Abstract

Collisions between photons of very high energy and intensity can be used to produce elementary particles. In photon colliders high energy photons are generated by Compton scattering of visible light on high energy electrons[1]. In order to get high energy electrons, we need linear accelerators. In this seminar I will explain the basic operation of linear accelerators, the layout of photon colliders and characteristics of photon spectrum.
1. Introduction

A common knowledge is that visible light does not interact with visible light. This is a consequence of linearity of electrodynamic equations. However, when intensity of photon beams becomes greater, one beam does begin to interact with the other. The effect of scattering light on light is purely a quantum mechanical effect; it would not happen classically[2]. If we increase the frequency of the light at first quantum electrodynamic effects occur, and pairs of electrons and positron are produced. At higher frequencies quantum chromodynamic effect occur, and elementary particles are produced.

The goal of photon colliders is to use the effects we just described, to make intense beams of gamma rays and having them collide so as to make elementary particles. Photon colliders use Compton scattering of visible light on high energy electrons for producing high energy gamma rays. Gamma rays are then collided to produce elementary particles.

The idea of constructing a gamma-gamma collider as an add-on to an electron-positron linear collider is possible with present technology and that it does not require much additional cost. Furthermore the resulting capability is very interesting from a particle physics point of view.

In the following chapters I will first describe linear accelerators, that are used for producing high energy electrons, some characteristics of colliders in general, then photon kinematics and spectra, at the end I will present physical reactions that can be studied with photon colliders.
2. Linear accelerator

A linear particle accelerator was invented in 1928 by Rolf Wideroe[3]. This type of particle accelerator is used to increase the velocity of charged subatomic particles or ions. In a linear particle accelerator particles are subjected to a series of oscillating electric potentials along a linear beamline. This machine is shortly called as linac.

Many applications like the generation of X-rays or radiotherapy and radiosurgery use linacs. Linacs can also be used for injecting particles into higher-energy accelerators or for the investigation of subatomic particles. Different types of particles are accelerated (electrons, protons or ions), depending on type of use. Linacs can have very different sizes from a 0.2 m to around 3 km long linac at the SLAC National Accelerator Laboratory.

Particles are accelerated in a straight line until reaching a target at one end. Often they are used to provide an initial low-energy kick to particles before they are injected into circular accelerators. To accelerate particles they use a linear array of plates (or drift tubes) to which an alternating high-energy field is applied. When particles approach a plate they are accelerated towards it by an opposite polarity charge applied to the plate[4]. As they pass through a hole in the plate, the polarity is switched so that the plate now repels them and they are now accelerated by it towards the next plate. Particles are usually accelerated in "bunches", so a carefully controlled alternating voltage is applied to each plate to continuously repeat this process for each bunch.

As the particles approach the speed of light the switching rate of the electric fields becomes so high that they operate at microwave frequencies. Consequently radio-frequency(RF) cavity resonators are used in higher energy machines instead of simple plates.

A linear particle accelerator is made of the following parts:

- Source of particles. Sources for electrons are a cold cathode, a hot cathode, a photocathode, or radio frequency ion sources. For protons or heavier particles (e.g. uranium ions) a specialized ion source is needed.
- A hollow vacuum waveguide. If the machine is used for X-ray production for inspection or therapy the waveguide is 0.5 to 1.5 meters long. In a synchrotron is around ten meters long. In a primary accelerator for nuclear particle investigations, it is several thousand meters long (figure 1).
- A high voltage generator for injecting particles into the waveguide.
- The waveguide contains electrically isolated cylindrical electrodes. Electrodes have different length along the waveguide. The length is calculated from the frequency and power of the driving power source and the nature of the particle. Segments are shorter near the source and become longer near the target. The mass of the particle has a large effect on the length of the electrodes.
- An appropriate target. Particles from a linac can be shot onto a fixed target or particles from two linacs can be collided creating head on particle collisions.

There is a difference between proton and electron acceleration. Protons are much heavier than electrons. For protons the accelerating structures (distance between gaps) need to be adapted to the changing velocity. Electrons instead are almost immediately relativistic and one
can use the same accelerating structure (optimised for \( v = c \)) for the entire linac. An electron is considerably lighter than a proton and so will generally require a much smaller section of cylindrical electrodes as it accelerates very quickly. Similarly, because their mass is so small, electrons have much less kinetic energy than protons at the same speed. Because of the possibility of electron emissions from highly charged surfaces, the voltages used in the accelerator have an upper limit, so we cannot just increase voltage to match increased mass.

