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Physics program with a low energy e^+e^-, $e^-\gamma$, $\gamma\gamma$ collider and electron beam on target at IRIDE

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I will discuss the particle physics opportunities at IRIDE (Interdisciplinary Research Infrastructure based on a Dual Electron Linac et Laser), a new multipurpose facility based on a combination of a high duty cycle radio-frequency superconducting electron linac (SC RF LINAC) and of high energy laser, presently under consideration at INFN.

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1. The IRIDE concept: technological breakthroughs as a basis for new research in fundamental and applied science

IRIDE (Interdisciplinary Research Infrastructure based on a Dual Electron Linac et Laser) is a new multipurpose facility based on a combination of a high duty cycle radio-frequency superconducting electron linac (SC RF LINAC) and of high energy laser. It will be able to produce a high flux of electrons (with energies up to few GeV), photons (with energies up to 60 MeV), neutrons, protons and positrons, that will be available for a wide national and international scientific community interested to take profit of the most worldwide advanced particle and radiation sources. The proposed IRIDE infrastructure will enable new, very promising synergies between fundamental-physics-oriented research and high-social-impact applications. Conceived as an innovative and evolutionary tool for multi-disciplinary investigations in a wide field of scientific, technological and industrial applications, it will be a high intensity “particles factory", based on a combination of a high duty cycle radio-frequency superconducting electron linac and of high energy lasers. It will be able to produce a high flux of electrons, photons (from infrared to γ-rays), neutrons, protons and eventually positrons and muons, that will be available for a wide national and international scientific community interested to take profit of one of the most worldwide advanced particle and radiation sources. We can foresee a large number of possible activities, among them:

- Science with IV generation light sources (IR-X FEL) ;
- Nuclear photonics with Compton back-scattered γ-rays;
- Fundamental physics with low energy linear colliders;
- Advanced neutron source by photo-production;
- Science with THz radiation sources;
- Physics with high power/intensity lasers;
- R&D on advanced accelerator concepts ;
- International Linear Collider technology implementation;
- Detector development for X-ray FEL and Linear Colliders;
- R&D in accelerator physics and industrial spin off.

The main feature of a superconducting (SC) linac relevant for our facility is the possibility to operate the machine in continuous (CW) or quasi-continuous wave (qCW) mode with high average beam power (< 1 MW) and high average current ($< 500\ \mu$A). The CW or qCW choice, combined with a proper bunch distribution scheme, offers the most versatile solution to provide bunches to a number of different experiments, as could be envisaged in a multipurpose facility.
The realization of such a large facility will allow INFN to consolidate a strong scientific, technological and industrial role in a competing international context both to deploy a national multipurpose facility along the scientific applications discussed in the following sections, and to prepare a strong role for the contribution to possible future large international high energy physics projects such as the International Linear Collider, or TLEP[2, 3]. For a technical review of the project, see Ref. [4].

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2. Particle phyisics opportunities at IRIDE

It is commonly accepted that the Standard Model (SM) of elementary particles interactions is the model, which describes the visible part of the nature and of the Universe. Recently the experimental results from the Large Hadron Collider at CERN have provided us with very important information on the mass of the Standard Model higgs-like particle. However, the existence of this particle with a given mass does not solve, by itself, all the long-standing puzzles of the SM, such as a problem of the SM hierarchy, the naturalness of the higgs boson and the electroweak (EW) symmetry breaking. Even though all the SM parameters are now measured to a high accuracy, the necessity of the New Physics (NP) existence for explaining the SM puzzles is still an open question. From a theoretical point of view, precise and complicated calculations are required to answer these questions, and high-precision input information on the SM parameters is a must. Due to the intrinsic complexity of the calculations, as one needs to study the running of the non-abelian gauge theory parameters over a dozen of orders of magnitude up to the Planck scale, even small experimental uncertainties in the SM parameters have a drastic impact on the conclusions, which can be drawn from such computations. The implications affect our understanding of the fundamental issues of the *conspiracy* between the SM couplings, the EW phase transition, Universe inflation, the cosmological constant, and also the nature of the Dark Matter (DM). It is important to stress that the precise values of the SM parameters, due to the renormalization group evolution, can be obtained only by simultaneous studies at high-energy and low-energy scales. The former point highly motivates the International Linear Collider (ILC) initiative, while the IRIDE project can pursue the latter one and serve as an accelerator-technology test installation and a research facility. The latter point motivates the possible use of the IRIDE facility as a precision tool for the SM exploration at low- and medium-energy scales, with a high priority on the information about the EW couplings of SM, which drives the evolution of the electromagnetic running coupling and the squared sine of the weak angle. Also a rich hadron phenomenology is accessible at these scales, which allows to study issues of the QCD confinement, where the ordinary perturbation theory approaches fail to work. It is anticipated that the construction of the IRIDE facility will be realized step-by-step starting with the physics program that can be pursued with an electron beam on target, further will be possible to investigate electron-photon collider, photon-photon collisions and finally electron-positron and electron-electron collider.

