LIVING WITH RADIATION
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ABSTRACT
Visible radiation, indispensable for plants to grow and animals to see, is absorbed like all electromagnetic radiation in the form of photons. Ultraviolet and other ionizing radiations from the outer space and heat emitted by the earth are absorbed and reflected by the atmosphere so that the climate is pleasant. Synchrotron radiation from remote radiogalaxies helps to unravel the secrets of the cosmos and the Northern Light gives valuable information on charges circulating in the ionsphere near the pole. Nowadays, radiation is produced artificially in accelerators and reactors and is essential for contemporary natural science, medicine and technology. A beautiful example is the diffraction of synchrotron radiation by large biomolecules revealing their atomic structure and which can be used in the design of drugs.

1. INTRODUCTION

The 1989 CERN Accelerator School was held in Uppsala which is situated 70 km north of Stockholm. Uppsala was a political and religious centre already in the year 500 AD. During the following four centuries it was the centre of the Swedish vikings. The university was founded in 1477 and is the oldest one in Scandinavia. Like the great French and Italian universities of the time, Uppsala had faculties of Theology, Jurisprudence, Medicine and Philosophy.

One effect of the Reformation was that the church ceased to assume any responsibility for Uppsala University. Thus the development was slow and not until the 17th century was the basis for a university of international standards created. The foremost natural scientist of the university during the 17th century, Olof Rudbeck, famous in particular for his discovery of the lymphatic vessels, was a professor of medicine.

The natural sciences at the university had a time of prosperity during some decades about the middle of the 18th century. The astronomer Anders Celsius, the mathematician and physicist Samuel Klingenstierna, the chemist Johan Gottschalk Wallerius and the botanist and zoologist Carl von Linné, the most famous scientist among them all, were at the time professors at the university.

In the 19th century, Anders Jonas Ångström measured the solar radiation, this resulting in a spectrum atlas. His last name is best known as a length unit defining the atomic scale. In the 20th century, a mark of continued excellence is that six Nobel Prizes have been awarded to Uppsala scientists. One of the laureats, the chemist The Svedberg, initiated and was responsible for the first high energy accelerator in Scandinavia. In the beginning of the 1950s, protons from the Gustaf Werner synchrocyclotron were accelerated to 185 MeV which for some years was the highest energy in Western Europe. The magnet of the first CERN accelerator, the 600 MeV synchrocyclotron was based on the Uppsala magnet design. Nowadays, the rebuilt Gustaf Werner synchrocyclotron and the cooler storage ring, CELSIUS, are important radiation sources in Uppsala.
Fig. 1. Students and professors relax and philosophize in Uppsala at the turn of the 19th century

In the present exposé, some examples show that radiation is an important ingredient of everyday life and is not restricted to the use of workers in accelerator laboratories. The stepwise absorption of radiation will be illustrated by using photography as an example. The quantum description of radiation is suitable for describing not only absorption but also production and stimulated emission of radiation. The latter process explains the functioning of the laser and a novel application of the cyclotron maser that will be described briefly. The changing composition of our atmosphere will be discussed since this problem is one of the major global problems at present and the effects on the radiation environment could be dramatic. The importance of radiation in medicine is well known and the increased use of accelerators in diagnosis and therapy will be mentioned. Finally, it will be pointed out that not only light from stars provides us with information from the cosmos but also radiation by molecules, ions and electrons in the sky is a useful source of knowledge.

2. **RADIATION AND PHOTOGRAPHY**

Water waves are absorbed efficiently by the barriers surrounding a harbour but how are waves of electromagnetic radiation extinguished? We shall illustrate the mechanisms of absorption of radiation by describing in some detail how light is absorbed in a photographic film. The film's emulsion consists of fine light-sensitive crystals of silver salts evenly dispersed in gelatine. Silver salts of bromine, iodine and chlorine are most commonly used. On exposure to light, small invisible clusters of precipitated silver form an image, usually called the latent image. In the subsequent development more silver from the developing fluid accumulates around the primary clusters of precipitated silver. Normally during development, the amount of precipitated silver in the emulsion increases a million times or more and a picture becomes visible.

