PAC investigation of qudropole interaction in nano-soft magnetic material $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ *

ZUO Yi(左翼) ZHENG Yong-Nan(郑永男) ZHOU Dong-Mei(周冬梅) YUAN Da-Qing(袁大庆)
LIU Meng(刘猛) FAN Ping(范平) CUI Bao-Qun(崔宝群) MA Ying-Jun(马英俊)
LI Li-Qiang(李立强) LI Ji-Zhou(李济州) ZHU Sheng-Yun(朱升云)1)

(China Institute of Atomic Energy, Beijing 102413, China)

Abstract The quadrupole interaction in nano-soft magnetic material $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ has been studied by perturbed angular correlation using ^{62}Zn probe nuclei from the ISOL radioactive nuclear beam facility at CIAE HI-13 tandem accelerator. Two quadrupole interaction frequencies $\omega_{01} = 440$ Mrad/s with a distribution width $\sigma = 0$ and $\omega_{02} = 90$ Mrad/s with a width $\sigma = 0.48$ are obtained. The fractions of ω_{01} and ω_{02} are 38% and 62%, respectively. The measured quadruple interaction parameters indicate that 62% of the implanted ^{62}Zn are located in the grain boundary and 32% in the grain.

Key words PAC, Kev-ISOL, $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$

PACS 61.46.Df, 23.20.En, 29.38.-C

1 Introduction

Nanocrystalline materials have a wide spectrum of applications due to their superior properties, which differ much from those of poly- and single-crystals. For an example, the Fe-based nano-soft magnetic material $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ exhibits excellent soft magnetic properties due to its ultrafine grain structure[1]. The high saturation flux density makes this alloy suitable for being used in many magnetic devices.

In order to gain better understanding of nano-structure on atomic scale, microscopic experimental techniques are needed[2]. In this paper the perturbed angular correlation (PAC) with ^{62}Zn as probe nuclei was used to microscopically investigate the nano-soft magnetic material $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ for the first time. PAC has been used widely to obtain microscopic information on the structural and dynamical properties of materials[3]. The possibilities for such investigations have been further expanded with the advent of most versatile radioactive nuclear beam (RNB) facilities, one of which is the on-line isotope separator (ISOL). The present experiment was performed with the ^{62}Zn nucleus as PAC probe provided by the ISOL radioactive nuclear beam (RNB) facility at China Institute of Atomic Energy (CIAE)

2 Experiment Details

The nano-soft magnetic material $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ was prepared from the magnetic alloy $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$. The alloy was melted and quench-condensed to room temperature to form $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ amorphous film. The amorphous film was then sintered at 823 K to become nano-soft magnetic material $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ with a grain size of 10 nm.

An isotope separation on-line (ISOL) has been constructed at CIAE, which is based on the HI-13

Received 8 July 2008

* Supported by National Natural Science Foundation of China (19935040)

1) E-mail: zhusy@ciae.ac.cn

tandem accelerator[4]. The ISOL consists of an electron beam plasma type target/ion source, an analyzing magnet with a mass resolution of better than 180, a beam diagnostic unit of tape transportation and an Einzel lens system. A PAC measurement terminal is located at the down-stream end of the ISOL. The ISOL and PAC set-up are shown in Fig. 1. ^{62}Zn probe nuclei are produced through the nuclear reaction ^{63}Cu(p, 2n)^{62}Zn by bombarding the Cu target located in the ion source by 23 MeV protons from the HI-13 tandem accelerator at CIAE. The energy of the produced ^{62}Zn radioactive nuclear beam is accelerated to 25 keV with an intensity of 4×10^{7} ions/s. The radioactive nuclei ^{62}Zn can be used as both the positron source and the PAC probe nucleus. The decay scheme of ^{62}Zn is shown in Fig. 2.

