

LIGHT TO REVEAL THE HEART OF MATTER



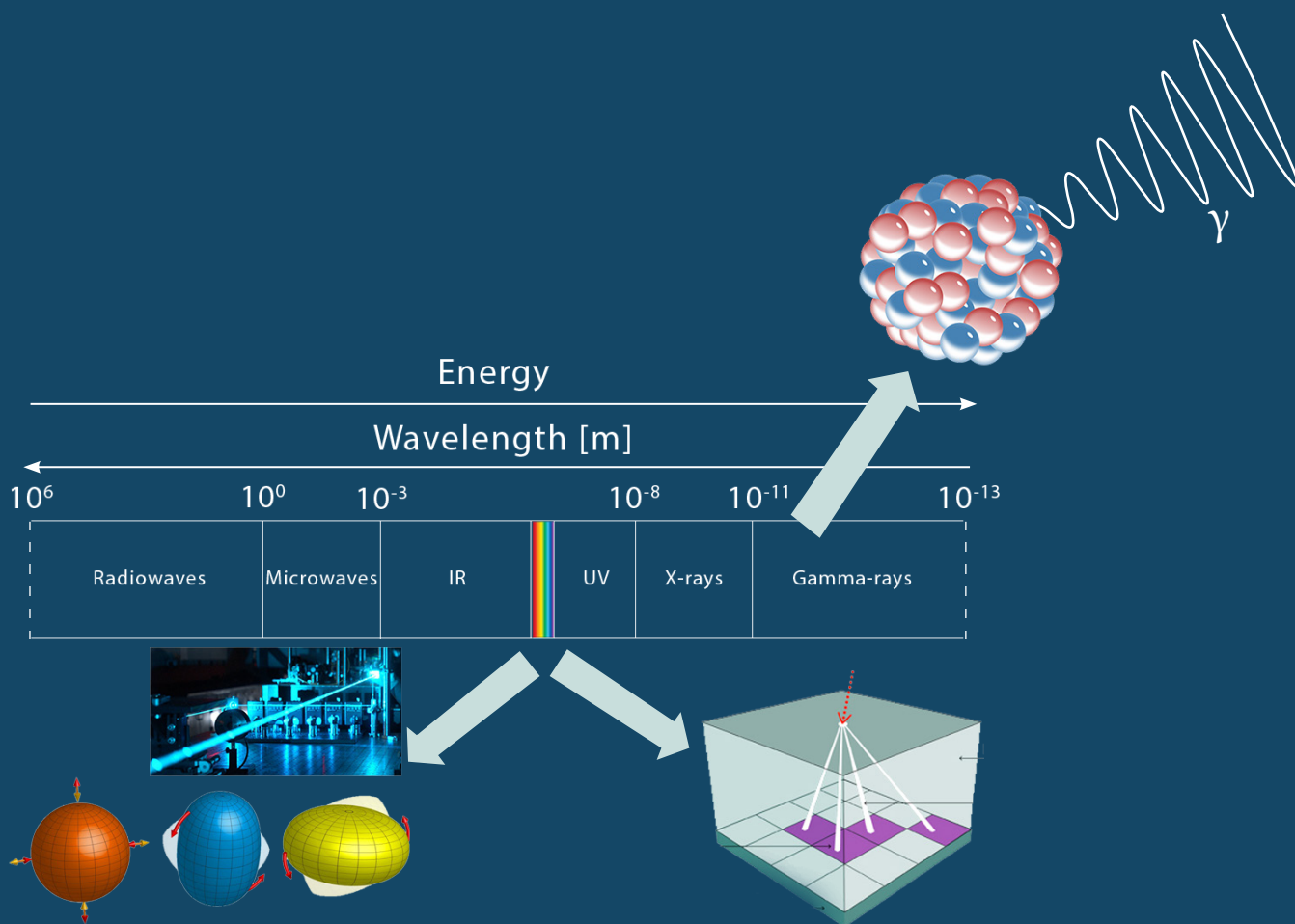
INTERNATIONAL
YEAR OF LIGHT
2015

Introduction

This brochure “**Light to Reveal the Heart of Matter**” is one of the contributions being made by NuPECC, the Nuclear Physics European Collaboration Committee (www.NuPECC.org), to the International Year of Light 2015 (www.light2015.org).

We would like to show the many facets of how the electromagnetic spectrum – light in its broadest sense – is featured in nuclear physics research, from high-energy gamma-rays down to scintillation light and lasers, looking into nucleons and nuclei, and connecting to other fields such as astrophysics and medicine.

NuPECC has particularly strong ties with ECT* (<http://www.ectstar.eu/>, the *European Centre for Theoretical Studies in Nuclear Physics and Related Areas*) which is contributing to the year of light with the “**International Winter School and Workshop on Strongly Correlated Fluids of Light and Matter**”.