We shall limit our discussion to the primary photographic process in which absorption of light leads to a latent image of silver. The emulsion is assumed to consist of silver bromide crystals slightly contaminated with silver sulphide. The positive silver ions and negative bromide ions in the crystal are arranged regularly and well separated. To be precipitated as a free silver atom, the positive silver ion must pick up a free electron. Such an electron not belonging to any special ion is usually called a conduction electron since it is able to move around freely and transport electricity in the crystal.
Fig. 2. When photographing, the exposure must be carefully matched to the sensitivity of the film. The light pulse is limited in space to the interior of the camera and in time to the selected exposure time.

The first step is the liberation of an electron from its binding in a bromide ion. An energy of 1 eV, corresponding to $1.6 \times 10^{-19}$ J, must be absorbed from the light wave by the bromide ion for the most weakly bound electron to convert to a conduction electron.

We know that a film with a sensitivity of 100 ASA units must be exposed for about 15 lux-seconds to have a picture with good contrast. This exposure corresponds to an absorbed energy of $2.5 \times 10^{-2}$ Jm$^{-2}$. Assuming that the energy is absorbed uniformly over the surface of the film, a bromide ion with an exposed surface of $12 \times 10^{-20}$ m$^2$ would receive a maximum energy of $3 \times 10^{-21}$ J. Hence, according to this reasoning, no silver would be precipitated since we know that $1.6 \times 10^{-19}$ J is necessary to break the bond between the bromide ion and the electron.

Fig. 3. After photon absorption, the electron originally bound to a bromide ion starts to circulate freely in the crystal. The residual bromine atom attracts an electron from a neighbouring bromide ion which in turn attracts an electron from another ion. In this way positive charge is transported towards the surface of the crystal where a silver ion of an impurity of silver sulphide takes over the transport of positive charge. Near the edge of the crystal, the energy conditions favour the capture of a conduction electron by a silver ion which is precipitated and, as free silver, contributes to the blackening of the film.

What is wrong? The amount of light required for a good picture is known by experience, and the energy necessary to break the bond of the loosest bound electron in a bromide ion is determined in laboratory
experiments. That the energy comes from light absorbed on one bromide ion only seems reasonable since we know that ions in a crystal lattice do not interact strongly with one another. But inspite of these considerations, the film is indeed blackened. We are in the same dilemma as the physicists were at the end of the nineteenth century when they tried to explain why electrons bound in a metal surface are ejected by light. Similar considerations, as in our example with the photographic film, showed that the intensity of the incident light should have been insufficient to liberate the electrons from the metal. It was observed that the energy of the ejected electron was dependent on the frequency of the light and below a certain frequency, ejection of electrons did not occur at all. Einstein in 1905 explained this photoelectric effect by postulating that the energy of light is carried in small localized quanta and that a quantum is transferred to an electron in a point-like fashion.

Hence, the energy of light is not uniformly dispersed in time and space but concentrated in quanta, now called photons. The energy of a photon is related to the frequency, \( f \), of the light wave according to the formula,

\[
E = hf
\]  

(1)

The constant of proportionality, \( h \), is named after the German physicist Max Planck, and is \( 4.135 \times 10^{-15} \) eVs\(^{-1} \). By this formula, we find that red light with a frequency of \( 4 \times 10^{14} \) Hz corresponds to a photon energy of \( 1.6 \) eV. The photons of violet light carry almost twice the energy of those of red light and the average energy of the photons of sunlight is \( 2.5 \) eV equal to \( 4 \times 10^{-19} \) J. Photons of visible light are apparently sufficiently energetic to liberate electrons from bromide ions.

We recall that the absorbed energy density should be around \( 2.5 \times 10^{-2} \) Jm\(^{-2} \) for a visible photographic picture. Hence the density of photons incident on the film can be estimated from the knowledge of the average photon energy of light. The result is that an area on the film equivalent to 100 closely packed bromide ions absorbs on average one photon.

A photon may pass several layers of atoms before being absorbed in the film. Absorption occurs only if a photon meets in one and the same point, an electron in a bromide ion. If this condition is not satisfied the photon passes through the ion and penetrates deeper into one or more neighbouring ions.

The first step in the formation of a silver atom is a reaction between a bromide ion and a photon indicated by the formula,

\[
\gamma + \text{Br}^- \rightarrow e^- + \text{Br}
\]  

(2)

After the reaction, the electron liberated from the ion moves freely in the lattice of the crystal. The neutral bromine atom attracts an electron relatively easily from a neighbouring negative bromide ion which becomes neutral. The so-formed bromine atom in turn attracts an electron from an adjacent bromide ion and so on. Thus, charges are transported within the lattice and this transport proceeds to the surface of the crystal.

