An 56Fe(d, p)57Fe Mossbauer Measurement

I. 8. An $^{56}Fe(d, p)^{57}Fe$ Mössbauer Measurement

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Introduction

It is well recognized that the Mössbauer spectroscopy is one of the powerful technique to study physical and chemical properties of solids through the hyperfine interactions of probe nuclei embedded in solids. Especially the ^{57}Fe Mössbauer spectroscopy has been applied to many research fields, because iron is an important element in material research and the resonant gamma-ray photon of ^{57}Fe has a quite narrow line width. Narrow line width of the resonant gamma-ray of ^{57}Fe is identical to an extremely high energy resolution in the range of nano eV and make it possible to detect the ultra-small energy-shifts like a gravitational red-shift of photon. Generally for the ^{57}Fe Mössbauer measurements, gamma-ray from ^{57}Co in Rh matrix which is relatively long-lived radioactive isotope and a mother nucleus of ^{57}Fe has been used as a photon source. To perform the Mössbauer spectroscopy the rather large facilities are not necessary in general and many researchs in material science have been performed in rather small size laboratories.

However, recent development and progress in the synchrotron radiation facility and its use for research in natural science show clearly the possibility to perform nuclear excitation experiments with synchrotron radiation. In fact, the new research field has been opened and started for the nuclear excitation experiments with synchrotron radiation. Nuclear excitation with synchrotron radiation should be performed in-beam condition, in which the coherent excitation and the subsequent de-excitation of the resonant nucleus have been detected simultaneously. In-beam Mössbauer spectroscopy using a short-lived radioactive isotope produced by a nuclear reaction in accelerator is also a technique to perform the simultaneous excitation and the detection of de-excitation photon from resonant nucleus. In-beam Mössbauer spectroscopy has many advantages for material research, since the method is principally source experiment in which nuclear excitation and de-excitation occurred simultaneously. These methods make it possible to perform some experiments which have not been possible in a conventional Mössbauer spectroscopy using a long-lived radioactive isotope.

In this letter, we present a brief description what kinds of in-beam Mössbauer spectroscopy are available now and preliminary results obtained by an $^{56}Fe(d, p)^{57}Fe$ reaction at CYRIC of Tohoku University.

In-Beam Mössbauer Spectroscopy

It is well known that the Mössbauer spectroscopy is related to the recoilless nuclear resonant absorption and emission of gamma-rays and its experiment has been performed using a combination of gamma-ray source and absorber or scatterer. In a conventional Mössbauer spectroscopy long-lived radioactive isotope embedded in standard material like Rh has been used as a gamma-ray source and a probe nucleus in the specimen is used as an absorber and/or scatterer. Such long-lived radioactive isotope was originally produced by the nuclear reaction using accelerators and/or nuclear reactor. Since the long lifetime of the isotope it is possible to use the gamma-ray source as off-line source from accelerator for the Mössbauer measurements. When the lifetime of the gamma-ray source is quite short, it is always necessary to perform the on-line measurements in which the creation of the source by the nuclear reaction and the detection of the resonance should be performed simultaneously.

One can define the in-beam Mössbauer spectroscopy as an Mössbauer spectroscopy by simultaneous creation of Mössbauer levels and detection of the resonant absorption or scattering using accelerator beams. Nuclear excitation of the Mössbauer levels with synchrotron radiation from the electron or positron storage-ring may be one of the in-beam Mössbauer spectroscopy because of its on-line measurement. From the above discussion, there are two distinguishable methods for the in-beam Mössbauer spectroscopy. One is an in-beam Mössbauer spectroscopy with synchrotron radiation and the other is the spectroscopy using accelerator like cyclotron. Following reactions have been reported for the in-beam Mössbauer spectroscopy using accelerators.

