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Review

Bright perspectives for nuclear photonics

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Abstract. With the advent of new high-power, short-pulse laser facilities in combination with novel technologies for the production of highly brilliant, intense γ beams (like, e.g., Extreme Light Infrastructure – Nuclear Physics (ELI-NP) in Bucharest, MEGaRay in Livermore or a planned upgrade of the HIγS facility at Duke University), unprecedented perspectives will open up in the coming years for photonuclear physics both in basic sciences as in various fields of applications. Ultra-high sensitivity will be enabled by an envisaged increase of the γ-beam spectral density from the presently typical $10^2\gamma$/eVs to about $10^4\gamma$/eVs, thus enabling a new quality of *nuclear photonics* [1], assisted by new γ-optical elements [2]. Photonuclear reactions with highly brilliant γ beams will allow to produce radioisotopes for nuclear medicine with much higher specific activity and/or more economically than with conventional methods. This will open the door for completely new clinical applications of radioisotopes [3]. The isotopic, state-selective sensitivity of the well-established technique of nuclear resonance fluorescence (NRF) will be boosted by the drastically reduced energy bandwidth (<0.1%) of the novel γ beams. Together with a much higher intensity of these beams, this will pave the road towards a γ-beam based non-invasive tomography and microscopy, assisting the management of nuclear materials, such as radioactive waste management, the detection of nuclear fissile material in the recycling process or the detection of clandestine fissile materials. Moreover, also secondary sources like low-energy, pulsed, polarized neutron beams of high intensity and high brilliance [4] or a new type of positron source with significantly increased brilliance, for the first time fully polarized [5], can be realized and lead to new applications in solid state physics or material sciences.

1 Introduction

High-energy photons offer a precise probe for nuclear properties and processes, including various fields of applications. Photonuclear physics can already look back onto a history of several decades, where mostly bremsstrahlung of electrons was employed as photon beam source, either used directly with its broad and exponentially decreasing energy characteristics [1], or in a refined manner, where photons of a specific energy are selected ("tagged") out of the continuous bremsstrahlung spectrum by detecting the corresponding electron in coincidence behind an electron spectrometer dipole

magnet [2]. However, these methods suffer from a limited spectral density of the γ beam and the copious production of background from Compton scattering or pair creation processes. Ideally, a monochromatic γ beam matched in energy bandwidth to the targeted nuclear resonance, ultimately limited by the thermal Doppler broadening, should be employed. A promising route towards this goal is provided by the method of Compton back-scattering of laser light from relativistic brilliant electron beams, as envisaged for next-generation γ-beam facilities like ELI-Nuclear Physics (Bucharest/Romania, [3]), MeGARay (Livermore/USA, [4]) or a planned upgrade of the HIγS facility (HIGS2) at Duke University [5]. Here, γ beams with unprecedented quality will become available, exhibiting high photon flux (10^{13}–10^{15} γ/s), small diameter (ca. $100\,\mu m^2$) and small energy bandwidth (Δ E/E$\approx 10^{-3}$–10^{-4}). Such high-brilliance γ beams will open up a whole wealth of new or significantly improved applications.

2 Highly efficient production of medical radio-isotopes

Photoexcitation (γ,$\gamma\prime$) or photonuclear reactions (γ, xn + yp) with highly brilliant γ beams allow to produce specific radioisotopes for nuclear medicine, like ^{47}Sc, ^{44}Ti, ^{67}Cu, ^{103}Pd, ^{117m}Sn, ^{169}Er, ^{195m}Pt or ^{225}Ac, with much higher specific activity and/or more economically compared to conventional techniques based on (ion, xn+yp) reactions (ion = p, d, α) from particle accelerators like cyclotrons or (n, γ) or (n, f) reactions from nuclear reactors [18].

In photonuclear reactions, the well-defined initial excitation energy of the compound nucleus will lead to a small number of reaction channels and thus will enable the use of new combinations of target isotope and final radioisotope. Photonuclear reactions also provide advantages compared to neutron- or charged-particle induced reactions when using radioactive targets (e.g. ^{226}Ra). Here the active material can be safely encapsulated into relatively thick metal walls, since γ rays penetrate better and cause less heating of the walls than charged particle beams would do.

In order to realize an optimized focal spot of the γ beam, novel focusing technologies based on refractive γ lenses can be employed [19,20], consisting of a stack of many concave micro-lenses.