3. Electron beam-on-target experiments

3.1 Electron beam dump experiment: dark forces

Hidden photons (γ') with masses in the MeV to GeV range are being searched for by many experiments in the world, both at colliders and at fixed target facilities. In particular, electron beam dump experiments are particularly well suited for probing low masses ($m_{\gamma'}$) and very low kinetic mixing values ε.

Results (derived by old experiments) have been obtained by the authors of Refs. [5, 6], where the potentials and limitations of this type of technique applied to possible future facilities are also discussed. Figure 1, taken from Ref. [7], shows the limits obtained so far by the aforementioned experiments in the plan $\varepsilon - m_{\gamma'}$ (note that the mixing parameter is there dubbed as χ), together

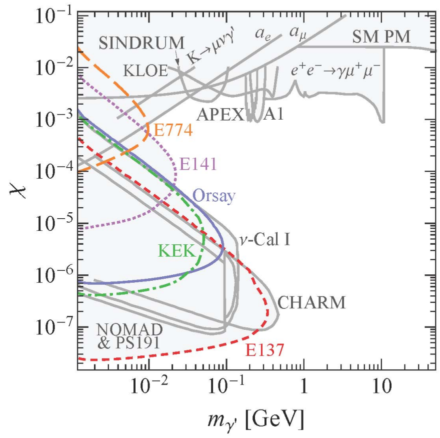

Figure 1: Limits on the hidden photon mass and kinetic mixing parameter (χ in the figure, ε in the text) obtained by past and current experiments [7].

with those obtained by detectors at colliders or by fixed target experiments on a thin target. As previously mentioned, beam dump results cover the leftmost part of the plot, while the others reach much lower sensitivity of the coupling while covering a much larger interval of the mass. New fixed target activities are in a construction phase, both at Mainz and Jefferson Lab, and are expected to deliver their first results within a few years. All of them plan to perform experiments using thin targets, thus being sensitive to the region of $\varepsilon > 10^{-5}$ and $100 < m_{\gamma'} < 500$ MeV.

It is conceivable to exploit the high intensity beam of IRIDE to perform a beam dump experiment. In principle this could allow one to be sensitive to very low effective couplings. Unfortunately, however, the sensitivity to ε scales only with the fourth power of the dumped current, therefore the improvement with respect to SLAC E137 would be only marginal, even operating with IRIDE at the highest possible currents. On the other hand, a relatively short dump, combined with the high beam intensity could allow one to probe the region of moderately long lifetimes. Using formula (3.14) of Ref. [7] one can see for instance that for $\varepsilon \sim 10^{-6}$ and $m_{\gamma'} \sim 200$ MeV, at IRIDE energies the mean decay path of a dark photon is of ~ 3 m. Note that the energy of the IRIDE beam is comparable to the one used for the Orsay experiment, but in the latter the dumped current was only ~ 3 mC. Moreover in the Orsay experiment the dump was about 1 m long, a value which probably can be consistently decreased.

3.2 Elastic electron scattering: proton weak charge

In the SM, the weak charge of the proton, Q^p_W, at low momentum transfer, Q^2, is related to the sine of the weak mixing-angle by the relation [8, 9] $Q^p_W = 1 - sin^2\theta_W \simeq 0.0716$. While for the neutron this quantity is -1, the proton coupling to the weak-force mediator is suppressed, making the measurement of Q^p_W sensitive to contributions from new physics. The SM connects the value of Q^p_W measured at low Q^2 with the one measured at the Z pole by running the weak mixing-angle from M_Z down to low energies.

New physics such as new neutral heavy bosons (called Z') could affect Z-pole and low-energy measurements in a different way [10].