In this seminar we will focus our attention on linear accelerators for electrons (positrons).

The energy gain of an electron passing a gap of length \( L \) with uniform electric field \( E \) is:

\[
\Delta W = e_0 \int_{-L/2}^{L/2} E_z(t) \, dz;
\]

\[ E_z(t) = E_0 \cos(\omega t(z)) \]

The particle speed is not necessarily constant. For the energies when the velocity becomes almost constant, we can assume \( t(z) = z/v + t_0 \). We get:

\[
\Delta W = e_0 E_0 \int_{-L/2}^{L/2} \left( \cos(\omega z/v + \omega t_0) \right) \, dz = e_0 E_0 L_0 \sin(L/L_0 + \omega t_0), \quad \text{where} \ L_0 = 2v/\omega
\]

The oscillatory electric field is used not only to speed up particles, but also to concentrate them in bunches. In order to speed up particles \( (\Delta W > 0) \), they have to be injected in the accelerator when alternating field is increasing, before it has reached maximum value. The particles that reach the gap too early are less accelerated than particles that come too late. In this way the middle of the bunch reaches all the gaps at the same phase. The bunch does not spread, it oscillates around a stable phase. This is called phase stabilization (figure 2).
Magnets surrounding the linear accelerator are used for focusing the beam (quadrupole magnets) and chromatic correction. We will focus our attention on quadrupoles (figure 3).

A quadrupole magnet consists of four magnetic poles arranged in a way that poles of same polarity stand in front of each other. The dimension of a quadrupole magnet depends on the particle momentum. Typical dimensions are of the order of 0.5 m. The total force on a particle with charge $e_0$ moving along the z-axis is the Lorentz force:

$$\vec{F} = e_0 \vec{v} \times \vec{B}$$

In our case the components are:

$$F_x = -e_0 v_0 z B_y, \quad F_y = e_0 v_0 z B_x, \quad F_z = 0.$$  

$B$ is positive for negative values of $x$ and negative for positive values of $x$. Consequently the component $F_x$ is always positive. The force $F_x$ deflects the particle away from the axis. The force $F_y$ instead converges the particle towards the axis.

The force on the positive particle is proportional to the distance from the axis. A linearly dependent magnetic field is sufficient:

$$B_x = -ay, \quad B_y = -ax,$$

where $a$ is a positive constant.

The motion of a particle is described by the following differential equations:

$$m \frac{d^2 x}{dt^2} = e_0 v_0 x, \quad m \frac{d^2 y}{dt^2} = -e_0 v_0 y$$
where $v$ is the particle speed.

At $v = \text{const.}$ we get $z = vt$ $\Rightarrow$ $\frac{d^2x}{dt^2} = \frac{d^2x}{dz^2} v^2$, $\frac{d^2y}{dt^2} = \frac{d^2y}{dz^2} v^2$

The solution of the equations is:

$$x = \frac{x'(0)}{K} \sinh Kz + x(0) \cosh Kz, \quad y = \frac{y'(0)}{K} \sin Kz + y(0) \cos Kz; \quad K = \sqrt{\frac{e_{0a}}{mv}}$$

We can write the equation in matrix form:

$$\begin{bmatrix} x(z) \\ x'(z) \end{bmatrix} = \begin{bmatrix} \cosh Kz & \frac{1}{K} \sinh Kz \\ K \sinh Kz & \cosh Kz \end{bmatrix} \cdot \begin{bmatrix} x(0) \\ x'(0) \end{bmatrix}$$

$$\begin{bmatrix} y(z) \\ y'(z) \end{bmatrix} = \begin{bmatrix} \cos Kz & \frac{1}{K} \sin Kz \\ -K \sin Kz & \cos Kz \end{bmatrix} \cdot \begin{bmatrix} y(0) \\ y'(0) \end{bmatrix}$$

In the limit of short quadrupoles (thin lens) we can assume that $Kz \ll 1$. If we assume also that particle moves parallel to the z axis at a finite distance from the axis ($x(0), y(0)$ are finite and $x'(0) = y'(0) = 0$), we get:

$$x(z) \approx x(0), \quad x'(z) \approx x'(0) K^2 z$$

$$y(z) \approx y(0), \quad y'(z) \approx -y'(0) K^2 z$$

This indicates that a single magnet is focusing in y direction and defocusing in x direction. Because of this we need two magnetic quadrupoles that are shifted in phase by $90^\circ$ placed one after another to focus the beam in both perpendicular directions. Particle accelerators can have hundreds of quadrupole pairs. They are positioned at places where beam focusing is needed.

