Extreme Light Infrastructure–Nuclear Physics (ELI–NP): New Horizons for Photon Physics in Europe

The European Strategy Forum on Research Infrastructures (ESFRI) and its roadmap [1] aim to integrate national resources into a common, pan-European effort. Currently the ESFRI roadmap, first issued in 2006 and updated in 2008, lists 43 large-scale projects selected from all science and engineering areas. Under the 7th Framework Programme the European Commission has funded the preparatory phases for 34 projects included in the 2006 ESFRI roadmap. In the area of physical sciences besides the two radioactive beam facilities FAIR (at GSI/Germany) and SPIRAL2 (at GANIL/France) also the project "Extreme Light Infrastructure" (ELI) [2] was selected. Already one year before the end of ELI's 7th Framework Preparatory Phase a decision was made in October 2009 to implement ELI as a joint European consortium of 17 nations consisting of three laser facilities that will be consolidated under the joint ELI project. The prime objective is to build a unified infrastructure based on three mutually supporting pillars.

One pillar will be located in Prague (Czech Republic), focusing on building a novel generation of secondary sources from high energy laser beams for interdisciplinary applications in physics, medicine, biology, and material sciences [3]. The second pillar, concentrating on the physics of ultrashort optical pulses on the attosecond scale, is scheduled for location in Szeged (Hungary) [4]. Finally, the third pillar will be built in Magurele, close to Bucharest (Romania) and will be dedicated to (photo-)nuclear physics [5], therefore termed ELI–Nuclear Physics (ELI–NP). With the termination of ELI's Preparatory Phase end of November 2010 and with funding of 280 million Euros in the process of being allocated from EU structural funds for ELI–NP in Romania, ground breaking for ELI–NP should start as early as 2011.

The laser backbone of ELI–NP will consist of several arms of high-power, short-pulse lasers, each of them providing 10 Petawatt laser power (Table 1). These "APOLLON"-type lasers are currently being developed by the group of Gerard Mourou and coworkers at the École Nationale Supérieure de Techniques Avancées (ENSTA) in Paris [6]. Here, a future fourth pillar of ELI is prepared, where many APOLLON lasers are envisaged to be combined for high-field science. The second source of ELI–NP, the γ-beam facility (Table 1), will be developed and provided by the group of Chris Barty at Lawrence Livermore National Laboratory (LLNL). Brilliant, intense, and energetic photon beams will be generated via Compton backscattering of laser photons from a high-quality electron beam [7]. The Livermore group is presently building a similar facility called MEGa-ray [8], with a normal-conducting electron linac

Table 1. Characteristics of the ELI–NP linear Compton back-scattering γ source and the high-powerlasers.

Parameters of γ-beam	Value	Parameters of APOLLON lasers	Value
max. e energy	600 MeV	power	$2 \cdot 10$ PW
max. γ energy	13.2 MeV (19.5 MeV)	OPCPA front end	
norm. emittance	0.18 mm mrad	Ti:Sapphire	
γ-energy spread (FWHM)	10^{-3}	high energy end	
total flux (ph/s)	10^{13}	100 TW	10 Hz
pulse repetition (macro p.)	12 kHz (120Hz)	1 PW	≥0.1 Hz
pulse duration	2 ps	10 PW	1/min
γ source size	10 μm	max. intensity	10^{24} W/cm^2
peak brilliance	$1.5 \cdot 10^{21}$	max. field strength	≈10^{15} V/m
ph/(mm^2 mrad^2 s 0.1% BW)		pulse duration	15 fs
average brilliance	$4 \cdot 10^{12}$	contrast (10 ps before)	10^{-12}
ph/(mm^2 mrad^2 s 0.1% BW)			