In the early days of experimental photography, it was known that a certain contamination of silver sulphide was needed to get a good picture. The silver sulphide gives off an electron to a neighbouring neutral bromine atom more readily than a bromide ion. When a bromine atom is formed near a molecule of silver sulphide, the transport of charges mediated by bromine ceases. The charge transport continues via the silver ions of the lattice.
At an edge of the crystal, a conduction electron floating freely in the lattice can be captured so that a silver atom is precipitated. The initial bromine atom that absorbed the photon and the finally precipitated silver atom lie near each other because the transport of charges by bromine and silver is limited to distances of fractions of a millimetre within one of the many crystals on a photographic film.

Fig. 4. A photon is absorbed in the photocathode of an image intensifier. The electron liberated is accelerated towards a channel plate at a high positive potential with respect to the photocathode. In one of the many tubes of the channel plate, up to a million electrons are produced and subsequently stopped in a fluorescent screen where photons are produced.

Other electromagnetic radiations of lower frequency than light, such as heat and radio waves are absorbed also in a step-wise fashion. The low energy of the photons of these radiations is however not able to separate electrons from their binding in atoms or molecules of a non-conducting medium. The molecules having absorbed these photons acquire additional motion and the resulting heat distributes itself after some time among all the molecules of the medium. On the absorption of photons by a conductor, excess energy is acquired by the conduction electrons which move about freely in the metal and spread their energy easily. This makes metals conduct heat very efficiently.

In a semiconductor, the difference in binding energy between electrons bound in atoms, the so-called valence electrons, and electrons moving around freely in the lattice, the conduction electrons, is small compared to the situation in an isolator. Normally, in a semiconductor very few of the electrons are free to move as conduction electrons. When irradiated by light, valence electrons may easily acquire sufficient energy to break the bond with their host atoms and become conduction electrons. If an electric tension is applied across a semiconductor, these liberated electrons give rise to a current. Photodiodes and other light-sensitive semiconductor components function according to this principle.

The above examples show how the energy of light is absorbed in a stepwise fashion and converted to kinetic energy of electrons, atoms and molecules. Photosynthesis and vision, most important processes in plants and animals, absorb light similarly.

3. RADIATION AND THE ATMOSPHERE

The earth receives visible radiation from the sun and itself radiates heat. The intensity of solar energy reaching the top of our atmosphere is 1.35 kWm⁻² and the wavelength distribution is well described by the radiation spectrum of a black body at a temperature of 5800 K. During its continued transit through the atmosphere, sunlight is absorbed and reflected back into space by atmospheric gases. If there had been no
atmosphere and the earth could have been considered as a blackbody, the average ground temperature would have been around 0 °C. In the presence of nitrogen and oxygen but without so-called greenhouse gases, the average temperature would have been around -20 °C since the atmosphere absorbs and reflects the incoming radiation.

![Black Body Curves](image)

**Fig. 5.** (A) Black-body curves for 6000 K and 255 K, which approximate the mean emitting temperatures of the sun and the earth. (B) Atmospheric gaseous absorption for radiation passing from the top of the atmosphere to the ground level. From Ref [1].

Half of the radiation energy is absorbed and reflected by the atmosphere so that at the ground level half the energy remains. The ultraviolet portion is absorbed by high-altitude ozone and the absorption elsewhere in the wavelength spectrum is due mainly to water vapour and oxygen.

All the energy incident on the earth’s surface must be radiated back into space in the form of heat. Water vapour, carbon dioxide and ozone help to absorb part of the escaping heat radiation. Therefore the average temperature on earth is +15 °C and about 35 degrees warmer than if these absorbing greenhouse gases had not been present. At present, the composition of these and other greenhouse gases in the atmosphere is changing and these changes could have dramatic consequences for the future radiation environment and climate on earth. Because of deforestation and fossil fuel usage, the relative concentration of CO₂ has increased from the fraction, 0.028 percent during pre-industrial times to 0.0347 percent today. In 1958 the measured value was 0.0315 which gives an idea of the rate of increase. Presently five billion tons of carbon, 1000 kg for each person on earth, in the form of CO₂ is produced annually from fossil fuel burning. Half of this remains in the atmosphere and the other half is reabsorbed in vegetation and oceans.

