Overview of Nuclear Resonance Scattering at PETRAIII

Ilya Sergeev

High Resolution Dynamics Beamline P01 at PETRAIII is the beamline which is partly dedicated to perform Nuclear Resonance Scattering experiments. Currently, it is possible to perform experiments with 5 Mössbauer isotopes: 57Fe, 119Sn, 121Sb, 125Te, and 193Ir at energies from 14 keV till 73 keV. Both, nuclear inelastic and nuclear forward scattering studies can be performed with those isotopes, except 193Ir, where only second technique is possible. In addition to the conventional synchrotron techniques, development of the 57Fe Synchrotron Mössbauer source is going on at the beamline.

In this talk, the overview of the nuclear resonance scattering at P01 will be presented including description of the X-ray optics and sample environment and presentation of few examples of the studies.

The ultimate X-ray microscope PETRA IV - New opportunities for Nuclear Resonance Scattering

Hans-Christian Wille

The 3rd generation synchrotron source PETRA III at DESY in Hamburg is envisaged to be upgraded to the ultra-low emmittance storage ring PETRA IV up to 2027. The project is currently in the technical design phase.
The talk will cover an overview of the project and the expected machine and beam parameters and then focus on the new opportunities for Nuclear Resonant Scattering provided by the new machine.

Nuclear Resonance Scattering of Synchrotron Radiation at the ^{193}Ir Resonance and Fast Detectors

In this presentation we will give an overview on the recently established nuclear resonance scattering of synchrotron radiation at the ^{193}Ir resonance at an x-ray energy of 72.9 keV. This research was triggered by the ongoing interest on electronic properties in strontium iridates, especially the arrangement of local magnetic moments. The 72.9 keV transition of the ^{193}Ir nucleus is a mixed M1/E2 transition, which can give valuable additional information on the arrangement of hyperfine fields as compared to the pure M1 transition.

In order to perform NFS experiments at 72.9 keV we developed two medium resolution monochromators adapted to the asymmetric Si (3 1 1) reflection of the cryogenically cooled high heat load monochromator: A two-crystal monochromator (asymmetrically cut Si(4 4 0) and Si(6 4 2) crystals) and a four-crystal monochromator arranged as two nested channel cut crystals (asymmetrically cut Si(4 2 2) and Si(8 0 0) crystals). In both cases we achieved an energy resolution of about 150 … 170 meV.

After proof of principle by measuring NFS time spectra of pure magnetic and electric hyperfine interaction, as well as relative isomer shift, we investigated magnetic properties of Sr_2IrO_4 and electronic properties of iridium-chlorine bioinorganic materials. Most experiments were performed at low temperature < 10 K, in order to increase the Lamb-Mössbauer factor.

One key requirement was the availability of a fast (500 ps time resolution) and reasonably efficient detector for this energy. We followed an earlier development at the ESRF – ID18, i.e., a multi-element avalanche photo diode (APD) detector consisting of 16 Hamamatsu S5443 APDs, illuminated in grazing incidence. We achieved an efficiency of approx. 10 … 15% and could adapt to the vertical beam size by careful angular alignment.

Sb and Te spectroscopy in backscattering geometry

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Nuclear inelastic scattering (NIS) for resonance above 30 keV were made possible through the development of sapphire backscattering monochromatization. We will discuss these developments in method and instrumentation for the ^{121}Sb and ^{125}Te resonances. The latest addition in capabilities at Petra III, P01 have required better focusing and purity management and have involved the development of miniature pressure cells for measurements at high pressure and low temperature[1]. The method has found a range of applications in material science and biochemistry, the latest reports spanning pressure induced phase transition[1] in TeO_2, bonding modifications in the $Sb_2(Se,Te)_3$ solid solution[2], combined NIS and inelastic neutron scattering studies of vibrational modes in lone-pair Sb_2O_3 compounds[3], vibrational analysis in [4Fe-4Te] metalloproteins[4], and bio-reduction of Sb(V) to Sb(III)[5]. For future developments, a reduction in beam size will lead to a tremendous gain in quality and data acquisition rate.

Work supported by the US Department of Energy, Office of Science, Office of Basic Energy Sciences, Materials Science and Engineering Division.

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Quantum Optics Experiments with Nuclear Resonances

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Albert Einstein, Willis Lamb and Roy Glauber are heroes of the 20th century who paved the way for the raise of quantum photonic sciences. As a result, at optical wavelengths the laser revolutionized this field and gave birth to the field of quantum optics, amongst many others. This trend continues today with the rise of accelerator-driven light sources like synchrotrons and x-ray lasers, bringing quantum optical phenomena at x-ray energies into reach.

A key role in x-ray quantum optics is played by the ultranarrow nuclear resonances of Mössbauer isotopes. Their ultranarrow resonance bandwidth facilitates to probe fundamental phenomena of the light-matter interaction like the observation of the collective Lamb shift [1] and electromagnetically induced transparency with nuclei [2]. Nowadays, x-ray photonic structures can be considered as new laboratory to realize quantum optical concepts at x-ray energies. Striking applications include spontaneously generated coherences [3], the reduction of the group velocity of light to a few m/s [4] and Rabi oscillations between nuclear ensembles [5], that could open new avenues towards nonlinear interactions between x-rays and matter.