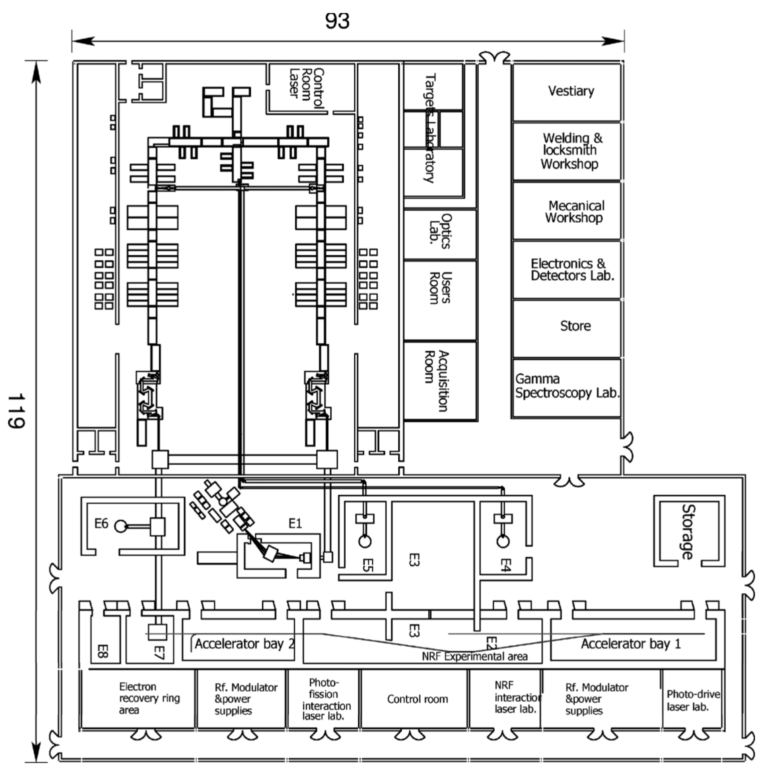

Figure 1. *Layout of the ELI–NP facility.*

based on X-band technology. This facility is a continuation of their previous γ-ray facilities PLEJADES [9] and T-REX [10]. Hence, the long-term expertise of the groups responsible for the key components of ELI-NP raise confidence for a timely completion of the main driver facilities for ELI–NP.

In this article, at a rather early stage of the project, we will outline the scope of ELI–NP. We will present the broad range of the physics cases targeted within ELI–NP, covering many facets of photonuclear reactions, but also astrophysics and fundamental physics. Moreover, we will illustrate the various perspectives for applications ranging from medicine to material science, life science, and radioactive waste management.

The experiments can be grouped into three categories: stand-alone γ-beam experiments, stand-alone APOLLON-type laser experiments, and combined experiments making use of both drivers, for example, the 600 MeV electron beam (for the γ-beam) and the high power lasers.

The layout of the ELI–NP facility, covering an area of about two football fields, is shown in Figure 1. It consists of two 10 PW lasers, shown in the upper part of the figure, which can be added phase-synchronized into a common focus. In the lower part the normal-conducting electron linac is shown, delivering γ beams from two beam ports. The high spatial accuracy of the beams requires a special design of the concrete base plate of the building to prevent vibrations. The laser hall will require clean-room conditions of class 6. The large amount of radioprotection concrete shielding is designed in a modular way to accomodate the planned experiments with a maximum of flexibility. Finally, an architect's vision of the ELI–NP facility is shown in Figure 2.

Nuclear Physics and Astrophysics

Experiments with Stand-Alone APOLLON-Type Lasers

The origin of the heaviest elements (e.g., gold, platinum, thorium, uranium) remains one of the 11 greatest unanswered questions of modern physics, according to a recent report by the U.S. National Research Council of the National Academy of Science [11]. A recent paper [12] outlines in detail, how dense, laser-accelerated ion beams open up a new access to very neutron-rich nuclei, relevant to this element production. In this proposal, we introduced the new "fission–fusion" nuclear reaction process that allows one to produce the decisive extremely neutron-rich nuclei in the range of the astrophysical *r*-process (the rapid neutron-capture process around the waiting point $N = 126$ [13, 14] by fissioning a dense, laser-accelerated thorium ion bunch in a thorium target (covered by a polyethylene layer), where the light fission fragments of the beam fuse with the light fission fragments of the target. So far the astrophysically relevant nuclei are about 15 neutrons away from the last known isotope of a given element and nothing is known about their nuclear properties (Figure 3).