The change in average global temperature is estimated by the use of sophisticated computer codes based on models which are necessarily very approximate. Calculated temperature increases are in the range 1.5 to 5.5 °C for a doubling of the concentration of CO₂ [2]. The increase in temperature is predicted to be higher above land areas than above the sea where the interaction between atmosphere and water moderates the temperature changes. The assumptions about the clouds are very critical since different kinds of clouds at different altitudes affect the radiation balance differently. Some models even predict a cooling due to the changing composition of the atmosphere.

Large scale production of other substances such as freon, methane and nitrous oxide also affect the greenhouse effect. These gases are believed to contribute as much to the temperature increase as CO₂. In addition to their contribution to the greenhouse effect, the freon molecules most probably destroy the high-altitude ozone layer which protects us from solar UV radiation. There are thus many reasons for reducing drastically the use of freon which will remain for prolonged times in the atmosphere because it does not combine readily with other substances.
A substantial portion of the solar radiation consists of ultraviolet light sufficiently energetic to ionize and act on the hereditary material of the living cell. Fortunately the energetic photons of ultraviolet light are absorbed to a great extent by atmospheric ozone concentrated at altitudes between 20 and 30 km.

Freon, otherwise known as a chlorofluorocarbon, CFC, is a man-made gas and one of the most inert gases in the atmosphere. It consists of fluorine (F), chlorine (Cl) and carbon (C) bound together by strong covalent bonds. The strength of the CF bond is 440 kJ/mole and that of the CCl bond 330. CFCs do not react easily with other gases and are non-toxic. They are hence ideal as propellants in spray cans, as cleaning solvents for microelectronic devices, for making plastic foam, and as cooling media in refrigerators and air conditioners. Since they are very inert, CFCs accumulate in the atmosphere. Only when reaching the upper part of the stratosphere do they disintegrate as a result of the energetic ultraviolet radiation which at lower altitudes has been absorbed efficiently by the layer of ozone. This layer is concentrated at altitudes between 25 and 30 km and protects life by shielding the earth from energetic ultraviolet radiation.

CFCs which initially were considered to be harmless are now thought to be among the most dangerous compounds in our environment since they cause large quantities of both ozone and atomic oxygen to be removed from the stratosphere. Atomic oxygen which can exist at reduced pressure is useful since it fuses with molecular oxygen to make up for natural loss of ozone. The rate of loss of ozone due to CFCs and other gases such as nitrous oxide N₂O and methane CH₄ assumes enormous proportions, as evidenced by the increasing hole in the ozone layer above the Antarctic.

Ironically, the CFCs are not very kind to their protector, the stratospheric ozone. Chlorine atoms liberated from CFCs by ultraviolet radiation in the upper stratosphere are very reactive and destroy ozone without being themselves removed. A chlorine atom first "steals" an oxygen atom from ozone forming chlorine monoxide (ClO) and an oxygen molecule. Then chlorine monoxide reacts with a free oxygen atom so that chlorine and molecular oxygen are formed. The net result is that one ozone molecule and one ozone atom merge into two oxygen molecules.

\[
\begin{align*}
\text{First step} & \quad \text{Cl} + \text{O}_3 \rightarrow \text{ClO} + \text{O}_2 \\
\text{Second step} & \quad \text{ClO} + \text{O} \rightarrow \text{Cl} + \text{O}_2 \\
\text{Net result} & \quad \text{O}_3 + \text{O} \rightarrow 2\text{O}_2
\end{align*}
\]

The same chlorine atom may react hundreds of times thereby consuming large quantities of ozone. However other processes interfere with the catalytic cycle shown in the formulae. For example, chlorine and methane form hydrochloric acid (HCl) while chlorine monoxide (ClO) and nitrogen dioxide (NO₂) form chlorine nitrate (ClONO₂). Both HCl and ClONO₂ represent relatively inert compounds which do not attack O₃ and serve as a temporary chlorine reservoir. Hence these interfering reactions reduce the efficiency of ozone destruction by the chlorine cycle particularly in the lower stratosphere.