(1) $^{54}Cr(\alpha, p; \alpha, p\gamma)^{57}Mn \rightarrow {}^{57}Fe$
(2) $^{56}Fe(n, \gamma)^{57}Fe$
(3) $^{56}Fe(d, p)^{57}Fe$
(4) Coulomb excitation

Especially the coulomb excitation method (4) using a high energy heavy ion beam is very important for the material research, because this method can create ^{57}Fe Mössbauer levels by Coulomb excitation and simultaneously recoil-implant the ^{57}Fe atoms into any kinds of materials even if the solid solubility of Fe is practically null.

In the reactions (2) and (3), ^{57}Fe Mössbauer levels have been created in the specimen by the bombardments of neutron or deuteron to the target of ^{56}Fe nuclei whose natural abundance is 91.8%. Mössbauer measurements have been performed using the gamma-ray followed by de-excitation of the nuclear levels and it is possible to perform a time dependent

Mössbauer measurement as a function of period from just after the nuclear reaction. Since the deuteron energy to accomplish the reaction (3) is much larger than the energy of neutron beam for (2) from nuclear reactor, the recoil energy of atoms and the radiation damage given by the reaction (3) are larger and heavier than those in the case of (2).

^{56}Fe(d, p)^{57}Fe Mössbauer Spectroscopy

Details of the reaction ^{56}Fe(d, p)^{57}Fe have been reported previously[1] during the course of the nuclear structural study of ^{57}Fe nuclei and the cross section of the reaction is relatively large.

Although the first Mössbauer measurement followed by this reaction was performed by the group in John-Hopkins University using a Van de Graaff accelerator[2] and followed by the group in Hahn-Meitner Institute[3-6], a detailed study for the material research has not yet been reported as one of the applications of the in-beam Mössbauer spectroscopy. We are interested in ^{56}Fe(d, p)^{57}Fe Mössbauer spectroscopy to apply the material research, because from this method it is possible to examine the detailed behavior of resonant Fe atoms in iron based intermetallic compounds just after nuclear reaction. For instance, one can ask and discuss from this method where is and how many final landing positions of Fe in such compounds just after reaction and how are their temperature dependencies. Present study aimed to perform the first step for such kinds of material research using simple combination of target material and detection system.

There is a sever technical problem for the in-beam Mössbauer spectroscopy, which is a high counting rate of the background noise superimposed on the Mössbauer resonant gamma-rays. Mössbauer gamma-ray has a relative low energy and the background noise is mainly due to the X-rays emitted after photoelectric effect induced in the target material. By a conventional detection system used in Mössbauer spectroscopy the signal to noise ration (S/N ratio) is too low to construct a good Mössbauer resonance pattern. In order to get a good Mössbauer resonance pattern, it is essential to extract the Mössbauer gamma-rays from the high intense X-rays induced by the deuteron bombardment to the target in accelerator. For ^{57}Fe in-beam Mössbauer spectroscopy, some methods have been proposed and performed to extract the Mössbauer gamma-ray from the intense background noise in order to increase the S/N ratio. One method is to use the coincidence technique between 14.4 keV Mössbauer gamma-rays and 122 keV gamma-rays emitted beforehand. Other methods are to use a delayed coincidence technique between the pulses for the operation of the accelerator beam and the detection signals from the target in order to avoid the high intense prompt signals. In present investigation, we have used another method to extract 14.4 keV Mössbauer gamma-rays from high intense background noise, that is to use the resonant conversion electron detector which contains a resonance material enriched by ^{57}Fe and is nearly insensitive to the X-ray photons. This method is the similar one to extract the photons to excite the nucleus from the broad band synchrotron radiation using a nuclear resonance filter.

Experimental conditions in present study are as follows:

(1) Accelerator : AVF cyclotron of CYRIC at Tohoku University.

(2) Energy of deuteron beam : 6 MeV.

(3) Current of deuteron beam : 600 nA.

(4) Target : 310 stainless steel foil whose thickness is 25 μm.

(5) Detector : Resonant conversion electron detector containing a 310 stainless steel foil enriched to ^{57}Fe 1mg/cm^2.