### 2.1 Collisions

Particle colliders are machines that use particle accelerators for speeding up particles and collide them with a fixed target or collide particles on particles. When particles collide the difference between kinetic energy and rest energy of the particles becomes available for the creation of new particles. According to equation $E = mc^2$ new particles with mass $m$ can be produced. The greater is the kinetic energy, more massive particles can be produced.

However not all the accelerated particles will collide. The probability for the collision is proportional to the cross section for a collision. The most important parameter for a collider is luminosity:

$$L = \frac{N_1 N_2 \nu}{4\pi \sigma_x \sigma_y},$$

where $N_1$ is the number of particles from the $e^+$ accelerator, $N_2$ is the number of particles from the $e^-$ accelerator, $\nu$ is the collision frequency, $\sigma_x$ and $\sigma_y$ are collision cross-sections for x and y direction.

The event rate $dN/dt$ in a collider is proportional to the interaction cross section $\sigma_{\text{int}}$ and luminosity:

$$\frac{dN}{dt} = L \sigma_{\text{int}}$$
3. Linac upgrade

In 1963 a group of Russian researchers[8] first produced high energy photons by Compton scattering of laser light off high energy electrons. Unfortunately, the conversion coefficient (number of photons generated from one electron) was very small (only $k \approx 10^{-7}$). For a photon collider we need $k \approx 1$. In the early 1980s Ginzburg et al.[1] proposed to create a photon-photon collider by adding high power lasers to an electron linear collider. This proposal opens up new possibilities for the study of elementary particles.

Due to the synchrotron radiation problem in $e^+e^-$ storage ring the energy above 500 GeV can only be explored by linear colliders. Linear colliders offer the opportunity to study $\gamma\gamma$, $\gamma e$ interactions. Using the laser backscattering method one can obtain $\gamma\gamma$ and $\gamma e$ colliding beams with an energy and luminosity comparable to that in $e^+e^-$ collisions.

Below are some arguments for photon colliders:

1. Some phenomena can be studied at photon colliders better than anywhere, for example, the measurement of the Higgs boson properties, described in some more details below.

2. Cross sections for the pair production of various known as well as so far undiscovered (but theoretically predicted) particles are larger in $\gamma\gamma$ collisions than those in $e^+e^-$ collisions by a factor of about 5[9]; for WW production (W+ and W- bosons are the carriers of the charged weak interaction) this factor is even larger: 10-20.

3. In $\gamma e$ collisions heavy charged and light supersymmetric particles can be produced directly, while in $e^+e^-$ collisions they are accessible via intermediate decay products. As a consequence, at the same center of mass energy, $\gamma e$ colliders provide more possibilities to study the properties of such particles than $e^+e^-$ colliders.

4. Linear colliders are very expensive facilities and their potential should be used in the best way. Two detectors (one for $e^+e^-$ and the other for $\gamma\gamma$ and $\gamma e$) can give much more results than the simple doubling of statistics in $e^+e^-$ collisions with one detector.

In wish to increase the number of accessible reactions, it is very important that a future linear collider, will be provided with at least two interaction regions (IRs): one for $e^+e^-$ collisions and a second one for $\gamma\gamma$ and $\gamma e$ collisions. The interaction region for a $\gamma\gamma$ collider consists of two conversion points (CPs), where the Compton conversion occurs, and the interaction point (IP) where the collisions of $\gamma\gamma$ occur(figure 4).

![Figure 4](image-url)
4. Photon collider at ILC

In the next 5 years the construction of The International Linear Collider (ILC) is planned to start. The location for the ILC has not yet been decided. It is a proposed linear particle accelerator that will have a collision energy of 500 GeV initially. It will be possible to upgrade it to 1000 GeV (1 TeV)[10]. The ILC will collide electrons with positrons. It will be between 30 km and 50 km long, making it the longest linear accelerator ever built. The ILC has a photon interaction region included.