Inside nucleons with photons

The investigation of the spectrum of 'light' emitted or absorbed by the constituents of matter is a powerful tool to reveal the structure of matter and the properties of the fundamental forces of nature. The discovery that atoms emit light only at characteristic wavelengths prompted the development of Bohr's atom model and laid the foundations of Quantum Physics and of Quantum Electrodynamics (QED), the fundamental theory of the electromagnetic interaction.

The atomic nucleus consists of protons and neutrons (together called 'nucleons') that are a factor of 100,000 smaller than the size of an atom. But nucleons also have a complex internal structure, being composed of quarks and gluons that interact via the strong force. The theoretical framework for describing these processes is called Quantum Chromodynamics (QCD).

It is found that the mass of an atom typically deviates by less than one part in a hundred thousand from the sum of the masses of its atomic nucleus and its electrons. In turn, the mass of a nucleus typically differs by about 0.1% – 1% from the sum of the masses of its nucleons. In both cases the final system is a little lighter than the sum of the masses of its constituents, and is understood in terms of nuclear binding energy. In stark contrast however, for protons and neutrons only about 1% of their mass stems from the masses of their constituents. The remaining 99% is generated dynamically by complex QCD interactions involving quarks and gluons and the "vacuum" inside the nucleons: a detailed understanding of these processes is one of the key challenges of modern physics.

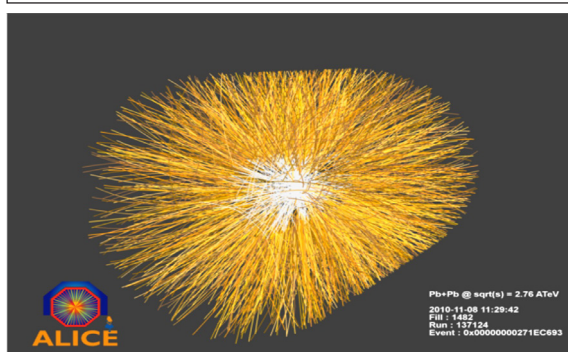
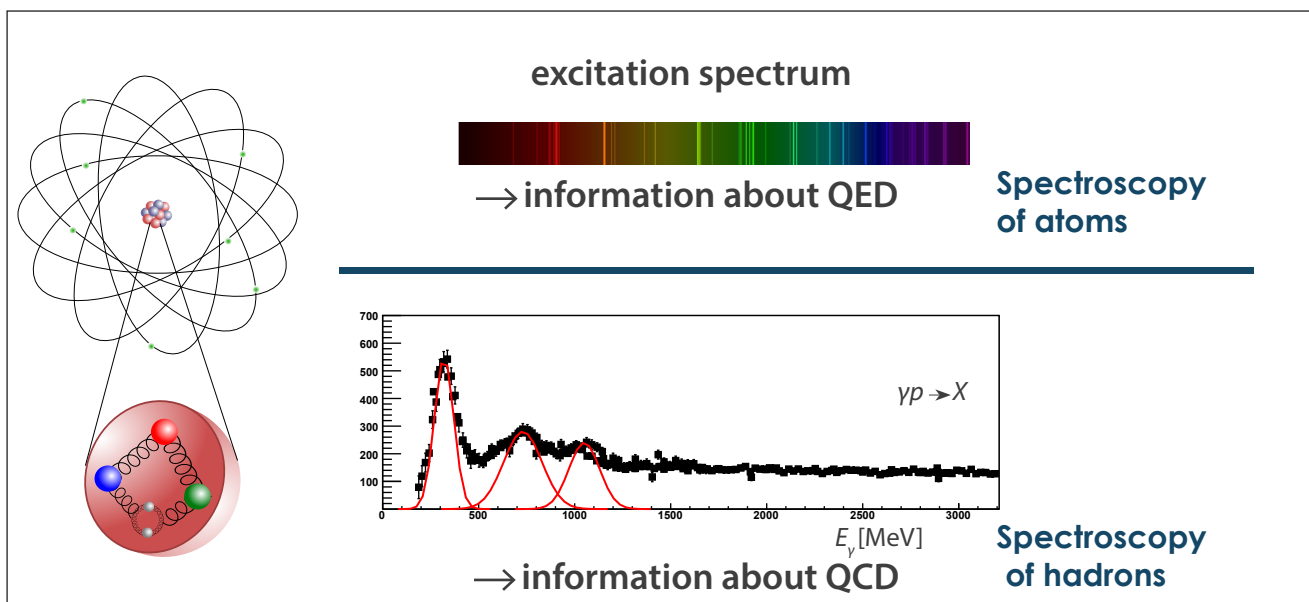


Fig. 1.2
One of the first collisions between lead nuclei measured with the ALICE detector at the Large Hadron Collider. Over 25000 charged and neutral particles are produced in each such central collisions.