Employing higher-order coherences of x-ray fields in the spirit of Glauber could even lead to novel concepts for quantum imaging at x-ray energies [6,7] with outstanding spatial resolution, e.g., for the determination of biomolecular structures. The future development of high-brilliance x-ray sources holds great promise for further breakthroughs in this exciting field.

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Nuclear resonant scattering program in China: past, present and future

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As the first 4th generation synchrotron source in China, the High Energy Photon Source (HEPS) is being built at Huairou district in the northeast of Beijing. [1] Featuring 6 GeV, 1.3 circumference storage ring with ultralow emittance (<60 pm rad), the HEPS source is promising in the quality of photons in terms of coherence and brilliance.

The nuclear resonant scattering program (NRS) was touched upon in the late 1980s and early 1990s in China [2]; however, the development of NRS program lagged behind due to the lack of a brilliant synchrotron source. In 2013, the high energy resolution monochromator has been selected as one of instrumentation development in the R&D projects for HEPS. [3] With the development of crystal optics and time-resolved detectors (i.e. Avalanched Photodiode Detector), the nuclear resonant scattering program is being launched, thanks to international collaborations and funding opportunities. [4]

The hard X-ray high energy resolution spectroscopy beamline was selected in the PHASEI of HEPS project, which began in 2019. [5] With special timing mode (72ns bunch spacing), the nuclear resonant forward scattering (NFS) will be performed for ^{151}Eu, ^{119}Sn, and ^{161}Dy nuclei isotopes. Fortunately, the nuclear resonant inelastic X-ray scattering (NIS) or nuclear vibrational spectroscopy can be readily performed for ^{57}Fe isotope. The focused beam size of 2μm (H) ×2μm (V) (FWHM) will be achieved using a pair of KB mirrors. The flux at sample is expected to be 3.50×10^{10}ph/s/2meV or 1.58×10^{10}ph/s/1meV for ^{57}Fe. The photon flux at sample position for ^{151}Eu, ^{119}Sn is around 1×10^{10}ph/s/1meV. The photon flux at sample position for ^{161}Dy will be slightly lower due to the reduced reflectivity of the first white beam mirror. The Mössbauer spectroscopy community, high pressure sciences, biochemistry, quantum optics and energy related materials sciences and many other fields will benefit from the new NRS beamline in China.

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Nuclear resonant scattering at future 3 GeV SKIF storage ring

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Until recently, ‘photon hungry’ hard x-ray synchrotron techniques remained barely feasible at moderate energy storage rings (2-3 GeV), so that nuclear resonant scattering (NRS), inelastic x-ray scattering (IXS) and x-ray Raman spectroscopy (XRS) were developing exclusively at high-energy facilities. However, achievements in design of high-field short-period undulators (superconducting and cryogenic – see review [1]) together with significant improvement of x-ray beam quality at 4th generation storage rings have finally changed this situation (Fig. 1).

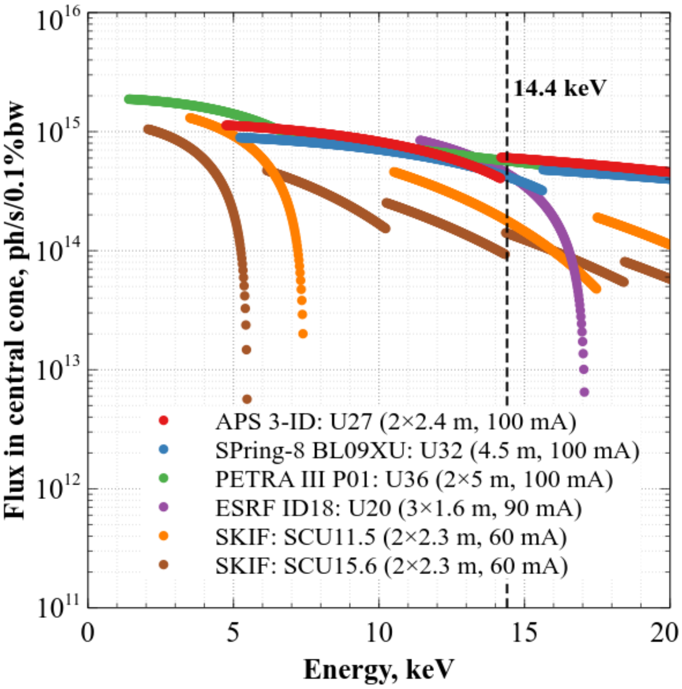

Figure 1. *Central cone flux of undulators used for ^{57}Fe NRS at high-energy storage rings compared with that of superconducting undulators of future 3 GeV SKIF facility*

SKIF (Russian acronym for ‘Siberian circular photon source’) is a 4th generation 3 GeV machine with perimeter of 476 m and emittance of ~75 pm·rad being currently built near Novosibirsk (Russia). A huge interest of national scientific community to NRS techniques at the energy of ^{57}Fe isotope stimulated us to include a fixed energy (14.4 keV) NRS end-station in the list of ‘first stage’ beamlines to be commissioned in 2024. The advantage of short-period superconducting undulators developed by Budker Institute of Nuclear Physics [2] together with low emittance of x-ray beam, which perfectly fits apertures of x-ray optics and acceptance of high-resolution monochromators, promise to achieve ~10^{10} ph/s in a submicron spot at ~2 meV bandwidth. Implementation of ultra-high resolution spectrographic monochromator [3] and synchrotron Mößbauer source [4] is also planned for future development of the end-station.

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