Nuclear Bragg Diffraction of Synchrotron Radiation in Yttrium Iron Garnet

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Monochromatization of synchrotron radiation down to about 10^{-8} eV at an energy of 14.4 keV has been achieved by double nuclear Bragg diffraction from ^{57}Fe-yttrium iron garnet single-crystal films set for the electronically forbidden {200} reflection. The monochromatized γ quanta have been analyzed with respect to time delay and capability of resonance absorption. By setting of appropriate energy and time windows a pure beam of resonant γ quanta at a rate of about 1 Hz is available.

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γ quanta with an energy width of 10^{-6} to 10^{-8} eV, which is typical for low-lying nuclear states, have a coherence length of 0.2 to 20 m. Thus a highly brilliant beam of such quanta would open new perspectives to experimental γ optics. Unfortunately, the usual radioactive sources are monochromatic but not brilliant whereas synchrotron radiation is very brilliant but white.

Resonant nuclear diffraction of synchrotron radiation as has been first pointed out by Ruby[1] is a suitable method to achieve the desired beam, which in addition would have a well-defined time structure and polarization pattern. A first attempt to observe resonant nuclear excitation in ^{57}Fe has been published by Cohen, Miller, and West.[2]

In order to maintain the outstanding brilliance of the synchrotron radiation only coherent reflections come into consideration, i.e., either grazing-incidence reflections[3] or nuclear Bragg and Laue diffraction.[4,5] Obviously the 14.4-keV resonance of ^{57}Fe is a good choice because the excitation energy is easily available from any synchrotron radiation source which covers the x-ray range and because the mean life $\tau = 140$ ns of the excited state allows the application of delayed-coincidence techniques. Furthermore, the chemistry and crystallography of iron compounds is well known, so that the needed large-size single crystals can be made.

While present experience with grazing-incidence antireflection films indicates that four sequential reflections are required in order to obtain the desired suppression of the nonresonant prompt radiation,[6] only two nuclear Bragg reflections will be sufficient if pure nuclear reflections are used. The greatest progress with this technique has been published by Chechin *et al.*,[7] who reported an enhancement of delayed counts behind an α-$^{57}Fe_2O_3$ single crystal positioned for the {777} pure nuclear reflection.

The occurrence of pure nuclear reflections from single crystals containing ^{57}Fe has been first observed

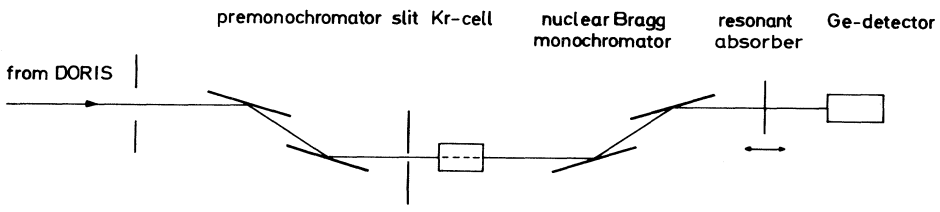

FIG. 1. Scheme of the experimental setup.

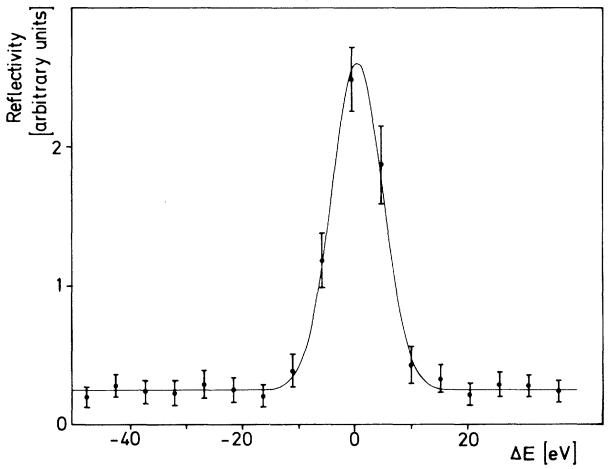

FIG. 2. Reflectivity of the resonant scattered radiation as function of energy. The energy scale is centered to the peak of the rocking curve.

with a ^{57}Co source by Black and Duerdoth[8] in $K_4Fe(CN)_6 \cdot 3H_2O$. A survey of laboratory work on pure nuclear diffraction with sources can be found in the work of van Bürck *et al.*[9] Especially interesting are the results on $^{57}FeBO_3$, which is a promising compound for future applications in connection with synchrotron radiation.