Fig. 1.1
Structure of matter: Spectroscopy

The excitation spectra of nucleons reveal the properties of the QCD interactions. The idea is sketched in Fig. 1.1. A typical experiment uses a gamma-ray beam ('light' of high energy or very short wavelength), which impinges on a proton target. The gamma-ray beams are generated when electrons are scattered in thin foils. High-energy electromagnetic radiation is produced in the scattering process and used to excite the protons. Fig. 1.1 shows a typical spectrum of the inclusive total photoabsorption spectrum of the proton. This is the reaction where 'light' (in this case with energy between 200 MeV and 3.2 GeV) irradiates a proton and the probability that the proton is excited is measured.

extremely hot fireball of the fundamental constituents of matter- the quarks and antiquarks, and the force carriers of the strong interactions, the gluons. The Universe is believed to have been in this state in the first microsecond after the Big Bang. We can now take the temperature of this super-energetic matter state directly by measuring the spectral distribution of the electromagnetic radiation that it emits, in analogy to the determination of the present day temperature of the Universe obtained by measuring the Cosmic Microwave Background radiation. In recent experiments, using the ALICE detector at CERN's Large Hadron Collider, a thermal photon component was identified consistent

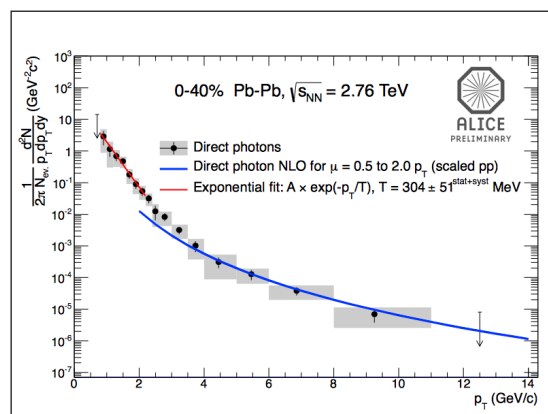
with temperatures of over 300 MeV, corresponding to about 4000 billion degrees. Fig. 1.2 shows the thousands of tracks originating from a single collision between two lead nuclei and Fig. 1.3 shows the measured direct photon spectrum.

In such high-energy reactions the electromagnetic field is intense and can be treated as a dense region of photons. From this region, new particles may be spawned, for example the J/Ψ particle that consists of a charm-quark and an anti-charm quark. This process is sensitive to the square of the gluon distribution inside the proton, and thus provides a new tool to study the density of gluons inside nucleons. When two heavy ion beams cross, the intense photon fluxes from each allow gamma-gamma collisions to be studied. Currently, the LHC is the world's most powerful gamma-gamma collider, but other initiatives are also underway to study intense photon fields, e.g. the ELI facility hosted by the Czech Republic, Hungary and Romania.

Extensive experimental programs in this field have been running for the last fifteen years, at electron accelerator facilities such as CLAS at JLab (USA), ELSA (Germany), GRAAL at ESRF (France), LEPS at SPring-8 (Japan), LNS (Japan), and at MAMI (Germany).

In collisions between heavy nuclei at ultra relativistic energies (in the TeV range), an ultra-dense and hot system called the Quark Gluon Plasma, is formed for a fleeting moment ($< 10^{-22}$ seconds). The QGP is an

Fig. 1.3
Distribution of photons from collisions between two nuclei of lead (Pb) at ultra relativistic energies, measured with ALICE. The red line indicates a thermal photon component with temperature 304 MeV corresponding to about 4000 billion degrees. This is interpreted as thermal radiation from the Quark Gluon Plasma.



Inside nuclei with photons

The nucleus is a unique many-body quantal system. Even after decades of study, the nucleus continues to surprise physicists, as increasingly sensitive instruments and techniques reveal completely unexpected properties.

The strongly interacting aggregation of nucleons in nuclei displays a remarkable diversity of phenomena and symmetries. Nuclei give us the most intricate examples of the interplay between single-particle motion, collectivity and two-nucleon pairing in a quantum many-body system. This interplay is seen as a rich tapestry of coexisting nuclear shapes and other exotic excitations. The spectroscopy of gamma-rays emitted by excited nuclei produced with reactions induced by gamma ray and heavy ion beams form the backbone for experimental studies of these complex nuclear structures. Preferred pathways in the de-excitation process occur, that are related to favourable arrangements of protons and neutrons and which can often be associated with specific symmetries or nuclear shapes. If a sufficient fraction of the gamma decay flows down a particular quantized pathway or band, then the associated structure becomes observable and can be studied in detail.

Rotations and vibrations are important nuclear degrees of freedom. For deformed nuclei the rotation can be detected and the nuclear deformation is known to be of disk or cigar type. Recently evidence was found in Rn isotopes for ground state of pear shape type.