Via the "hole-boring" (HB) mode of laser Radiation Pressure Acceleration

Figure 2. *Architect's view of the ELI–NP facility.*

(RPA) [15, 16] using a high-intensity, short pulse laser bunches of ^{232}Th with solid state density can be generated very efficiently from a Th layer (approx. 0.5 μm thick), placed on a deuterated diamond-like carbon foil $[CD_2]_n$ (with approx. 0.5 μm thickness), forming the production target. Laser-accelerated Th ions with about 7 MeV/u will pass through a thin $[CH_2]_n$ layer placed in front of a thicker second Th foil (both forming the reaction target) closely behind the production target and disintegrate into light and heavy fission fragments. In addition, light ions (d,C) from the $[CD_2]_n$ backing of the Th layer will be accelerated as well, inducing the fission process of ^{232}Th also in the second Th layer. The laser-accelerated ion bunches with near solid state density, which are about 10^{14} times more dense than classically accelerated ion bunches, allow for a high fusion probability of the generated fission products when the fragments from the thorium beam strike the thorium layer of the reaction target.

In contrast to classical radioactive beam facilities, where intense but low-density radioactive beams of one ion species are merged with stable targets, the novel fission–fusion process draws on the fusion between high-density, neutron-rich, short-lived, light fission fragments both from beam and target. Moreover, the high ion beam density may lead to a strong collective modification of the stopping power in the target by "snow-plough-like" removal of target electrons, leading to significant range enhancement, thus allowing one to use rather thick targets.

Using a high-intensity laser with 300 J and 32 fs pulse length, as, for example, envisaged for the ELI–Nuclear Physics project in Bucharest (ELI–NP), order-of-magnitude estimates promise a fusion yield of about 10^3 ions per laser pulse in the mass range of $A = 180 - 190$, thus enabling to approach the *r*-process waiting point at N = 126. The produced nuclei from the fission–fusion process will

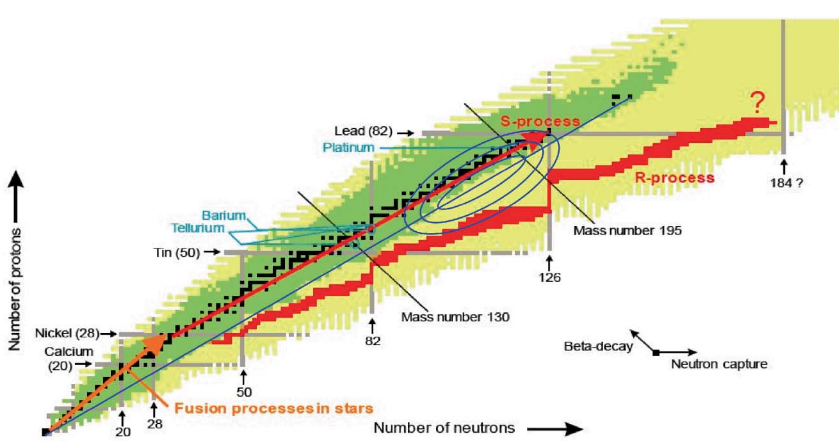

Figure 3. *Nuclidic chart, showing the different nucleosynthesis processes like the r-process, the s-process, or the fusion processes in stars together with contour lines of the new fission–fusion process for producing very neutron-rich nuclei close to N = 126 waiting point of the r-process.*

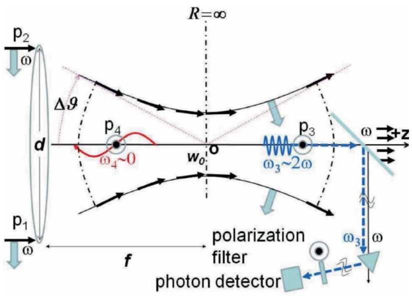

Figure 4. *Suggested experimental setup to detect low-mass elementary particles by mediating the two photon transition in vacuum of an intense laser focus.*

be injected into a Penning trap to measure their nuclear binding energy, a measure for shell quenching, with high accuracy [12]. This information will constrain possible sites for the astrophysical r-process decisively.

Experiments with γ-Beams

Employing intense, brilliant γ beams the fine structure of many E1 and M1 excitations can be probed in detail with their many decay branches. Specific parity-violating mixtures between parity doublets (e.g., 1^+ and 1^- states) allow a very sensitive access to parity violating nuclear forces [17]. The gateway states to switch from the ground state via γ-excitation–deexcitation to a longer-lived isomer or from one isomer to the next with still higher spin and K quantum number can be explored in detail. The transition from regular nuclear motion at lower energies to chaotic nuclear motion at higher excitation energies, which recently has been reviewed in detail [18], can be studied by many tools like nearest-neighbor level distributions or Porter-Thomas width distributions. Very high-resolution γ spectrometers, similar to the GAMS spectrometer at ILL [19], will become more important. Once we reach excitation energies with particle unstable states, fine structures like the Pygmy Dipole Resonance (PDR) become important for astrophysical processes.