The appearance of pure nuclear reflections from the hyperfine superlattice in yttrium iron garnet (YIG) has been predicted by Winkler *et al.*,[10] for a series of reflections. The lowest order is the {200} reflection for the tetrahedral *d* positions and the {110} reflection for the octahedral *a* positions.

We have built up a nuclear Bragg monochromator with two 15-μm-thick single-crystal films of YIG at HASYLAB (Hamburg). The films with ^{57}Fe enriched to 88% were epitaxially grown on the {100} surface of a gadolinium gallium garnet (GGG) single crystal 30 mm in diameter.

During our measurements the storage ring DORIS has been run in a four-bunch mode at 50–80 mA and 3.69 GeV. That means that every 240 ns a radiation pulse of about 150-ps duration is emitted.

In Fig. 1 the scheme of the experimental setup is given. The premonochromator consists of two germanium crystals cut perpendicular to the ⟨111⟩ direction. They are controlled by a microprocessor to minimize the influence of radiation heating and to suppress the harmonics of the 14.4 keV as far as necessary.

The energy calibration has been done by means of the *K* edges of Br (13.474 keV), Kr (14.326 keV), and Rb (15.200 keV).[11] During the measurements the actual energy has been monitored by the *K* edge of krypton. The intensity behind a slit of 2 mm × 20 mm has been measured to be $(3–6) \times 10^{10}$ photons/s.

The nuclear Bragg monochromator has been set to the strong {200} reflection at 4°[10] with both crystals magnetized by a field of 30 mT in the scattering plane to achieve maximum reflectivity. The adjustment has been done by the nonforbidden harmonic at 57.7 keV. This yields a position which is correct except for a 70-μrad shift, which is caused by the different index of refraction.

The detection has been performed with a high-purity germanium detector of about 1-keV energy resolution and a conventional fast-slow coincidence between the 14.4-keV quanta and the DORIS bunch trigger.

The performance of the setup has been checked in three steps. First, the total counting rate of pulses arriving between 32 and 137 ns after the prompt trigger

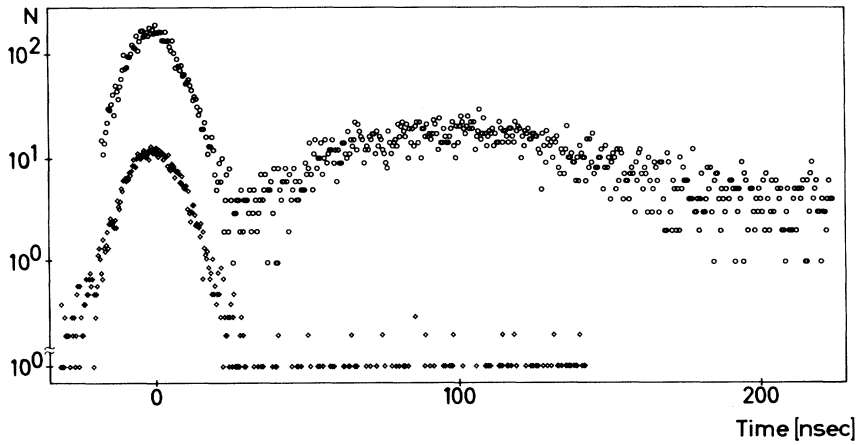

FIG. 3. Time spectra of the transmitted radiation at resonance (upper curve) and off resonance (lower curve). The maximum at about 100 ns contradicts an incoherent mother-daughter decay and shows the combined coherent diffraction of the two YIG crystals.