When a nucleus is made to rotate it behaves like in external magnetic field: it tries to align individual particles along the axis of rotation (see Fig. 2.4), and this destroys correlations between nucleonic pairs. This reduction of pairing correlations with rotation gives rise to quenching or total collapse of the nuclear superfluidity. Interestingly, rotational states have also been observed in very heavy nuclei with more than 250 nucleons suggesting an unexpected enhanced stability, illustrating the importance of a detailed understanding of rotation.

Vibrations of different types (or multipolarities) have spectral distributions of their strengths that cover a rather wide range of frequencies (or nuclear excitation energies). Depending on their type, they are characterized by small amplitude oscillations of quantities such as the nuclear surface, the nuclear density and the nuclear matter with its spin and isospin degrees of freedom. Most of the intensity of these oscillations is at frequencies corresponding to excitation energies above the nucleon binding energy and are known as giant resonances. At these excitation energies the nucleus has a large density of levels and is characterized in general by a chaotic behaviour. The coexistence of order (giant resonances) and chaos in the nuclear system is intriguing. With very high resolution gamma-beams, an understanding of the order to chaos couplings is expected to be within reach in the near future.

A simple nuclear vibration is the electric dipole oscillation in which protons oscillate in antiphase with neutrons. The corresponding giant resonance, the electric giant dipole resonance, involves all nucleons and is a characteristic nuclear degree of freedom also at finite temperature. The dipole oscillation of the outer neutrons has been identified in several nuclei and, because of its much-reduced strength, is called the pygmy dipole resonance (see Fig. 2.2).

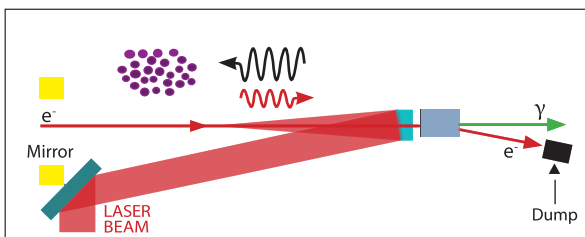


Fig. 2.3
Collision of a low frequency Laser beam with an electron beam producing a gamma ray beam. (green arrow)

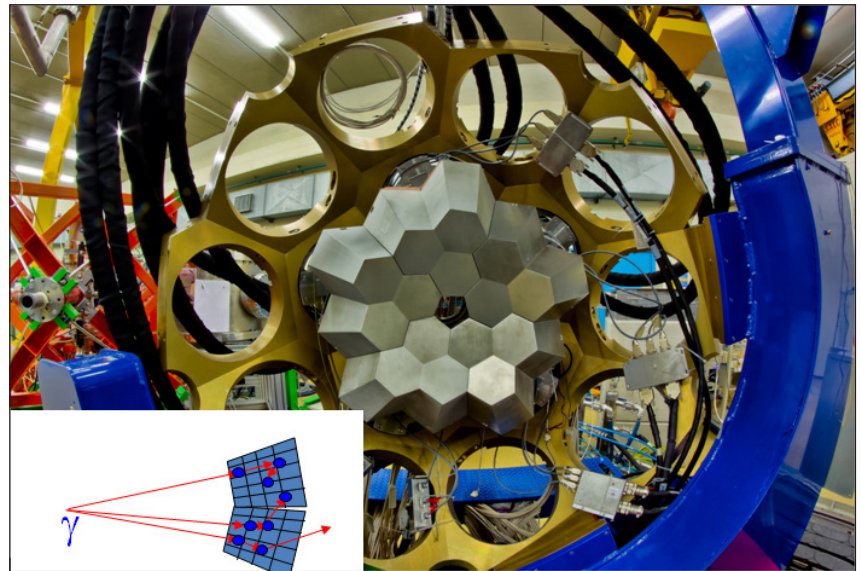


Fig. 2.1
The detection array of the European collaboration AGATA at the INFN laboratory of Legnaro. Inset: schematic of the gamma-ray interaction in the detector.

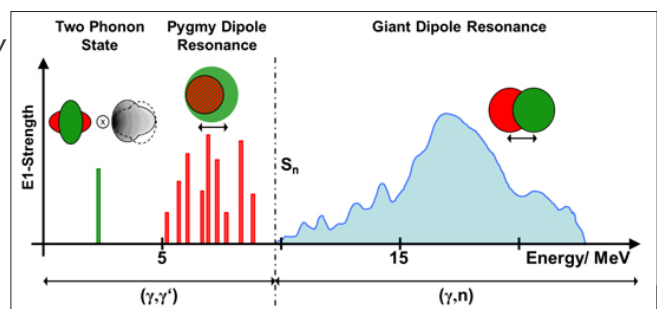


Fig. 2.2
Schematic of the electric nuclear response of dipole type as a function of energy. The green circles represent neutrons, the red ones protons.