A competing project called the Compact Linear Collider (CLIC) is also promising. CLIC has significantly higher energies (3 to 5 TeV) and is smaller than the ILC.

5. Gamma rays

5.1 Producing the gamma rays

The best manner to make intense gamma rays is by Compton back-scattering of almost visible photons from an intense, high energy electron beam. A diagram of the creation of gamma rays in the conversion region is shown on figure 5.

The laser light is focused on the electron beam in the conversion region C, at a distance of \( b \) cm from the interaction point IP[1]. After Compton scattering, the high energy photons follow along the initial electron trajectories with a small additional angular spread \( \approx \frac{1}{\gamma} \), i.e., they are in focus at the interaction point IP. The \( \gamma \) beam collides either with an oppositely directed electron beam or another \( \gamma \) beam.

![Collision scheme](image)

Figure 5: Collision scheme[1].
5.2 Spectrum and helicity

Here we will discuss the main characteristics of backward Compton scattering. The Feynman diagram for this process can be seen on figure 6.

![Feynman Diagrams](image)

Figure 6: Left: Feynman diagram for Compton scattering, right: Compton scattering of photons on relativistic electrons.

Instead of normal Compton scattering, we have Compton scattering of photons on relativistic electrons. In the conversion region, a laser photon of energy $\hbar \omega_0$ collides with a high-energy electron of energy $E_0$ at a small collision angle $\alpha_0$ (almost head-on). The energy of the scattered photon $\hbar \omega$ depends on the photon scattering angle $\theta$ with respect to the initial direction of the electron.

If we assume the angles $\alpha_0$ and $\theta$ are small, we can calculate the energy of the scattered photon from conservation of four-momentum:

- four-momentum of electron before collision: $(E_0, cp_0, 0, 0)$
- four-momentum of photon before collision: $(\hbar \omega_0, -\hbar \omega_0, 0, 0)$
- four-momentum of electron after collision: $(E, cp, 0, 0)$
- four-momentum of photon after collision: $(\hbar \omega, \hbar \omega, 0, 0)$

Conservation of energy gives us the equation:

$$E_0 + \hbar \omega_0 = E + \hbar \omega$$

Conservation of momentum gives us the equation:

$$cp_0 - \hbar \omega_0 = -cp + \hbar \omega$$

Using $E_0 \approx cp_0$ and $E = \sqrt{m^2c^4 + c^2p^2}$ we get: $\hbar \omega \approx cp_0 - \sqrt{m^2c^4 + (-cp_0 + \hbar \omega_0 + \hbar \omega)^2 + \hbar \omega_0}$ and finally

$$\hbar \omega \approx cp_0 - \frac{m^2}{4\hbar \omega_0}$$

If we consider collisions are not colinear ($\alpha_0$ and $\theta$ cannot be neglected), we get a more general equation as described in[1]:

$$\hbar \omega = \frac{\hbar \omega_m}{1 + (\theta/\theta_0)^2}, \quad \hbar \omega_m = \frac{x}{x+1} E_0, \quad \theta_0 = \frac{mc^2}{E_0} \sqrt{x + 1},$$
\[ x = \frac{4E\hbar \omega_0}{m^2 c^4 \cos^2 \alpha_0} \approx 19 \left[ \frac{E_0}{\text{TeV}} \right] \frac{\mu m}{\lambda}, \]

where \( \hbar \omega_m \) is the maximum energy of a scattered photon and \( x \) is a dimensionless quantity that measures the energy of the colliding system.

For typical values \( E_0 = 250 \text{ GeV}, \hbar \omega_0 = 1.17 \text{ eV} \) (\( \lambda = 1.06 \mu m \)) (most powerful solid-state lasers) we get: \( x = 4.5 \) and \( \hbar \omega_m/E_0 = 0.82 \). Formulae for the Compton cross section can be found elsewhere[11].

With increasing \( x \), the energy of the backscattered photons increases, and the energy spectrum becomes narrower. However, at large values of \( x \), photons may be lost due to creation of \( e^+ e^- \) pairs in collisions with laser photons[1]. The threshold of this reaction is \( \hbar \omega_m \hbar \omega_0 = m^2 c^4 \), which corresponds to \( x = 2(1 + \sqrt{2}) \approx 4.8 \). One can work above this threshold, but with a reduced luminosity. Therefore, \( x \approx 4.8 \) is the most preferable value. The corresponding wavelength of laser photons is \( \lambda = 4.2E_0 [\text{TeV}] \mu m \).