Within a rather short period compared to the isotopic half-lives, the brilliant and intense γ beam allows to irradiate and efficiently convert a small target area of the order of $100\,\mu m^2$. Therefore much less of the often costly target material is required. The produced radioisotopes are concentrated in a small target volume, hence resulting in a much high specific activity than presently achievable and allowing the use of enriched target isotopes. In case radioactive targets have to be used, they will be more efficiently converted into the required product isotopes, hence more compact and less active targets can be employed, requiring to handle less activity and to less dose rate exposure.

The narrow-bandwidth photo-excitation may make use of collective resonances in the γ width, leading to increased cross sections. (γ,$\gamma\prime$)-induced isomer production via specifically selected γ cascades will allow for producing high specific activities in multiple excitations, where no back-pumping of the isomer to the ground state will occur.

Significant advantages also result from the high monochromaticity achievable with the novel *gamma*-ray beams: The high cross-section for monochromatic beams leads to a short interaction lengths of a few mm or less, which in turn allows to strongly reduce the required target mass. This further reduces the target costs and, correspondingly, increases the resulting specific activity. Also a much reduced γ-ray heating per useful reaction rate will occur when using monochromatic beams. Moreover, a much

reduced radiation damage is to be expected due to monochromatic beams. It may become possible to first dope and then activate materials (e.g. organic, nanoscale materials) that would not withstand irradiation in a nuclear reactor or a white γ-ray spectrum. Isotopic enrichment of target materials may in many cases not necessarily be needed, since the resonant cross section for interaction with the targeted isotope is much higher than accompanying non-resonant interactions with other target isotopes. In photonuclear reactions it will become possible to selectively excite resonances that decay by neutron, proton, α, etc. emission. Thus the wanted reaction channel can be enhanced over competing reaction channels leading to non-useful or disturbing products. Therefore also less stringent requirements apply concerning chemical impurities of the target material, since non-resonant activation of impurities is suppressed with respect to resonant excitation of the wanted production channels. Longer-lived nuclear isomers (such as ^{117m}Sn, ^{119m}Sn, ^{123m}Te, ^{125m}Te, ^{135m}Ba) that decay by the emission of γ rays and/or conversion electrons to the respective ground state are of interest for various applications, if they can be produced with high specific activity: Moessbauer spectroscopy sources or nuclear medicine.

Isotopes produced via these methods will enable new clinical applications of medical radioisotopes. For example, ^{195m}Pt could be used to verify the patient's response to (widely used) chemotherapy with platinum compounds prior to performing the tumour treatment. In targeted radionuclide therapy, the short-range Auger and conversion electrons of ^{195m}Pt and ^{117m}Sn enable a very localized treatment. The generator isotope ^{44}Ti (which so far cannot be produced in clinically relevant quantities) allows for performing diagnostic medical imaging with a modified positron emission tomography (PET) technique, based the fact that the daughter nucleus ^{44}Sc in addition to its β^+ decay emits a (prompt) 1.157 MeV photon from an excited state of the decay product. Exploiting, in addition to the (conventionally used) line-of-response (LOR) between the two 511 keV positron annihilation photons, the intersection between the LOR and the trajectory of the prompt third photon, a significantly enhanced source reconstruction sensitivity for this novel "γ-PET" method can be obtained [13,14]. The well-established technique of nuclear resonance fluorescence (NRF), in combination with the novel highly-brilliant and intense γ beams, will also allow to study the distribution of ^{7}Li in patient brains following Li-based medication during manic depression treatments. Spatially resolved resonance fluorescence of the 478 keV fluorescence following the ^{7}Li(γ,$\gamma\prime$) reaction may reveal the so-far unknown domains of Li-based drugs in the human brain.

3 Sensitive assay of radioactive materials via γ-induced tomography/microscopy

Nuclear Resonance Fluorescence (NRF) using highly brilliant, laser-driven *gamma* beams will also allow for a sensitive non-destructive detection of materials, even if those might be hidden behind haevy shields such as several centimeters of iron or lead. Such detection of clandestine materials is of importance e.g. for applications in nuclear engineering: the management of nuclear materials produced by nuclear power plants, the detection of nuclear fissile material in the recycling process, and the detection of explosive or nuclear materials hidden in packages or cargo containers. A non-destructive assay [17] has been proposed, based on the extremely high photon flux of a laser-driven Compton scattering γ source, where the elemental and isotopic composition of the targeted material is measured using nuclear resonance fluorescence (NRF). In this context the high societal impact of such techniques, in particular in the regime of non-invasive nuclear waste management, should e stressed. Precise and remote identification and quantification of isotopes like ^{239}Pu, ^{235}U or most abundant