Fundamental Physics

Pair Creation from the Vacuum with 600 MeV Electrons Seeding a very Intense Laser Focus

The typical quasi-static threshold electric field for pair creation from the vacuum is $E_s = m^2c^3/e\hbar = 1.3\cdot10^{18}$ V/M, which correspond to laser intensities of $4.3\cdot10^{29}$ W/cm^2. Due to the very strong exponential dependence of the pair production rate [20] in the focused laser fields of ELI–NP, we cannot reach pair creation with the laser field alone. Here, Nina Elkina and colleagues [21] of Hartmut Ruhl's group (LMU, Munich) performed detailed simulations focussing 600 MeV electrons as seeds into the focus of two counter-propagating circularly polarized APOLLON-type lasers. By strongly non-linear quantal effects the electrons emit hard γ rays (up to 500 MeV) in the laser focus, which then in a second step decay into e^+e^- pairs. These pairs are re-accelerated, resulting in further hard γ rays and pairs. Elkina's simulations showed a quadratic increase of pairs in the laser focus with time, less than exponential, due to the loss of electrons and positrons from the focal laser region. At ELI–NP this strong radiation damping, the predicted spectra and angular distributions of hard γ rays, electrons and positrons will be compared to experimental data, resulting in conclusive tests of the computer simulations for strong laser-field interaction.

Searching for Light Elementary Particles with High Power Lasers

In stand-alone experiments with the APOLLON-type lasers the fundamental properties of vacuum can be probed. Here, Kensuke Homma and colleagues [22] have proposed new experiments: Very light elementary particles below 1 eV (like candidates of dark energy) couple very weakly to matter and have not been detected until now. Here, the very intense semi-macroscopic laser fields may open a new window to find these new particles via coupling to laser photons, by observing the generation of second-harmonic radiation in the quasi-parallel colliding system of a single focused laser. Schematically this experiment is shown in Figure 4.

Applications

With the γ-beam of ELI–NP several new applications can be developed, giving many nuclear excitation cross-sections a new importance. Many of the applications (e.g., in medicine or radioactive materials and radioactive waste management) open new perspectives in a socioeconomical context.

New Medical Radioisotopes Produced with γ-Beams

In Ref. [23] about 50 radioisotopes are described, which can be produced with better specific activity and absolute activity by γ beams compared to present production schemes, being of interest for medical diagnostic and/or therapeutic purposes. With the narrow bandwidth γ beams we will find specific gateway states or groups of resonant states for many of the isotopes, where the production cross-sections can be increased by 2–3 orders of magnitude compared to the existing average cross-sections [23], making them even more interesting for large-scale industrial applications. Here we shall focus on some of the most interesting isotopes to give a flavor of the new possiblities.

^{195m}Pt: Determining the efficiency of chemotherapy for tumors and the optimum dose by nuclear imaging In chemotherapy of tumors most often platinum cytotoxic compounds like cisplatin or carbonplatin are used. We want to label these compounds with ^{195m}Pt for pharmacokinetic studies like tumor uptake and want to exclude "nonresponding" patients from unnecessary chemotherapy, while optimizing the dose of all chemotherapy treatments. For such type of diagnostics a large-scale market can be foreseen, but it would also save many people from painful but useless treatments. It is estimated in Ref. [23] that several hundred patient-specific uptake doses could be produced with a γ beam facility per day. However, this probably may be increased to 10^5, if optimum gateway states can be identified by scanning the isomer production with high γ beam resolution.

^{117m}Sn: An emitter of low-energy Auger electrons for targeted tumor therapy Auger-electron therapy requires targeting into individual tumor cells, even into the nucleus or to the DNA, due to short range (below 1μm) of Auger electrons; however, this method is of high relative biological efficiency (RBE) due to the shower of many (typically 5–30) Auger electrons produced. On the other hand, Auger radiation is of low toxicity, while being transported through the body. Thus Auger-electron therapy needs special tumor-specific transport molecules like antibodies or peptides. Many of the low-lying high spin isomers produced in (γ,γ′) reactions have strongly converted transitions, which trigger these large showers of Auger cascades.

