Diffraction of nuclear γ radiation by a synthetic multilayer structure

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(Submitted 23 July 1991)
Pis'ma Zh. Eksp. Teor. Fiz. **54**, No. 4, 220–223 (25 August 1991).

The Bragg diffraction of 14.4-keV γ rays from ^{57}Co by a synthetic multilayer ^{57}Fe–Sc structure has been studied. The test sample consisted of 20 layers of ^{57}Fe and Sc, with respective thicknesses of 20 and 33 Å. It was synthesized by magnetron sputtering. The structure was studied by x-ray diffractometry, Hall-effect measurements, and conversion-electron Mössbauer spectroscopy. The ^{57}Fe layers were found to be amorphous and nonmagnetic. The hyperfine structure of the nuclear sublevels consists of an unsplit system of several components with a total width of about $8.5\Gamma_0$. The angular and energy distributions of the diffraction of the Mössbauer radiation were measured.

Hyperfine spectroscopy of low-lying nuclear levels, based on measurements of the time-varying spectra of nuclear fluorescence excited by synchrotron radiation pulses, is a rapidly developing field.[1-7] A problem of current interest in this field is that of developing methods for filtering out bands of submicroelectron-volt width near the resonance energies of various isotopes.

One way to solve this problem might be to develop resonant mirrors, i.e., synthetic multilayer structures containing layers with a resonant isotope.[8] Substantial recent progress[9-13] in the synthesis of such structures has set the stage for suggestions of specific structures for resonant mirrors of this sort.[14,15]

An ideal resonant mirror for the isotope ^{57}Fe (for example) should reflect radiation only in an energy interval about 1 μeV wide near the resonance energy of 14.4 keV. The quality of a resonant mirror is determined by the quality of the synthetic multilayer structure, which can be studied by x-ray diffractometry, and also by the nuclear parameters of the layers of the resonant isotope (the hyperfine structure of the splitting of the nuclear levels, the magnetic properties of the layer, etc), which would have to be studied by means of the Mössbauer effect.

In this letter we are reporting a study of the resonant diffraction of 14.4-keV nuclear γ rays by a ^{57}Fe–Sc multilayer synthetic structure. A structure of this sort makes it possible to study the basic properties of resonant synthetic multilayer structures.

The test sample was prepared by magnetron sputtering in an argon medium at a pressure of 6.0×10^{-3} Torr. Twenty layers of ^{57}Fe and Sc, with thicknesses of 20 and 33 Å, respectively, were deposited in alternation on an extremely smooth glass substrate with dimensions of 80×40 mm. The ^{57}Fe deposition was carried out using direct

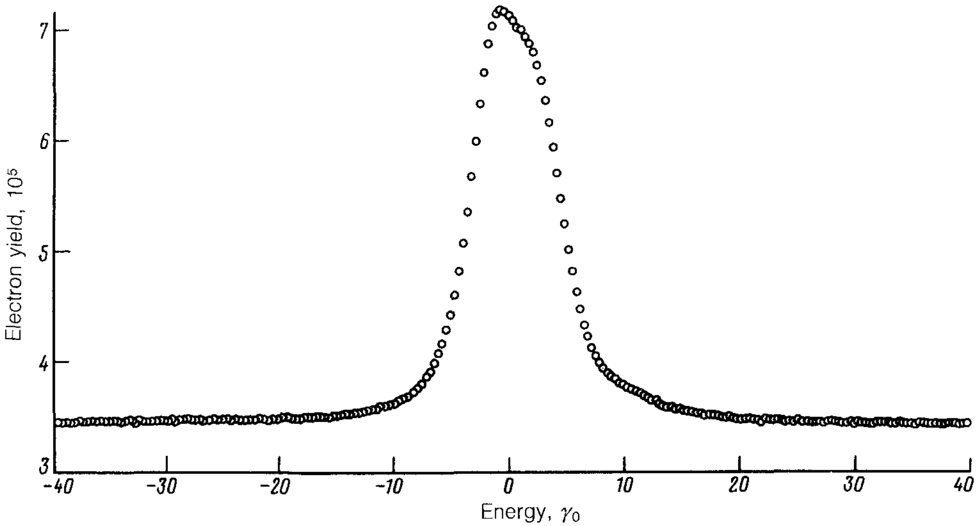

FIG. 1. Conversion-electron Möosbauer spectrum of a multilayer ^{57}Fe–Sc structure.

current, while the Sc was deposited out in an rf discharge. The technological conditions[10] were regulated within 1%. The quality of the structure was studied on an x-ray diffractometer with the help of Cu $K\alpha$ radiation. The x-ray studies of the synthetic multilayer structure revealed that the layers of both iron and scandium were in an amorphous state. Measurements of the Hall effect revealed no magnetization in the sample.

The hyperfine structure of the ^{57}Fe nuclear levels was studied by conversion-electron Mössbauer spectroscopy. The shape of the spectrum supports several suggestions. It can be assumed that the spectrum (Fig. 1) is an unsplit structure of several quadrupole doublets. Evidence for this suggestion comes from data on the amorphous and nonmagnetic state of the layers obtained by the x-ray and Hall-effect measurements. These data are in agreement with the results of Refs. 11 and 13, where it was shown that the iron layers in Fe/Dy and Fe/Nd systems, with layer thicknesses of 20 Å and less, remain in a nonmagnetic amorphous state. On the other hand, characteristics of this sort might be exhibited by a system in which the magnetic moment undergoes a rapid relaxation. These questions require further study.

The angular and energy distributions of the resonant diffraction of nuclear γ rays were measured on a two-crystal Mössbauer diffractometer. The activity of the ^{57}Co(Cr) Mössbauer source was about 200 mCi. An unenriched Fe(110) crystal, with a reflection angular width of 30″, was used as a monochromator and collimator of the γ rays in order to increase the luminosity of the experiment. The intensity of the 14.4-keV γ rays incident on the synthetic multilayer structure was 5.4 γ/s.