Figure 1 shows the top and side views of the resonant conversion electron detector containing an ^{57}Fe enriched 310 stainless steel foil. Using this detector, the S/N ratio during the continuous operation of the cyclotron at the above conditions is high enough to construct the good Mössbauer emission spectrum of 310 stainless steel foil. Figure 3 shows the Mössbauer emission spectrum obtained by 310 stainless steel foil in which ^{56}Fe(d, p)^{57}Fe reaction occurred under the above conditions of the cyclotron. By the relatively short measuring period the quality of the emission spectrum is not excellent but we can see a single resonance line of 310 stainless steel whose full width at half maximum (FWHM) seems to be large compared to the spectrum obtained from usual transmission geometry using a ^{57}Co radioactive source. It is not yet clear that the large FWHM causes by the deuteron bombardments or after effects of the nuclear reaction. It is worthwhile to continue the measurements of ^{56}Fe(d, p)^{57}Fe Mössbauer spectroscopy in order to clarify the effect of recoil and nuclear reaction in target material.

Summary

We performed an ^{56}Fe(d, p)^{57}Fe Mössbauer spectroscopy using AVF cyclotron of CYRIC at Tohoku University. Using a resonant conversion electron detector containing an ^{57}Fe enriched 310 stainless steel foil, an Mössbauer emission spectrum has been successfully obtained from the target of 310 stainless steel foil at 300 K.

References

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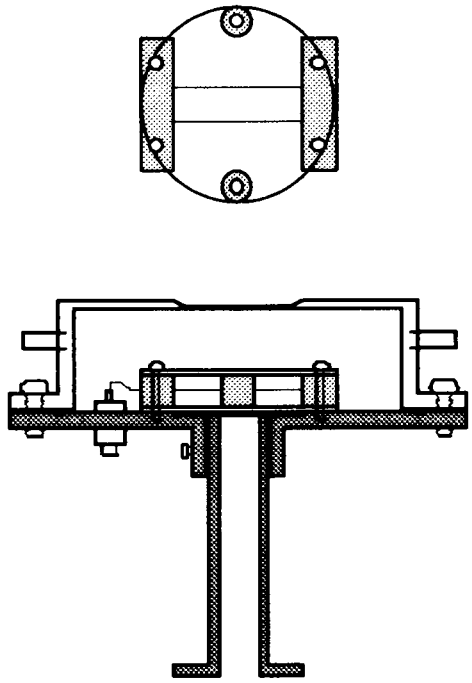

Fig. 1 Schematic drawing of the conversion electron Mössbauer detector containing an ^{57}Fe enriched 310 stainless steel. Top and side views are shown.