The resulting gamma rays will have a spectrum that extends up to approximately 80 percent of the electron energy. The energy spectrum of the scattered photons depends on the average electron helicity and that of the laser photons.

Helicity is the projection of the spin \( \vec{S} \) onto the direction of momentum \( \vec{p} \):

\[ h = \vec{J} \cdot \hat{\vec{p}} = \vec{L} \cdot \hat{\vec{p}} + \vec{S} \cdot \hat{\vec{p}} = \vec{S} \cdot \hat{\vec{p}}; \quad \hat{\vec{p}} = \frac{\vec{p}}{|\vec{p}|} \]

In our case helicity of electrons is denoted by \( \lambda_e \) and helicity of laser photons by \( P_c \). The "quality" of the photon beam, i.e., the relative number of hard photons, is improved when one uses beams with a negative value of \( \lambda_e P_c \). The energy spectrum of the scattered photons for \( x = 4.8 \) is shown in figure 7 for various helicities of the electron and laser beams.

![Figure 7: Energy spectrum of Compton scattered photons for three combinations of laser photon \( \lambda_l \) and electron \( P_c \) helicities: a) \( 2\lambda_l P_c = -1 \), b) \( 2\lambda_l P_c = 0 \) and c) \( 2\lambda_l P_c = 1 \).](image)

The mean helicity of backscattered photons at \( x=4.8 \) is shown in figure 8 for various helicities of the electron and laser beams.

![Figure 8: Mean helicity of backscattered photons at \( x=4.8 \).](image)
If we want to use electrons from $e^+e^-$ accelerators, we need to produce one gamma ray from one electron, because in a collision between a laser photon and an electron, the electron transfers almost all of its energy to the photon and is therefore not available for the production of another gamma ray. From the cross-sectional area of the laser pulse, we can estimate that about $10^9$ laser photons need to be collided with each electron to make one high energy photon (gamma ray) back-scattered\cite{2}. For a typical collider bunch of $10^{10}$ electrons, we need $10^{19}$ laser photons. If the incident photon intensity is too large, there will be undesirable nonlinear quantum electrodynamic effect. These can be simply avoided by making the conversion region longer.

The incident photons must not be too energetic. If they are the incident photon stream will interact with the back-scattered gamma rays and produce electron pairs. Furthermore, one should be close to the limit. Thus for a 250 GeV $\times$ 250 GeV collider, the photon wavelength should be about 1 $\mu$m. Now a 1 micron photon has an energy of 1 eV and thus, although $10^{19}$ photons is a lot of photons, it is only about 1 J of energy. A laser able to produce an energy of 1 J is not excessive at all. Such lasers are common today.

6. The laser

A key element of photon colliders is a powerful laser system which is used for $e \rightarrow \gamma$ conversion. The main problem used to be the high repetition rate, about 10-15 kHz, with a pulse structure repeating the time structure of the electron bunches. Lasers with the required flash energies $\approx 1$ J, pulse duration $\approx 1$ ps and 10-15 kHz repetition rate are available today.

For constructing an optical system for the photon collider, we have to predict the required laser power and flash energy. The dependence of the conversion coefficient on the laser flash energy $A$ can be written as

$$k = N_\gamma/N_e \approx 1 - e^{-A/A_0},$$

where $A_0$ is the laser flash energy for which the thickness of the laser target is equal to one Compton collision length. The value of $A_0$ can be roughly estimated from the collision
probability. The flash energy is proportional to the electron bunch length. For \( \sigma_z = 0.3 \) mm (r.m.s. length of laser bunch at ILC) it is about 1 J.

7. Examples of possible particle physics studies

If the Higgs boson will be discovered at the Large Hadron Collider (LHC), photon colliders will be very useful to produce enough amounts of this particle to study it in detail. While the hadron colliders - such as the LHC - are extremely capable machines to search for yet undiscovered particles in a wide range of high energies, the \( e^+e^- \) colliders and their possible extension to the \( \gamma\gamma \) colliders are much more appropriate for detailed studies of individual particle properties. In the hadron collisions the interaction happens among the quarks inside the hadrons, causing the latter to decay and producing a huge amount of final state particles detected by the detectors. On the other hand, in the \( e^+e^- \) collisions typically a single (or a pair of particles) is produced resulting in a final states composed of only particles to which the particle under the study decays into. The most important photon collider program would be the measurement of the Higgs boson properties.