Precision measurement of the proton weak-charge at low Q^2 are performed by measuring the cross-section asymmetry of longitudinally polarized electrons scattering from the proton. The Qweak Experiment at JLab [11, 12] collected, during 2011 and 2012, 2,500 hours of collisions of a 150 μA electron-beam with an 85% longitudinal polarization incident with energy of 1.16 GeV on a LH_2 target. They are now analyzing data and aim at a relative precision on the proton weak charge of 4%, corresponding to a parity-violating new physics at a scale of 2.3 TeV. At these Q^2 and energy, the hadronic and box corrections contribute with a 1.5% to the final error. Beam polarization is measured at percent level both with Compton and Möller scattering. In the latter case a polarized electron target is used. The P2 Project [13] proposes a new measurement at the MESA accelerator in Mainz, reaching 2% relative precision on Q_W^p. They plan to operate at a lower Q^2, about 0.003 GeV^2, in order to reduce the hadronic contributions to a negligible level. Moreover, choosing a beam energy E = 200 MeV the $\gamma - Z$ box correction to Q_W^p is also strongly suppressed. The proposed experimental conditions foresee a 150 μA electron-beam with an 85% longitudinal polarization incident with an energy of 200 MeV on a LH_2 target almost a factor 2 thicker (60 cm) than the one used at JLab. They plan to take data for 10,000 hours. Beam polarization is expected to be measured at 0.5% level. The MESA commissioning is expected by the end of 2017. Given the difficulty of such measurement, the comparison of results from experiments with different systematics is mandatory. A future experiment at IRIDE should take into account the contribution of theoretical and experimental errors and choose the best working point in term of beam energy and Q^2. For instance, MESA is limited to 200 MeV while IRIDE could choose a higher energy. While this choice would increase the contribution of hadronic and box corrections, below 300 MeV polarization measurement with Compton scattering is difficult if not impossible [14].

4. Electron-photon interactions

A high brightness linac like IRIDE could be used, in a stand alone operational mode, to drive a Compton γ-ray source. In this way γ-rays with energies of 1-100 MeV can be produced and directed head-on against electrons of 100-1000 MeV. A reach physics program can be studied [15], which includes -among others- the precise measurement of the π^0 width through the Primakoff process $e\gamma \to \pi^0 e$, and the search for light dark bosons in the energy region of a few to hundreds MeV. These measurements, which provide important tests of the SM, are not possible at present electron-photon colliders due to the low photon intensities of the machines.

4.1 π^0 width measurement

The axial anomaly of Adler, Bell and Jackiw (non-conservation of the axial vector current) is responsible for the decay of the neutral pion into two photons. It bridges the strong dynamics of infrared physics at low energies (pions) with the perturbative description in terms of quarks and gluons at high energies. The anomaly allows to gain insights into the strong interaction dynamics of QCD and has received great attention from theorists over many years. Due to the recent advances, the π^0 decay width is now predicted with a 1.4 % accuracy [16]. The major experimental information on this decay comes from the photo-production of pions on a nuclear target via the Primakoff effect [17]. The PrimEx Collaboration, using a Primakoff effect experiment at JLab, has recently achieved a 2.8 % precision [18]. This improved the PDG average for the width and mean lifetime of the pion. Nevertheless, the uncertainty of the width average is still inflated (a scale factor 1.2 at the moment), which gives an additional motivation for a new precise measurement of the pion lifetime and the two-photon decay width. The Primakoff effect-based experiments on a nucleus target suffer from model dependence due to the contamination by the coherent and incoherent conversions in the strong field of a nucleus [19]. Therefore, a measurement using a different method is highly desirable. At IRIDE we propose to use electron-photon collisions as a source of π^0 mesons produced via the Primakoff effect having the electron as a target instead of a nucleus. On the one hand, in this way one looses the Z^2 factor enhancement of the event rate; and thus a high intensity of the photon and electron beams is required. On the other hand, the photon-electron collision is a much cleaner environment as compared to the photon-nucleus case. A Monte Carlo generator for the π^0 production has already been developed and we have started the simulation studies, taking into account the possible beam spread (at a level of 0.1% for the electron and 10% for the photon beam) and looking for suitable event selection criteria. Our preliminary calculation shows that by colliding photons of 20 MeV photons against 750 MeV electrons a cross section of 1-2 nb for the process $e\gamma \to e\pi^0$ can be expected. This means that with a Luminosity of $10^{30} cm^{-2} sec^{-1}$ for the $e\gamma$ collider (well within reach of this proposal) a measurement of 1% is possible.