The sensitivity for the detection of gamma-rays emitted by excited nuclei produced in nuclear collisions has greatly improved during the years. The most recent effort in this direction, being made as a large European collaboration, is the construction of the AGATA array. This uses the new technology of gamma interaction tracking (see Fig. 2.1) that allows rejection of events undergoing scattering with electrons (process known as Compton effect) in the detector, and this increases the detection sensitivity to low intensity transitions. In contrast, using electron beams, the Compton scattering process in its reversed kinematic condition (i.e. with the electron moving instead of being at rest) is being exploited to produce gamma-ray beams to be shined on nuclei (see Fig. 2.3). Indeed the Compton inverse technique

is the basis of the next generation of gamma-ray beams to be produced at the ELI-NP facility in Bucharest. The gamma-ray beam will be generated by the collision of fast moving electrons (with kinetic energy up to 700 MeV) with an intense laser beam so that the Compton inverse process leads to a beam of photons with energy up to approximately 20 MeV. These gamma-ray beams will be characterized by very narrow energy width and high intensity.

In addition to the small amplitude oscillations seen in giant resonances, the nucleus displays also large amplitude oscillations that lead to nuclear fission. At ELI-NP an interesting aspect of nuclear fission can be investigated. Deformed nuclei are often characterized by the presence of more than one deformation (super- and hyper-deformations). Nuclei excited to these states are expected to have a mixed nature, and can be populated selectively with gamma beams with very narrow width. These states may then be identified by their fission decay.

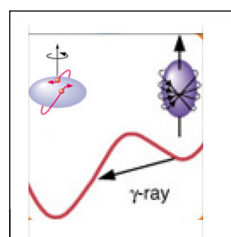


Fig. 2.4
The orbiting nucleons in nuclei aligning with the axis of rotation.

Photon induced reactions for astrophysics and for other applications

Nuclear reactions induced by photons are important for several types of applications ranging from those in nuclear astrophysics to those in nuclear medicine, cultural heritage, energy and homeland security.

The central problems in nuclear astrophysics are the energy generation and the nucleosynthesis processes, that have led to different chemical elements now present on Earth.

The heavy elements above the so-called iron peak are mainly produced in the neutron capture processes: rapid neutron capture occurs in environments with high neutron densities while slow neutron capture occurs at much lower neutron densities. Neutron capture reactions are not accessible to direct measurements in all cases, and thus the inverse (γ, n) reaction is often used to provide parameters for nuclear models that are then in turn used to predict a more reliable neutron capture cross section. In addition, data of the inverse (γ, n) reaction in some cases also yield information for the calculation of Stellar Enhancement Factors (SEF), often the main source of uncertainty for reaction probability in the stellar environment.

Properties of unstable nuclei that play key roles in explosive stellar environments have been a forefront interest of astrophysical nuclear research since its emergence. With high intensity lasers a new world of possibilities opens up to study their behaviour for the first time under the extreme temperature and pressure conditions present in the inner cores of planets and stars. In this connection the study of possible enhancement of the decay of the long-lived ^{26}Al radioisotope in astrophysical environments is very important.

The γ -ray mapping of the ^{26}Al decay across the galaxy provides one of the most interesting constraints on nuclear physics parameters in astrophysical environments. The ^{26}Al nucleus was the first radioisotope detected in the interstellar medium, by the observation of the characteristic 1809 keV γ -emission associated with the decay of its ground state. The presence of this nucleus provides evidence of ongoing galactic nucleosynthesis. Wolf-Rayet stars and Asymptotic Giant Branch (AGB) stars and novae have been suggested as possible sources of the origin of ^{26}Al . New theoretical works predict a dramatic temperature dependent reduction of the effective life time of $^{26}\text{Al}_{gs}$. This significant decrease of the effective life time is due to a variety of physical processes triggered and influenced by hot plasma environments. A schematic illustration of the measurement for Al using a Laser beam is in Fig. 3.1.

Another interesting case is the possible use of Auger electrons for tumour therapy that requires targeting into individual tumour cells, even into DNA, due to the short range ($< 1\mu\text{m}$) of the Auger electrons. Many of the low lying high spin isomers produced in (γ, γ') reactions decay with electrons, which trigger large showers of Auger cascades.

The isotope ^{44}Ti generator of ^{44}Sc can be produced with the $^{46}\text{Ti}(\gamma, 2n)^{44}\text{Ti}$ reaction and is much requested for new developments in medical imaging.

The ^{44}Sc isotope is the best candidate to supply two 511 keV annihilation photons from positrons from beta decay of ^{44}Ti together

decay from the resonance, is a powerful tool for applications in various domains that require the knowledge of the content of specific isotopes in material samples. Nuclear fluorescence resonance probability typically has very large peak values in a range of a few MeV. Nuclear fluorescence resonance is very effective in providing a fingerprint for isotope identification (see Fig. 3.2 and Fig. 3.3).