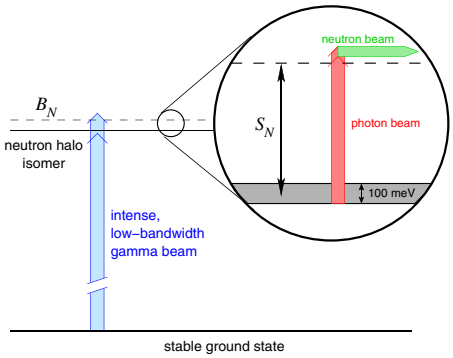

Fig. 1. Schematic picture of the neutron production: With focused, monochromatized, intense γ beams neutron halo isomers are produced below the neutron binding energy B_N at a separation energy S_N. In a second step, a photon beam of much lower energy is used to release the neutrons [6].

fission products will enable new handling scenarios for longterm storage of radioactive waste, a so-far not satisfactorily solved problem worldwide.

4 Brilliant neutron micro beams

Amongst the secondary particle sources that may become accessible upon the availability of highly brilliant, laser-driven γ beams, intense, brilliant low-energy pulsed neutron beams will open new perspectives for solid state physics and material sciences.

While presently the use of reactors or spallation sources to produce thermal or cold neutron beams via the moderation of energetic (MeV) neutrons down to the meV regime leads to very large sources with diameters of several meters and thus to correspondingly limited neutron flux densities. In Ref. [6] the possibility is discussed to populate weakly bound neutron halo isomeric states which, after stopping, are used to release a directed, low-energy, brilliant micro neutron beam when irradiating them with a second laser or an X-ray beam. This production scheme is illustrated in Fig. 1.

A first step will be to search for such neutron halo isomers populated via γ-capture in stable nuclei with mass numbers of about A = 140–180 or A = 40–60, where the $4s_{1/2}$ or $3s_{1/2}$ neutron shell model state reaches zero binding energy. These halo nuclei can be produced for the first time with the new γ beams of high intensity and small bandwidth ($\sim$0.1%), as achievable via Compton back-scattering off brilliant electron beams. This will offer a promising perspective to selectively populate these isomers with small separation energies of 1 eV to a few keV. According to [6], the expected properties of the resulting neutron beams will be intriguing: starting with a γ-beam intensity of $10^{13}\gamma$/s with an energy of about 7 MeV and a bandwidth of about 7 keV ($\Delta E/E = 10^{-3}$), compound nuclear resonances can be excited with a width of $\sim$100 meV, resulting in an intensity of ca. 10^8 isomers/s in a target spot of $\sim$0.1 mm diameter. The (p-wave) neutrons are emitted with $(100\,\mathrm{mrad})^2$ opening angle and a bandwidth better than 0.1%. Thus a rough average brilliance of $\sim 10^6$/[(mm mrad)^{2}0.1% BW s] can be estimated. This value may be reduced by one order of magnitude to $\sim 10^5$/[(mm mrad)^{2}0.1% BW s], since not always 0.1% BW may be reached. Nevertheless, this value is already about 2 orders of magnitude better than the best average brilliance of a reactor, e.g., the H12 beam line of the ILL

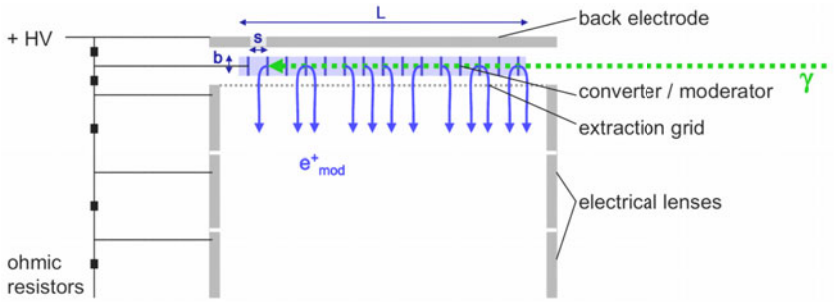

Fig. 2. Experimental setup for a γ-beam driven source of moderated positrons. The Pt foils are used as a converter/moderator. The thickness d_w of the W foils is determined by the average e^+ energy. The diameter b of the foils determines the spacing s between the foils with b:s=3:1 for efficient extraction. The total length L $\approx N(s + d_W)$ is determined by the number N of converter foils [9].

reactor [7]. Due to the target isomer thickness of ∼1 mm (required to absorb all resonant photons of the compound nuclear resonance) and the slow movement of the neutron with about 2000 m/s, the resulting monoenergetic neutron beam will be pulsed with 1 μs pulse duration. Thus the peak brilliance will be further increased by a factor of 10^6 compared to the average brilliance, thus reaching a peak brilliance of $\sim 10^{11}/[(\text{mm mrad})^2 0.1\%\ \text{BW s}]$.