A variety of other important medical radioisotopes can be produced (see Ref. [23]): New "matched pairs" of isotopes of the same element become available, one for diagnostics, the other for therapy, allowing to contol and optimize the transport of the isotope by the bioconjugate to the tumor. Also new therapy isotopes become available, such as ^{225}Ac, where four consecutive α decays can cause much more efficiently DNA double-strand breaking. Developing these techniques and applications is a promising task of ELI–NP with a strong societal impact.

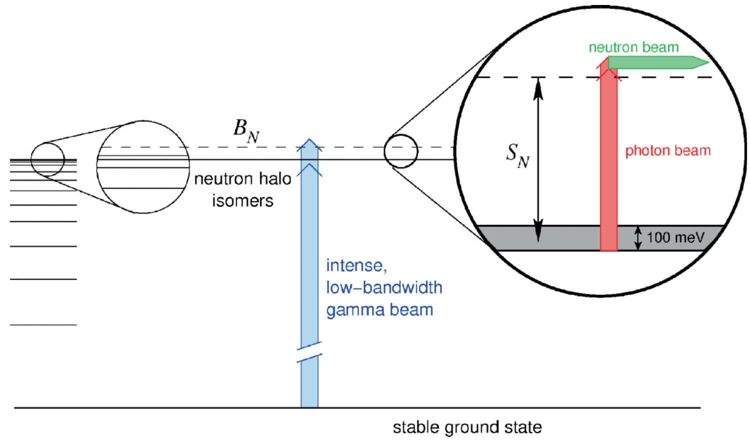

Figure 5. *Schematic picture of the new neutron production scheme, using the γ-beam to excite neutron-halo isomers with a neutron separation energy S_N below the binding energy E_B. The left level scheme shows the increasing number of compound nuclear resonances as a function of the excitation energy. The halo isomer is fragmented into several high-lying resonances, resulting in halo isomers with different binding energies. The two blue arrows indicate the width of the γ beam. Then in a second step, a photon beam of much lower energy, shown in red, generates the neutron beam by dissociating the neutron halo states.*

New Brilliant, Intense Micro-Neutron Source Produced by Intense, Brilliant γ-Beam

ELI–NP includes the proposal to develop a brilliant, low-energy neutron beam from the γ beam. In Ref. [24], it is described in detail, how low-energy neutrons will be released without moderation and without producing a broad range of fission fragments as in nuclear reactors, or a broad range of spallation products as in spallation neutron sources. Thus, the new neutron facility has the advantage of producing only small amounts of radioactivity and radioactive waste and thus requires only moderate efforts for radioprotection, therefore being very different from present reactor or spallation facilities. The new source can be operated as a multi-user neutron facility and could deliver several orders of magnitude

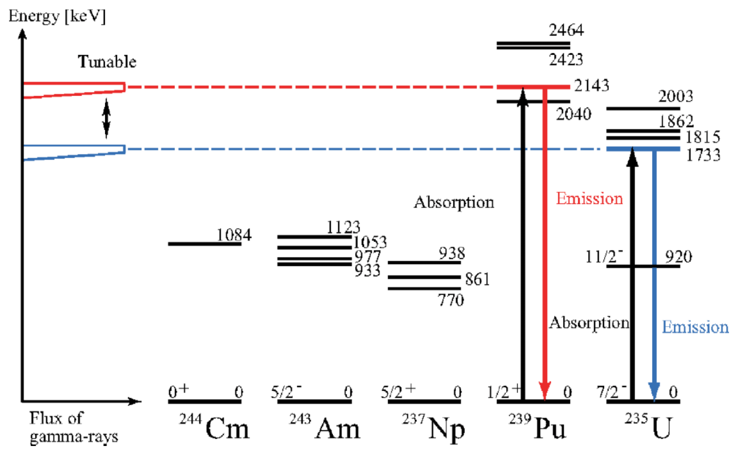

Figure 6. *Nuclear resonance fluorescence of several actinides, demonstrating the high sensitivity of the method [26].*

more brilliant neutrons compared to the best existing neutron sources. When producing the neutrons, we envisage to use a two-step process: with the high-energy γ beam in a first step neutron-halo isomers will be populated, while in a second step neutrons are released from the stopped neutron-halo isomers by a second photon pulse (Figure 5).