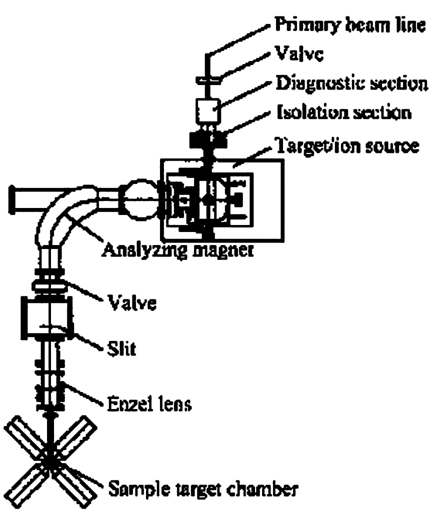

Fig. 1. Schematic drawing of the ISOL facility.

^{62}Zn decays into the excited states of 596.65 keV and 507.5 keV in its daughter nucleus ^{62}Cu as shown in Fig.2. From these excited states the 596.65 keV plus 507.5 keV and 40.9 keV cascade $\gamma-\gamma$ rays are emitted via a spin I=2 intermediate state with a half-life of 4.8 ns. The perturbed angular correlation was performed on this $\gamma-\gamma$ ray cascade. The emitted γ_1 (596.65 keV and 507.5 keV) is detected by a "start" detector, which defines the time t=0 when the nucleus decays to the intermediate excited state and most importantly selects a set of nuclei having a higher probability of emitting γ_1 and a alignment direction of the angular momentum I. The intermediate excited state is de-excited to the ground state by the emission of γ_2 (40.9 keV) detected by a "stop" detector. The detection of γ_2 determines the spin precession.

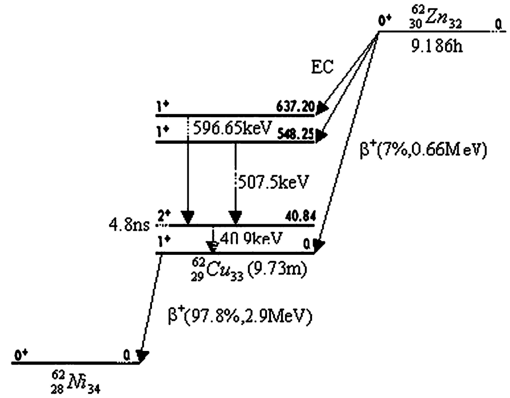

Fig. 2. Decay scheme of ^{62}Zn.

Delayed coincidence time spectrum of $\gamma_1-\gamma_2$ is given by

$$I(\theta,t)=I_0\mathrm{e}^{-t/\tau}W(\theta,t)+B \ . \tag{1}$$

$W(\theta,t)$ is the perturbed angular correlation function

$$W(\theta,t)=1+\sum_k A_kG_k(t)P_k(\cos\theta) \ , \tag{2}$$

where A_k is the anisotropy coefficient, $P_k(\cos\theta)$ is the Legendre polynomial and $G_k(t)$ is the perturbation factor determining the time variation of the perturbed angular correlation function. In case of pure electrical quadrupole interaction the perturbation factor is given by

$$G_2(t)_{\rm ele}=\sum_n S_{2n}[f_0+\sum_i f_i\mathrm{e}^{-n\sigma(i)t}\cos(n\omega_{0i}t)] \ . \tag{3}$$

In (3) the summation runs over all perturbations, f_i the fraction associated with the $i^{\rm th}$ perturbation, f_0 is the unperturbed fraction of the probe nuclei, ω_{0i} the $i^{\rm th}$ quadrupole interaction frequency and σ_i the width of the $i^{\rm th}$ interaction frequency distribution. For spin I=2, n=0, 1, 3, 4. The quadrupole interaction frequency ω_0 determines the EFG by the quadrupole coupling constants $\nu_{Qi}=eQV_{zzi}/h$. The EFG is highly related to the microscope structure of material. Therefore, the PAC is an advanced technique for microscope investigation of matertials structure. A detailed description of PAC can be found elsewhere[5—7].