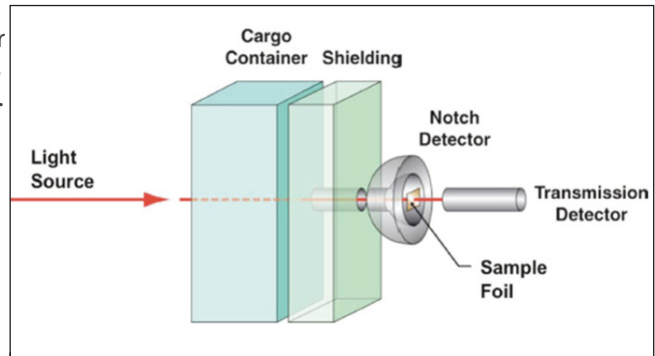


Fig. 3.3
Schematic illustration of the application of the nuclear resonance technique.

The present challenges are to increase the sensitivity to small amounts in samples and to be able to scan large volumes in short times.

In the current geopolitical environment, proliferation of nuclear and radiological materials is a major concern. Many efforts are underway to develop systems using nuclear fluorescence that can rapidly identify and characterize illicit nuclear and radiological materials. A comprehensive approach to the detection of weapons of mass destruction containing special nuclear materials requires the ability to rapidly and efficiently determine a region of interest in three dimensions. A typical example is to identify and quantify nuclear isotopes such as ^{235}U and ^{239}Pu . One important aspect is that the confidence of finding special nuclear material must be very high while the rate of false alarms must be very low, thus ensuring effective detection without impeding the flow of commerce. High intensity gamma-ray beams with narrow energy width exciting nuclear fluorescence resonances are ideal in this connection.

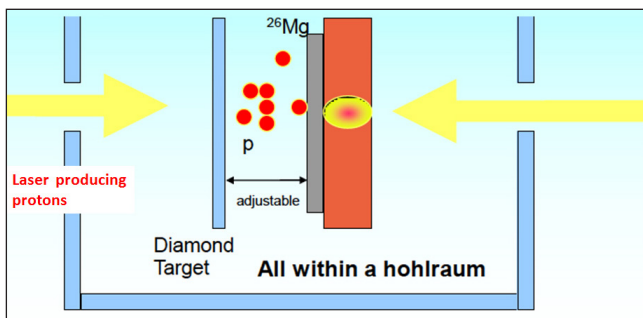


Fig. 3.1
Schematic illustration of proton capture in nuclei using Laser.

In nuclear medicine, diagnostics and therapeutics, gamma-ray beams will be used to produce radioisotopes via gamma-ray induced reactions. Gamma-ray beams, with good energy resolution, facilitate production of useful isotopes through specific gateway states or groups of resonant states where their generation probability can be increased by 2-3 orders of magnitude compared to other production techniques. This makes them even more interesting for large scale industrial applications. For example, the metastable state of ^{195}Pt is used for determining the efficiency of chemotherapy for tumours and the optimum dose by nuclear imaging.

with a strongly populated gamma transition (see Fig. 3.4). By measuring the position and direction of this γ photon accurately with a Compton spectrometer, together with the two 511 keV photons, the location of the emitting nucleus can be determined in 3 dimensions. Developing these techniques and applications is a task in the field of nuclear physics undertaken to improve human life quality.

The process of nuclear fluorescence resonance, corresponding to the excitation of a nuclear state by photon beams followed by either beam absorption measurements or by the measurement of gamma