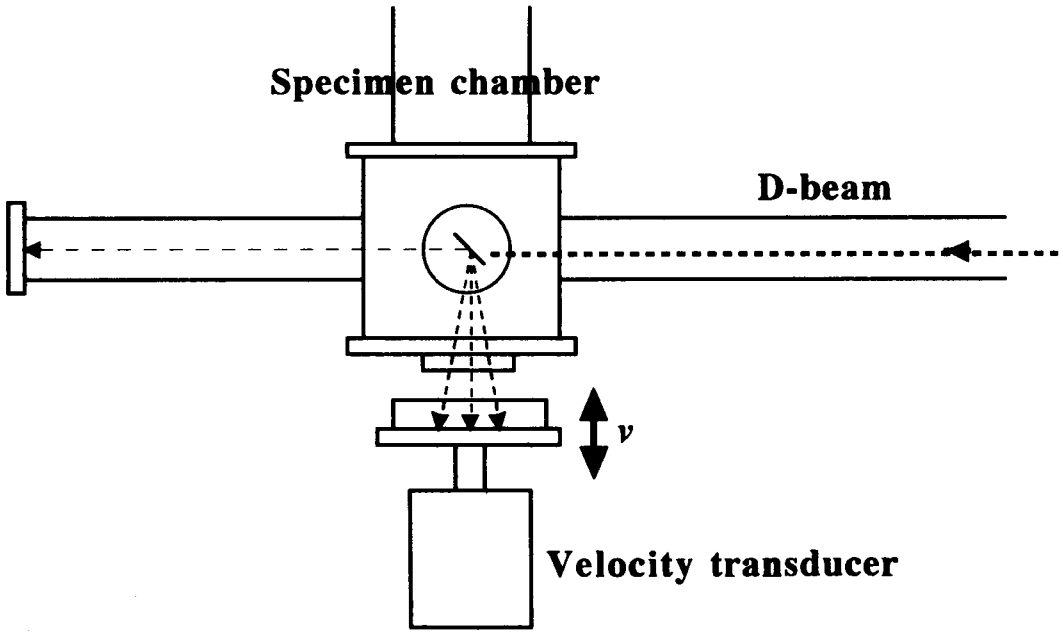

Fig. 2 Experimental arrangement for in-beam $^{56}Fe(d, p)^{57}Fe$ Mössbauer measurements at CYRIC of Tohoku University.

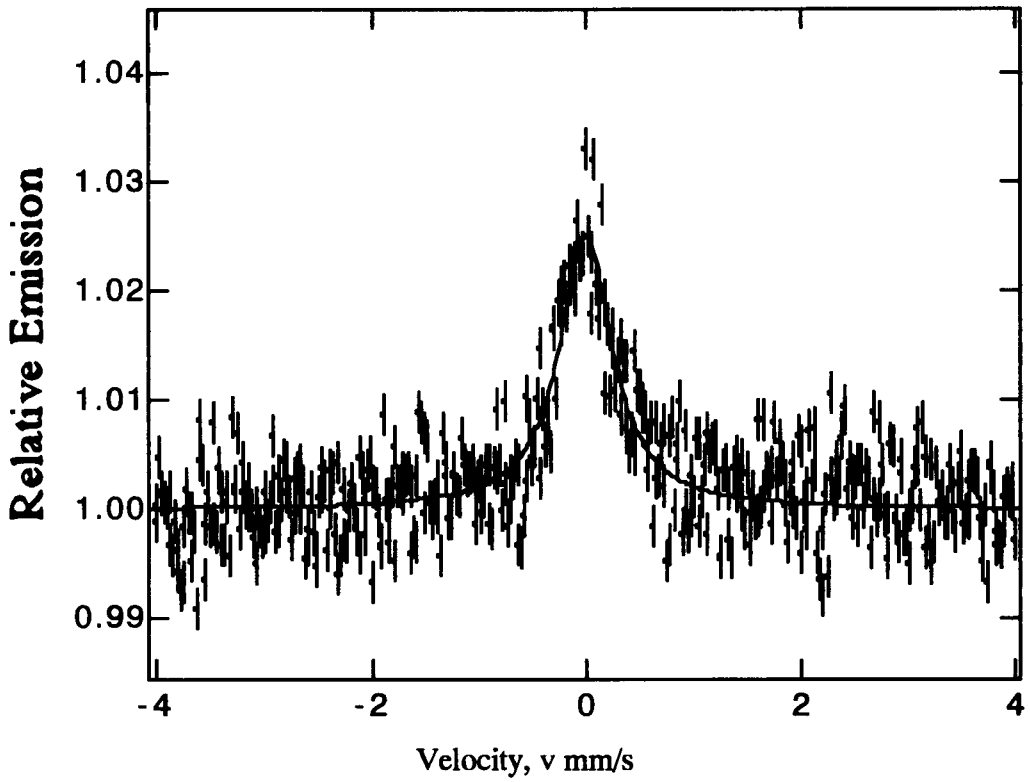

Fig. 3 ^{57}Fe Mössbauer spectrum of 310 stainless steel foil at 300 K resulting from ^{56}Fe(d, p)^{57}Fe reaction by 600 nA, 6 MeV D-beam at CYRIC of Tohoku University. Detection was performed by using a CEMS detector and an experimental setup as shown in Figs. 1 and 2.