
- 0.6 photons per macro pulse in detector
- pp-count rate 6 Hz
- 1000 counts per 3 min

- narrow band width 0.5%

8 HPGe detectors
2 rings at $90^0$ and $127^0$
$\varepsilon_{rel}(\text{HPGe}) = 100\%$
solid angle $\sim 1\%$
photopeak $\varepsilon_{pp} \sim 3\%$
- narrow bandwidth allows selective excitation and detection of decay channels
Deformation and Scissors Mode

- Decay to intrinsic excitations