The Higgs boson is a hypothetical particle that is predicted by the Standard Model (SM) of particle physics. From recent experiments on the LHC it is estimated Higgs has a mass between 115 GeV/\( c^2 \) and 135 GeV/\( c^2 \) (figure 9). Bosons are characterized by an integer value of their spin quantum number. The existence of the Higgs boson, if confirmed, will explain how spontaneous breaking of electroweak symmetry (the Higgs mechanism) takes place in nature and consequently why other elementary particles have mass.

![Figure 9: Diphoton invariant mass spectra. The bottom plot shows the residual of the data with respect to the fitted background. The signal expectation for a Higgs boson with a mass of 120 GeV is shown on top of the background fit[12].](image)

The cross sections for pairs of scalars, fermions or vector particles are all significantly larger (about one order of magnitude) in \( \gamma\gamma \) collisions compared with \( e^+e^- \) collisions. For example, the maximum cross section for supersymmetric \( H^+H^- \) production with unpolarised photons is about 7 times higher than that in \( e^+e^- \) collisions[13]. With polarised photons and not far from
threshold it is even larger by a factor of 20[13]. Using the luminosity given in the Table 1 the event rate is 8 times higher.

\[
\begin{array}{|c|c|c|c|}
\hline
2E_0 [\text{GeV}] & 200 & 500 & 800 \\
W_{\gamma\gamma,\text{max}} [\text{GeV}] & 122 & 390 & 670 \\
W_{\gamma e,\text{max}} [\text{GeV}] & 156 & 440 & 732 \\
L_{\gamma\gamma} [10^{34} \text{ cm}^{-2} \text{s}^{-1}] & 0.43 & 1.1 & 1.7 \\
L_{e\gamma} [10^{34} \text{ cm}^{-2} \text{s}^{-1}] & 0.36 & 0.94 & 1.3 \\
L_{e^+e^-} [10^{34} \text{ cm}^{-2} \text{s}^{-1}] & 1.3 & 3.4 & 5.8 \\
\hline
\end{array}
\]

Table 1: Energy and luminosity of $\gamma\gamma$, $\gamma e$ collider based on ILC[13].

It is evident from Figure 10, that the cross section for production of the Higgs boson at the photon collider is several times larger than the Higgs production cross section in $e^+e^-$ collisions. Although the $\gamma\gamma$ luminosity is smaller than the $e^+e^-$ luminosity (Table 1), the production rate of the Standard Model (SM) Higgs boson with mass between 130 and 250 GeV in $\gamma\gamma$ collisions is 110 times the rate in $e^+e^-$ collisions at $2E_0 = 500$ GeV.

![Figure 10: Total cross sections of the Higgs boson production in $\gamma\gamma$ and $e^+e^-$ collisions. To obtain the Higgs boson production rate at the photon collider the cross section should be multiplied by the luminosity in the high energy peak $L_{\gamma\gamma}$ given in the Table 1[13].](image)

Hence the history may be repeated in some sense. In 1983 detectors UA1 and UA2 at the proton-antiproton collider at CERN discovered the neutral $Z^0$ bosons, carriers of the neutral weak interaction. In 1989 an electron positron collider was built at CERN, where the collision...
energy was equal to the mass of the $Z^0$ boson. The collider was capable of abundant production of the $Z_0$ bosons enabling the studies of their properties (decays into various final states). Nowadays the carriers of the weak interaction are among the best experimentally studied particles. A similar scenario could happen to the Higgs bosons with the Large Hadron Collider (proton - proton collisions) and a future linear $e^+e^-$ collider with $\gamma\gamma$ colliding option.

8. Conclusion

Photon colliders give a possibility to study reactions above energy 500 GeV. These reactions are not accessible to standard storage ring particle colliders, because particle lose energy through synchrotron radiation. Collisions between $\gamma$ photons have less background than collisions between protons or $e^+e^-$ collisions and higher cross-sections. Adding a photon interaction region to a linear $e^+e^-$ collider nearly doubles the number of possible reactions that can be studied.

References

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