It seems that polar stratospheric clouds set the scene for a chlorine catalyzed ozone destruction by stimulating the conversion of the major chlorine-reservoir species (HCl and ClONO₂) to active chlorine (Cl and ClO). These clouds are formed in the polar stratosphere during winter at very low temperatures (around 185 - 195 K) through condensation of nitric acid and water vapours. The HNO₃ stratosphere above the South Pole is
Fig. 6. One possible structure of CFC is CF₂Cl₂. The covalent bond breaks on absorption of a photon of ultraviolet light. The released chlorine atom is oxidized by an ozone molecule. The chlorine monoxide reacts in a second step with atomic oxygen so that molecular oxygen and a free chlorine atom is produced. The same chlorine atom repeats this cycle with the result that hundreds of molecules of ozone may be destroyed.

slightly colder than above the North Pole and therefore the ozone reduction started probably at the South Pole. A critical question is whether or not the ozone depletion will remain restricted to the South Pole or whether the antarctic ozone hole is a first sign of a global erosion of the stratospheric ozone layer. The scenario of a chlorine-catalysed ozone destruction may be influenced also by other atmospheric gases like CO₂, CH₄ and N₂O which result from combustion and agricultural processes. These gases presently accumulate in the air and cool the stratosphere by emitting infrared radiation and hence they may lower stratospheric temperatures. In fact, as seems probable at present, if the reduction of ozone is favoured by low temperatures, a positive feedback may occur due to the mentioned atmospheric gases.

Initially regarded as harmless, CFCs are now considered to be among the most dangerous compounds in our environment since they erode the ozone layer of the stratosphere. A first manifestation of a reduction of the stratospheric ozone occurred in the late seventies, when at the South Pole, a hole in the ozone layer started to develop each spring. Since then this Antarctic "ozone hole" has returned every spring and has increased in size. In 1987 its area was comparable to that of the Antarctic continent or the United States. There is increasing evidence that the Antarctic ozone hole is caused primarily by the chlorine cycle. Although many questions concerning the formation of the ozone hole are still open to debate, the potential risk of a global erosion of the stratospheric ozone layer has to be taken very seriously. This is particularly true since the residence times of the most important CFCs are long. In other words, even if the release of these substances were stopped today, they could still develop their destructive potential for decades to come. Obviously it would be dangerous to ask for an ultimate proof, namely a significant global reduction of stratospheric ozone before taking serious measures against the release of CFCs.
4. RADIATION SERVING MEDICINE

Radiation becomes more and more important in medicine for diagnosis and for therapy [3]. Tomographic imaging based on X-rays, Nuclear Magnetic Resonance, NMR, and Positron Emission Tomography, PET, give complementary information. In PET, a short-lived positron emitting nuclide such as carbon-11 is first produced from an accelerator and by chemical methods subsequently attached to suitable molecules. These labelled molecules are then injected into the body and positrons emitted continuously for a few hours when the molecules spread and interact with the organs. After having passed a few millimetres in tissue, the positron annihilates with an electron and the two resulting product photons move in opposite directions and are recorded in detectors external to the body. Space lines are reconstructed from detector pairs hit by the photons giving an image of molecular activity. For example images of the metabolism of glucose can be followed as a function of time. Many other different substances can be labelled and traced and it is quite appropriate to say that PET is an effective method for mapping the biochemistry of the body.

Mapping of the atomic structure of large biomolecules is done by means of diffraction techniques using X-rays and neutrons as radiation particles. An exciting scattering experiment was made using a virus as the target for synchrotron radiation from the Cornell synchrotron [4]. A human common cold virus, rhinovirus-14, was used and assembled into a crystallized structure used as the target. The analysis of the very complex pattern of the scattering radiation was done on a supercomputer. The 3D atomic structure, the first ever measured of an animal virus, reveals narrow canyons in the spherical shell of the virus. The canyon is about 2.5 nm deep and may be the site for cell-receptor binding. An antibody molecule whose fragment would have a size of the order of 3.5 nm would not be able to reach the canyon floor. Thus the structure in the deeper part of the canyon would not be prone to immune selection and could remain constant, permitting the virus to retain its ability to seek the same cell receptor.

Research is presently in progress to find inhibitor molecules (virus antibiotics) that are small enough to reach the canyon floor. These inhibitors have either to block the receptor site or prevent ions from entering a channel into the virus thereby preventing it from disassembling and pouring its RNA content into the cell.