Measurement of η and η' widths or search for U bosons in e-γ interections are also possible at IRIDE [4].

5. Photon-photon interactions

The IRIDE accelerator complex can generate colliding photon-photon beams by Compton backscattering, and this opens up the fascinating field of low-energy photon-photon physics. A good hold on the technology needed to carry out a photon-photon physics program at energies close to 1 MeV would disclose new developments at higher energies [20], where a photon-photon Higgs factory could be a nearly ideal discovery machine [21]. However, even at low energy, such a collider would provide plenty of interesting physics, especially as a testing ground of Quantum Electrodynamics (QED). There are indeed a few processes that afford a direct view into QED vacuum, and photon-photon scattering is one of them. This process has no tree-level graph, and the first order contribution comes from the one-loop graph. The photon-photon cross-section is directly related to the fermion loops that polarize vacuum, and therefore a photon-photon scattering experiment with photon energies in the 0.5-0.8 MeV range where the cross-section is reasonably large would be an important test of our understanding of the QED vacuum.

6. Electron-positron collider

The systematic comparison of Standard Model (SM) predictions with precise experimental data served, in the last decades, as an invaluable tool to test this theory at the quantum level. It has also provided stringent constraints on “new physics” scenarios. The (so far) remarkable agreement between the measurements of the electroweak observables and their SM predictions is a striking experimental confirmation of the theory, even if there are a few cases where the agreement is not so satisfactory. On the other hand there are clear phenomenological facts (dark matter, matter-antimatter asymmetry in the universe) as well as strong theoretical arguments hinting at the

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presence of physics beyond the SM. The LHC, or future high-energy e^+e^- colliders will hopefully answer many questions. However, their discovery potential may be substantially improved if combined with more precise low energy tests of the SM. In this framework an electron-positron collider with luminosity of $10^{32} cm^{-2}s^{-1}$ with centre of mass energy ranging from the mass of the ϕ-resonance (1 GeV) up to $\sim$ 3.0 GeV, would complement high-energy experiments at the LHC and future linear or circular colliders. Such a machine can easily collect an integrated luminosity of about 5 fb^{-1} in a few years of data taking, a statistics much larger than that collected at any previous machine in this energy range. This will allow one to measure the e^+e^- cross section to hadrons with a total fractional accuracy of 1%, a level of knowledge that has relevant implications for the determination of SM observables, like, the g-2 of the muon and the effective fine-structure constant at the M_Z scale. The latter are, through quantum effects, sensitive to possible beyond SM physics at scales of the order of hundred GeV or TeV. The only direct competitor project is VEPP-2000 at Novosibirsk which will cover the center-of-mass energy range between 1 and 2 GeV with two experiments. This collider has started first operations in 2009 and is expected to provide a luminosity ranging between $10^{31} cm^{-2}s^{-1}$ at 1 GeV and $10^{32} cm^{-2}s^{-1}$ at 2 GeV. Other "indirect" competitors are the higher energy e^+e^- colliders (τ-charm and B-factories) that can cover the low energy region of interest only by means of radiative return (ISR). However, due to the photon emission, the equivalent luminosity produced by these machines in the region between 1 and 3 GeV is much less than the one expected in the collider here discussed. The description of the most relevant physics issues that can be explored at IRIDE in the e^+e^- collider configuration can be found in Refs. [4, 22, 23].

7. Conclusion

The Particle Physics program offered by IRIDE is quite reach: it goes from precision test of the Standard Model through a precise determination of the anomalous magnetic moment of the muon and the effective fine-structure constant, as well as the squared sine of the weak angle. It allows also to search for something new at low energy, like, e.g., elusive light bosons, and therefore firmly establish (or strongly constrain) new physics effects. IRIDE will complement high-energy activities at the LHC and future linear or circular colliders through its ability to improve the determination of precision observables of the SM, like, e.g., (g-2) of the muon, which are, through quantum effects, sensitive to possible BSM physics at high scales of the order of hundred GeV or TeV. Also a rich hadron phenomenology is accessible at these scales, which allows to study issues of the QCD confinement and test effective field theory of strong interaction, where the ordinary perturbation theory approaches fail to work and one has to rely on models. Low-energy photon-photon collisions give a direct view into the vacuum properties of Quantum Electrodynamics (QED), allowing for precision tests of QED in the MeV range, and more generally of Quantum Field Theory (QFT).

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