By switching the polarization of the primary laser beam, the polarization of the neutron beam can be switched from shot to shot. Since the spin of the neutron is coupled to its magnetic dipole moment, the detailed manipulation of the polarization of the neutron beam becomes available [6].

As outlined in [6], a broad interest exists in the solid-state community in high-quality cold neutron beams: in the field of neutron scattering, there is a large development towards cold and thermal micro-neutron beams for studying the structure and dynamics (excitations) of small samples under extreme conditions, for example in the area of solid-state and soft-matter physics. Here, in particular the large field of reflectometry, small-angle neutron scattering (SANS) and diffraction will profit from highly brilliant and small beams. Thus the development of highly-brilliant micro neutron beams may lead to major improvements in future neutron scattering techniques similarly to the invention of synchrotron sources in the field of X-ray scattering.

5 Brilliant (laser-driven) positron beams

Positron beams have a broad range of applications in research fields like solid-state physics or surface physics, e.g., to diagnose complex structures of matter like Fermi surfaces, defects, surfaces or interfaces. Novel laser-driven intense, highly-brilliant γ beams will allow to transfer these qualities to secondary (micro) positron beams. Starting from an intense photon beam of $5 \cdot 10^{15}\gamma$/s with (2.5 ± 0.5) MeV, an intense moderated positron beam of about $5 \cdot 10^9$ e^+/s can be obtained via the (γ,e^+e^-) reaction [9]. Due to the small diameter of the well-directed γ beam, a brilliance of about 10^9 $e^+/[\text{s(mm mrad)}^2\ 0.1\%\text{BW}]$ can be expected for such a new type of positron source, which is about 6 orders of magnitude more brilliant than the presently strongest positron sources at nuclear reactors (e.g. the NEPOMUC positron source at the FRM-2 neutron source in Garching [8]).

In Ref. [9] a layout of a new type of (moderated) positron source is described, taking advantage of the small diameter of the focused γ beam of only a few μm, impinging on a stack of Pt converter foils, as shown in Fig. 2.

Employing not a broad range of capture γ lines, but selecting an optimum γ energy, allows for using lower primary positron energies, which in turn allows for much thinner converter foils with correspondingly higher conversion efficiency by improved extraction. Another practical advantage of such a small-size positron source is the easy (and thus time-saving) access to the converter or moderator, compared to the demanding procedure required when access to a positron source close to a reactor fuel element is needed.

Using fully polarized photon beams, for the first time it will be possible to realize an intense, fully polarized positron beam.

The new brilliant source is best suited for micro-positron beams, e.g., in positron microscopy. Polarized positron beams open up a totally unexplored research area, where polarized electrons in, e.g., magnetic structures can be studied.

6 Conclusions and perspectives

Laser-driven, highly brilliant and intense γ beams from Compton backscattering, provided by next-generation facilities like ELI-Nuclear Physics and MeGaRay or an upgraded HIγS [21] facility, will open new horizons for a new quality of photonuclear science, called "nuclear photonics". Unprecedented γ beam properties with a high monochromaticity of $\Delta E/E \leq 10^{-3}$ and a spectral density of $\geq 10^4 \gamma$/eVs will in particular open new perspectives for various fields of applications, in particular using the novel γ beams for the production of new radioisotopes for nuclear medicine with very high specific activity, that may complement and extend the presently used portfolio of radioisotopes for nuclear medicine applications. In addition, secondary particle sources with unique properties will emerge. Cold micro-neutron beams with significantly higher brilliance than achievable with reactors or spallation sources or a high-brilliance positron source come into reach.

Moreover, recent intriguing results of realizing high peak power laser systems with simultaneous high average power by coherent funneling of many fibre-laser beams [22] might lead in the future to even further-reaching applications in the field of nuclear photonics.

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