For the realization of such a neutron source we first plan to study the new neutron-halo isomers in detail. We propose to search for 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 states reach zero binding energy. These halo nuclei can be produced for the first time with the new γ beams of high intensity and small band width. This production scheme thus offers a promising perspective to selectively populate these isomers with small separation energies of 1 eV to a few keV. Similar to single-neutron halo states for very light, extremely neutron-rich, radioactive nuclei [25], the low neutron separation energy and short-range nuclear force allows the neutron to tunnel far out into free space, much beyond the nuclear core radius. This results in prolonged half-lives of the isomers for the γ-decay back to the ground state in the 100 ps-μs range. Similar to the treatment of photodisintegration of the deuteron, the neutron release from a neutron-halo isomer via a second, low-energy, intense photon beam has a much larger cross-section with a typical energy-threshold behavior. In the second step, the neutrons can be released as a low-energy, pulsed, polarized neutron beam of high intensity and high brilliance.

Similar to the situation 30 years ago, when synchrotron sources led to increases in brilliance of x-ray beams by many orders of magnitude, the production of pulsed neutron beams with extremely high brilliance will lead to a dramatic leap in the field of neutron scattering. The well focused beams of highest intensity will allow the accurate determination of the structure of biological samples, heterostructures, and of new functional materials. These materials are often only available in small quantities. The exceptionally strong scattering of neutrons by hydrogen and other light materials will provide key information concerning the functionality of bio-materials, which cannot be easily obtained using synchrotron beams or existing neutron sources. In addition, the brilliant neutron beams will allow for the first time the investigation of collective excitations (i.e., magnons and phonons), and relaxation as well as diffusion processes in samples that are only available in smallest quantities. Moreover, the by orders of magnitude smaller duration of the neutron pulses will allow for the investigation of time-dependent processes and the dynamics in systems far away from equilibrium. The new neutron beams will therefore open completely new scientific opportunities in the fields from biology to hard condensed matter to geosciences and nuclear physics. In Ref. [24] many new possibilities are described in more detail.

Nuclear Resonance Fluorescence of Nuclear Materials and Nuclear Waste Management

The non-destructive detection of materials hidden by heavy shields such as iron with a thickness of several centimeters is difficult. Such detection of clandestine materials is of importance, for example, 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 materials hidden in packages or cargo containers. A non-destructive assay [26] has been proposed with the extremely high-flux Laser Compton Scattering (LCS) γ source. The elemental and isotopic composition is measured using nuclear resonance fluorescence (NRF) with LCS γ-rays. Figure 6 illustrates how characteristic resonances of these elements can be identified via NRF.

Here, one has to stress the political importance of this project. Measuring remotely and precisely isotopes like ^{239}Pu, ^{235}U or dominant fission products is very important for radioactive waste management. The handling of radioactive waste and its long-term storage are partially unsolved problems not only in Europe but worldwide, as exemplified by the strong interest and encouragement by IAEA on this development.

Acknowledgments

A large number of persons have contributed to the development of the ELI–NP project, but also to ELI in general, to all of them we are very grateful. However, we cannot name these people individually, since, for example, more than 100 people have contributed to the ELI–NP Whitebook and to the main components of the ELI–NP infrastructure. We thank the EU for funding the ELI Preparatory Phase within the 7th Framework Programme.

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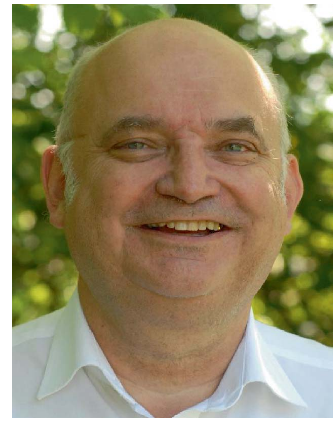

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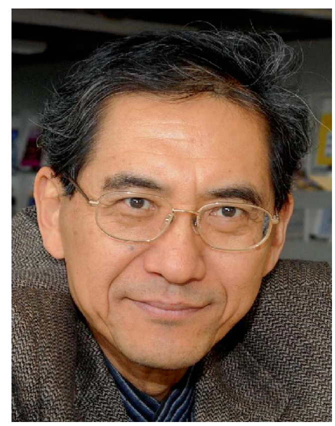

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