It is expected that other important animal viruses of similar structure, e.g. polio and AIDS, could also be known at the atomic level. The polio viruses exist in three different forms (sero types) and are combated by vaccines. Against the 89 different forms of cold viruses it is not possible to find an effective vaccine and some sort of antibiotics adopted to their atomic structure may evolve as a result of scattering experiments. It will be fascinating to follow how insight at the atomic level of such a large structure as a virus may give clues to some of our common diseases.

Nearly half of all cancer cases are treated by radiation (X-rays and γ-rays) which is as frequent as conventional surgery and more frequent than chemotherapy.

Early work in Berkeley and Uppsala [5] showed the advantage of using protons for medical treatment. A medium-energy proton of 200 MeV has a range of 25 cm in tissue and can reach all points in the human body. The differential ionization and hence the cell damage is largest just prior to the protons coming to rest. In this respect, protons are different from X-rays and neutrons which are attenuated as they penetrate deeper and deeper. Proton beam surgery, for the affection of small regions of the brain, initiated 30 years ago in Uppsala, and
irradiation of small tumours in the eye carried out routinely in several laboratories are two examples of precise radiotherapy in which medium-energy protons are preferred to other radiation particles. Small accelerators for electrons and protons are now in frequent use at hospitals. At many accelerator centres, part of the program is allocated to medical applications. In Harvard, Fermilab, KEK Tsukuba, TSL Uppsala and in three Russian laboratories, INP Gatchina, ITEP Moscow and JINR Dubna, protons of medium energy are used for surgery and therapy. The first medium energy proton accelerator fully dedicated to medicine, a proton synchrotron, is being built presently at the Loma Linda University hospital in California.

5. **RADIATION EMITTED BY PARTICLES ACCELERATED IN THE SKY**

The Northern Light, or the Auroral Light as it is also called, is a spectacular phenomenon seen normally at northern latitudes near the pole. Its origin is to be found in the sun's "wind" which consists of slow electrons and protons emitted from its corona. At an altitude of some 500 km at the top of the atmosphere there are electrically charged ionized layers with potential differences of 10,000 V. At the North and South poles, the electrons can travel parallel to the magnetic field and penetrate a long distance into the atmosphere. They are accelerated to an energy of some 10,000 eV since they are not deflected by the vertically directed magnetic field. As the density increases, the electrons collide more and more frequently with atoms and molecules of the atmosphere. In these collisions, energy is transferred to the atoms and molecules which are excited and carry excess energy for a short while. However, after some billionth of a second, they decay to their stationary states by emitting light. At an altitude of 100 km, the density of molecules and atoms is sufficiently great to cause visible effects on the earth's surface. The blue-green colour, characteristic of the Northern Light is emitted primarily when excited oxygen returns to the normal ground state.

![Fig. 7 Auroral Light over northern Scandinavia seen from 800 km altitude by an American weather satellite. The energy in the Auroral Light corresponds to the energy consumption of Europe. Photo: Air Force Geophysical Lab, USA.](image)

High energy electrons moving in the magnetic fields of galaxies give rise to radiation that may be measured on earth. This form of radiation is named synchrotron radiation since it was seen first in synchrotrons. Electrons
orbiting in a synchrotron lose energy continually in the form of photons emitted tangentially from the orbit. The energy lost every turn by an electron can be computed from the expression:

\[ \Delta E = \frac{6 \times 10^{-15}}{R} \left( \frac{E}{m_0c^2} \right)^4 \]

where \( \Delta E \) is the energy loss per turn, \( m_0c^2 \) the rest energy of the particle, \( E \) its total energy and \( R \) the radius of curvature. The units used are MeV and metre. Since the mass of the electron is 2000 times less than that of the proton, an electron of given energy and radius of curvature loses much more energy than a corresponding proton. Radiogalaxies are gigantic very remote objects in the universe and they emit synchrotron radiation which is detected using large radiotelescopes. Since radio waves easily pass through galactic and intergalactic matter, the intensity of the radiation from radiogalaxies is not absorbed as strongly as visible light.

Fig. 8. Radiography of the radiogalaxy Cygnus A. The picture has been made by means of the very large array, VLA. The radiation emitted from the galaxy in the centre interacts with the intergalactic gas and two clouds (lobes) are seen to the left and right of the mother galaxy seen as a small dot in the centre of the picture. Photo: R A Perley, J W Dreher and J J Cowan, The National Radio Astronomy Observatory, Ani, USA.