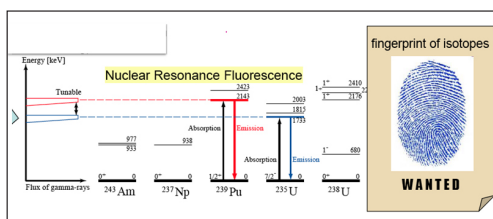
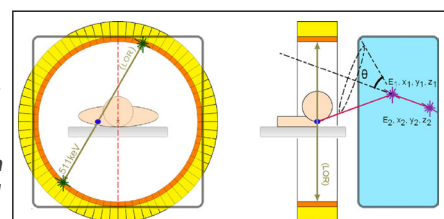
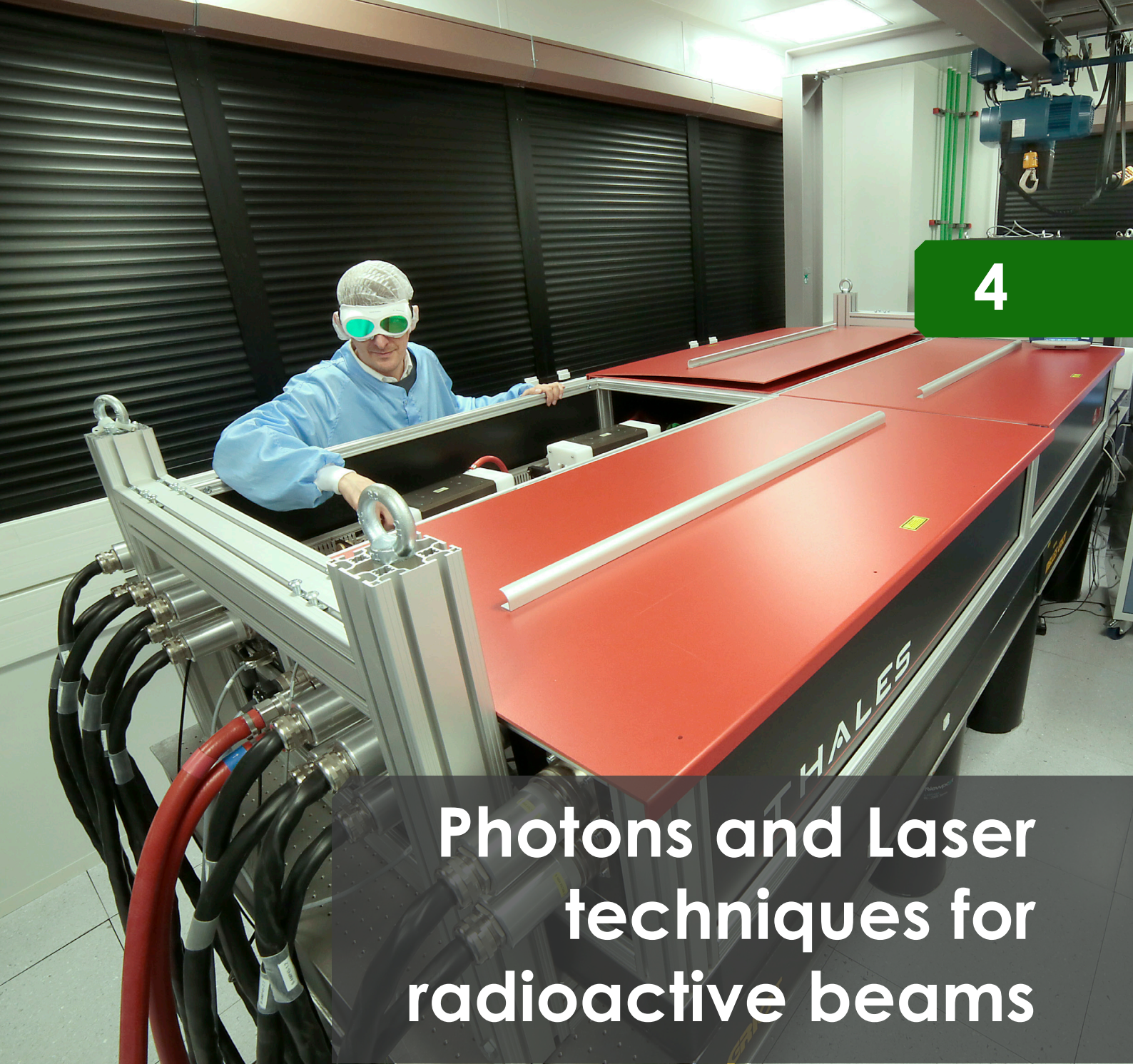


Fig. 3.2
Excitation via gamma irradiation of nuclear states (nuclear fluorescence resonance) characterizing specific isotopes of chemical elements.

Fig. 3.4
Schematic illustration of the use of radioisotopes emitting nuclear radiation to make imaging for medicine.



A person wearing a blue lab coat, a white hairnet, and green safety goggles is working on a large, red and black industrial machine. The machine has the word 'HALES' written on its side. The person is leaning over the machine, which has a red top and black base. There are several black cables connected to the machine. The background shows a dark, corrugated metal wall and some industrial equipment.

Photons and Laser techniques for radioactive beams

Lasers shine light on radioactive isotopes

An atom consists of a tiny nucleus at its core and a cloud of electrons that orbit around the nucleus at relatively far distance. For comparison, if the atomic nucleus were the size of a pea put at the center of a football field, the electrons would be on average moving in the spectator stands.

The nucleus is built from certain numbers of protons and neutrons kept together by the so-called strong or nuclear force. Atoms with the same number of protons but different numbers of neutrons are called isotopes. Nuclear-physics research aims to understand the fundamental interactions at play in the atomic nucleus by, among others, studying the properties of atoms with extreme numbers of protons and/or neutrons. However, as these atoms are radioactive, they only exist for a short period of time (often less than a second) and cannot be found on Earth. Hence they have to be synthesized at particle accelerators or research reactors.