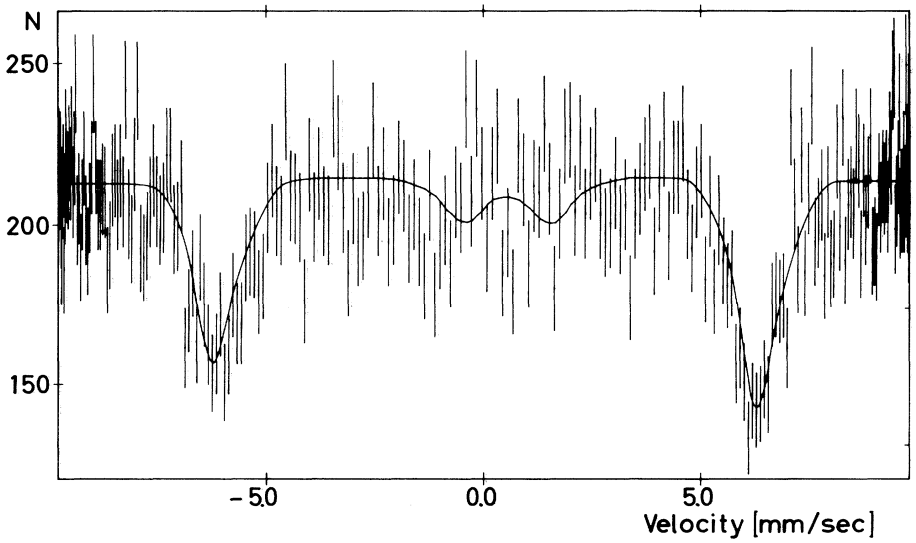

FIG. 4. Mössbauer spectrum after the two YIG crystals analyzed with a stainless-steel absorber. The solid line is the calculated theoretical spectrum.

has been recorded versus the input photon energy. The energy has been varied in steps of about 5 eV, i.e., about $\frac{1}{3}$ of the bandwidth of the premonochromator, by a changing of the angle of incidence at the entrance and subsequent fine tuning of both YIGs for optimal transmission. Figure 2 shows the result of this procedure. The maximum is at 14.41(1) keV as determined by calibration with the above-mentioned K edges. This result is in accordance with the more precise value of 14.412 47(29) keV known from literature.[11] During the following measurements the premonochromator has been kept fixed at resonance energy.

We have then taken the time-differential spectrum of the transmitted beam. As expected, it consists of a prompt component from diffuse scattering and a delayed component characteristic for a two-stage process of resonant diffraction (see Fig. 3). Details of the time response which depend on the beam properties and the hyperfine structure of the scatterer will be discussed in a forthcoming paper.

Finally, the feasibility of resonance absorption with the transmitted beam has been proven by a conventional Mössbauer experiment with a stainless-steel absorber (1 mg ^{57}Fe/cm^2). Figure 4 displays the recorded counts as a function of absorber velocity. Two peaks of slightly different intensity are observed. They correspond to the strongest resonances of two nonequivalent tetrahedral d positions in YIG as predicted in Ref. 10. A theoretical transmission curve was calculated with the known hyperfine parameters of the YIG spectrum by use of the dynamical theory of nuclear diffraction.[12] The calculation takes into account a broadening by growth-induced distortions of the rocking curve of 30 μrad and the line broadening by folding with the response function of the analyzing stainless-steel absorber. The result reproduces the position and intensity ratio of the lines as well as their asymmetry.

In conclusion, one may say that at this stage a 1-Hz source of nearly pure resonant γ quanta is available. Progress is possible, especially with improved new YIG crystals. A beam of 20 Hz seems to be realistic at HASYLAB. Thus, first scattering experiments with polarized radiation can be done. The biggest improvement yielding intense sources can be achieved by wigglers and undulators which will be available at the new dedicated storage rings planned or under construction.

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