Microwaves may also be emitted from excited molecules in the remote cosmos and a consequence of changes in the rotational states of excited molecules. The radiation emitted when excited molecules lose their energy appears as lines in a spectrum of wavelengths. Any given species of a molecule can be identified by a number of lines which form a characteristic "finger print" of the molecule.

In 1963 the first molecule, \( \text{OH}^- \) was discovered in the interstellar space. Later discoveries include carbon monoxide which is quite abundant and is present in our own galaxy, in a concentration of one part in 10 000 of the hydrogen content. The structure of other galaxies is often studied using carbon monoxide and atomic and molecular hydrogen as radiation sources. Observations of radio waves from space molecules are of increasing importance in astrophysics and, in certain cases, new information about the molecules themselves may be inferred from the radiation observed. One example is the molecular ion \( \text{NH}_2^+ \) which is so reactive that it cannot be isolated on earth. Among the numerous known space molecules, ethyl alcohol was discovered in 1974. The molecular cloud Sagittarius, B2 could contain as much alcohol as is present in \( 10^{28} \) bottles of whisky!

6. **STIMULATED CYCLOTRON RADIATION**

Accelerator science requires knowledge of both classical and quantum physics which is illustrated by a new scheme for fast cooling of particle beams presented recently by Ikegami [6]. Cooling times of the order of a
microsecond are predicted. In the proposed scheme, electrons or ions are cooled very rapidly by making use of the principle behind the cyclotron maser [7]. Here, electrons of a few keV circulate in a strong magnetic field under the influence of an electric rf field. If the frequencies of the cyclotron motion and of the electric-field change are nearly identical the electrons may be stimulated to emit large amounts of radiation. The emitted radiation can become much stronger than the radiation absorbed by the stimulating rf field and this condition is used when designing high-power cyclotron maser amplifiers.

![Diagram](image)

Fig. 9. Arrangement of the gyrotron. Distribution of static $H_0$ and alternating $E = |E| e^{i\omega t}$ fields. From Ref [7].

The idea of stimulated cyclotron radiation was developed originally by Twiss [8] in a paper that described "negative" absorption at radio wavelengths where the medium behaves like an amplifier. Twiss suggested that cyclotron radiation is much more probable at radio than at optical frequencies and may be a common phenomenon in the universe. The mechanism can be understood quantum mechanically as transitions between Landau states that are states associated with the circular motion and separated by the energy $E = hf$. The frequency, $f$, of the orbiting particle is inversely proportional to its total energy. An external rf field may stimulate emission of photons by a circulating particle or give away photons to the particle. The level spacing is proportional to the particle circulation frequency which is dependent on its total energy. A quantum emitted by the particle in a given level therefore has somewhat higher energy than a quantum being absorbed by the particle in that level. This fact explains why under certain conditions the energy lost by the particle due to stimulated emission may exceed the energy received due to absorption. A quantitative formula for the magnitude of the effect was developed by Schneider [9].

Ikegami suggested that the stimulated emission of radiation from particles in cyclotron orbit can be utilized for the cooling of high-energy particle beams. It is necessary to have a strong axial magnetic field along the main direction of particle motion. In this way, the particles move in helical orbits. The transverse motion is affected by an rf field that acts transversely to the main direction of particle motion. The loss of energy due to the radiation gives rise to a friction term in the equation for the transverse circular motion of the particle.
The idea can be tried at a storage ring such as CELSIUS. A portion of a straight section of a ring must have a strong solenoidal magnetic field in the same direction as the particle beam. In the solenoid, the particles move in a cork-screw orbit and the frequency of the electric rf field applied along a transverse direction has to be the same as the frequency of particle circulation in the transverse plane.

7. CONCLUSION

Accelerator science has developed into its own discipline on the border line between classical and modern physics and closely related to plasma-, magnetosphere- and ionosphere-physics. The deep experience gained in accelerator laboratories on how particles can be accelerated, made to radiate and interact with matter is a very important basis for exploration of the microcosmos and for the technology of today and tomorrow.

The examples discussed in this paper show also that knowledge of radiation is much more important in everyday life than is generally believed. Such knowledge will guide us in devising future nuclear and solar energy sources, recyclable material such as wood, ceramics, glass and food produced in harmony with the environment.

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