Figure 2 shows angular distributions of the reflection (a) far from the resonance and (b) at the resonance. The maximum reflection coefficients are 17% and 9%, respectively; the angular widths of the reflection are 2.1 and 2.6 arc min. The broad

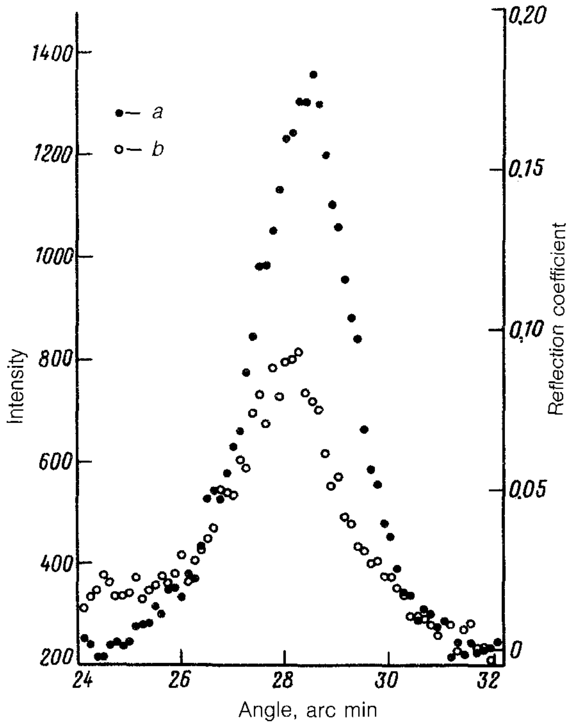

FIG. 2. Angular distribution of the reflection coefficient of the synthetic multilayer restructure at the energy of the Mössbauer radiation (a) away from the resonance and (b) at the resonance.

reflection interval in each case is determined by the small value of the Bragg angle, 0.46°. The relatively large angular divergence of the incident radiation rules out an identification of the fine features of the angular distributions. It can nevertheless be seen that the reflection maximum at the resonance (Fig. 2b) lies to the left of the reflection maximum far from the resonant energy (Fig. 2a). This difference agrees with the difference between the resonant scattering by the nuclear system of the crystal and the potential scattering by the electron system.

Figure 3 shows a Mössbauer spectrum of the diffraction at the angular position corresponding to the reflection maximum. This curve is asymmetric because of an interference between the resonant nuclear scattering and the Rayleigh electron scattering. The interference is destructive on the left and constructive on the right of the resonant energy. The nonmonotonic behavior near $7\Gamma_0$ is a consequence of one of the lines of the hyperfine structure. Interestingly, this line is seen more clearly in the diffraction spectrum than in the spectrum of conversion-electron Mössbauer spectroscopy, where it is seen as a slight bump on the right-hand slope. The large energy width of the minimum and maximum of the Mössbauer spectra—tens of natural linewidths—is interesting. It suggests that the amplitude for nuclear scattering is large and that there is a pronounced coherent broadening of the nuclear resonance.

The results of this study of a synthetic multilayer ^{57}Fe–Sc structure show that

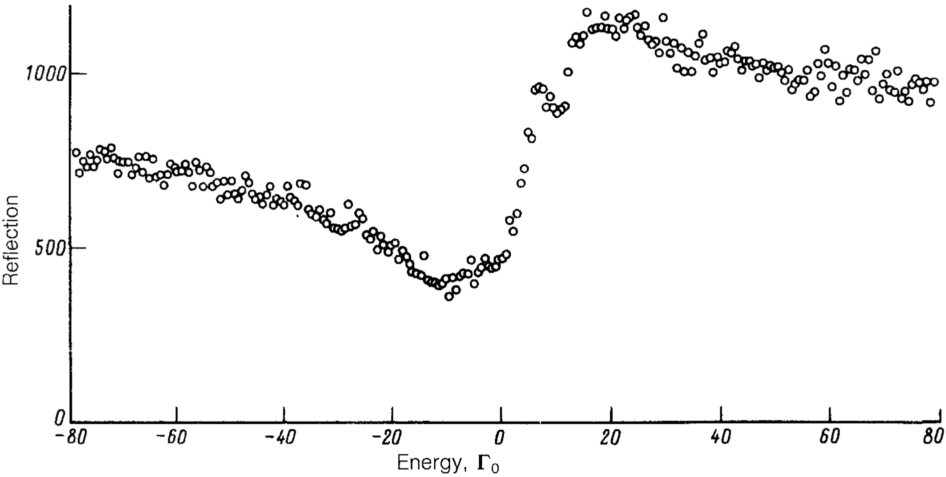

FIG. 3. Mössbauer spectrum of the diffraction of radiation by a synthetic multilayer structure in the angular position corresponding to the reflection maximum, $\theta_{Br} = 0.46°$.

resonant synthetic multilayer structures hold promise for use in various branches of the physics of radiation–matter interactions. The problem of filtering out the resonant component of synchrotron radiation, for example, can be solved by alternating the isotopic composition of iron layers. In this case, a periodicity of the density of ^{57}Fe nuclei at twice the period of the structure arises, so the purely nuclear reflection occurs at a Bragg angle smaller by a factor of 2. On the other hand, resonant synthetic multilayer structures can be convenient for use in the physics of the coherent interaction of Mössbauer and synchrotron radiation with resonant targets. Finally, measurements of the Mössbauer spectra of nuclear diffraction can provide new information on the magnetic properties of synthetic multilayer structures, which are presently the subject of active research.

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Translated by D. Parsons