Lasers are an essential tool to investigate radioactive isotopes (Fig. 4.1). By probing the electrons surrounding the nucleus of the isotope with laser light, information on the nucleus itself can be obtained.

This may come as something of a surprise! How is it possible, for example, to study the tiny detailed shape of the 'pea' by determining the way the electrons move in the spectator stand? The answer is that the electrons travelling around the nucleus carry a fingerprint of the nucleus and the key to seeing this is the extreme precision with which laser spectroscopy measurements can be performed, even on short-lived radioactive atoms. By measuring tiny changes in the colour of the laser light, the shape of the nucleus or the way the protons and neutrons are put together to form a nucleus can be investigated. In other words, the changes let us see if the 'pea', i.e. the nucleus, has the shape of a sphere, like a football, or is deformed, like the shape of a rugby-ball. If it is deformed the electrons move differently and this can be 'seen' by the lasers. In a deformed nucleus the protons and neutrons are arranged differently, and we hence can 'look' inside the atomic core by shining laser light onto the outside of the isotopes.

Some radioactive isotopes are only produced in very small quantities, perhaps as low as one atom each second, and these may have to be separated from the billions of other atoms also being produced at the same time. Lasers provide a solution here too. Every chemical element of Mendelev's periodic table, like oxygen or gold, has its unique chemical colour scheme, and lasers can be used to identify those isotopes with the right fingerprint, thus allowing their selection (Fig. 4.2).

Lasers literally bridge the gap between the physics of the atom and its nucleus. They are used in many other aspect of nuclear physics research like e.g. polarized target production and are an integral component for many of the world's leading radioactive isotope facilities, for example ISOLDE-CERN-Switzerland, GSI-Germany, JYFL-Finland, ALTO-France, ISAC-TRIUMF-Canada, and RIKEN-Japan.



Fig. 4.1

Photo: CERN

Laser laboratory of the ISOLDE-CERN facility where short-lived radioisotopes are selectively ionized and send for experiments.

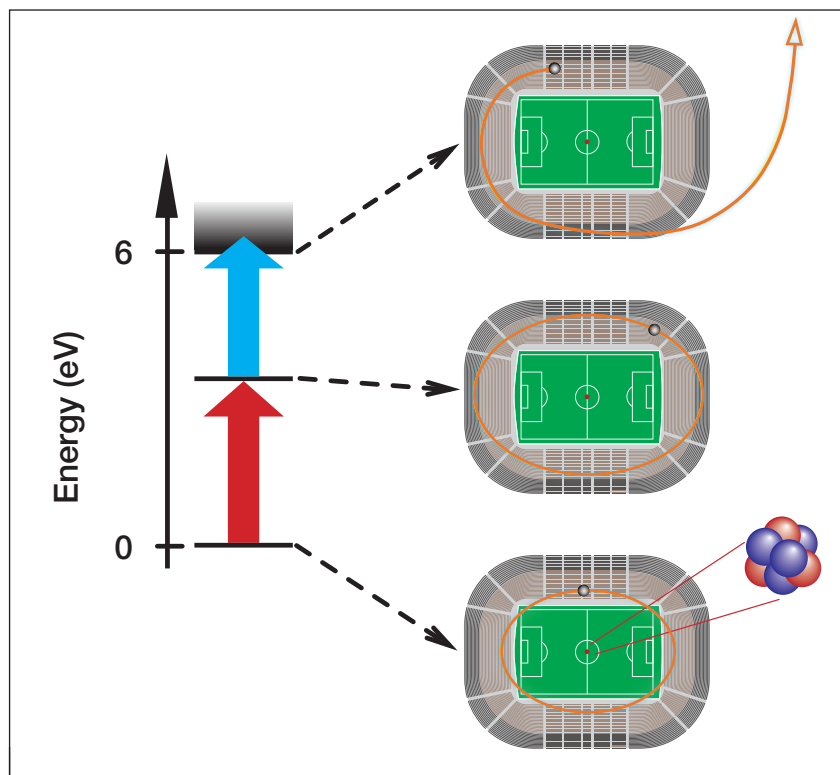


Fig. 4.2

Two laser beams with different colors are used to remove one electron from the atom by lifting it to higher energy states until it reaches the grey zone where it leaves the atom; the electron leaves the football stadium. The remaining ion (an atom with at least one electron removed) are transported to the experimental set-up using electrical and magnetic fields. To give an idea of the different sizes: If we assume that a pea in the center of the football lawn is the nucleus, the electron orbit (in orange) will be at the border of the lawn. Once the electron is excited by the first laser (in red) will gain energy and move to the seats in the middle of the football stadium. With the energy gained by the second laser (in blue) it will escape and the atom will get ionised

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