PAC measurements are typically carried out by using a standard set-up composed of four BaF2 scintillation detectors arranged in a planar 90°—180° geometry, yielding simultaneously 4 delayed coincidence time spectra. The time resolution of the set-up used in the experiment is 0.35 ns. In the data analysis the spin rotation function (or counting rate ratio) is usually formed from the background subtracted delayed coincidence time spectra $I(\theta,t)$:

$$R(t)=\frac{I(\theta_1,t)-I(\theta_2,t)}{I(\theta_1,t)+I(\theta_2,t)} , \tag{4}$$

where $I(\theta,t)$ are the delayed coincidence time spectra recorded at angle $\theta(=\pm 90^\circ$ and $\pm 180^\circ)$. The measured spin rotation function is fitted with the analytical expressions:

$$R(t)\approx A_2G_2(t) , \tag{5}$$

where $G_2(t)$ is the corresponding perturbation factor given by Eqs. (3) and (4). The fitting yields hyperfine interaction parameters A_2, f_i, ω_{0i} and σ_i, which result in useful information of material properties.

3 Result and discussion

The measured and fitted spin rotation functions are shown in Fig. 3. Two quadrupole interaction frequencies ω_{01} and ω_{02} were gained from the fitting, indicating there are two implantation sites of ^{62}Zn. The measured frequency $\omega_{01} = 440$ Mrad/s with a distribution width $\sigma = 0$ is almost equal to the frequency determined in the polycrystalline $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$. The second frequency ω_{02} is shifted greatly to a lower value of 90 Mrad/s and broadened by a width of $\sigma=0.48$. The fractions of ω_{01} and ω_{02} are $f_1=38\%$ and $f_2=62\%$. The structure of $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ grain comprises the nanocrystal core and the amorphous grain boundary[7]. Therefore, f_1 and f_2 are ascribed to the fractions of lattice sites occupied by ^{62}Zn in the grain core and in the amorphous outer region of grain boundary, respectively.

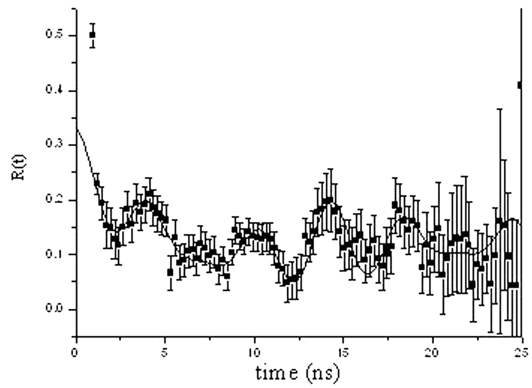

Fig. 3. The measured and fitted spin rotation functions.

4 Summary

The quadrupole interaction has been measured in nano-soft magnetic material $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ by perturbed angular correlation using ^{62}Zn probe nuclei from the HI-13 tandem accelerator based ISOL at CIAE. Two quadrupole interaction frequencies $\omega_{01} = 440$ Mrad/s with a distribution width $\sigma = 0$ and $\omega_{02}=90$ Mrad/s with a width $\sigma=0.48$ were obtained. The fractions are 38% and 62% for ω_{01} and ω_{02}, respectively. The experimental results clearly indicate that 62% of the implanted ^{62}Zn nuclei occupy the grain boundary and the rest the grain core.

References

1 Hofmann H. IEEE Trans. Magn., 1973 **Mag-9**: 17

2 Lauer St, GUAN Z et al. Nanostructured Materials, 1999, **12**: 955

3 ZHU Sheng-Yun et al. Journal of Radioanalytical and Nuclear Chemistry, 2007, **272**(3): 615—621

4 CIU Bao-Qun et al. Nuclear Instrument and Methods in Physics Research B, 2003, **204**: 58—61

5 Wichert Th, Recknagel E. in Microscopic Methods in Metals, ed. U. Gonser, Topics in Current Physics, 1986, **40**: 317

6 ZHU S Y, DONG M L, ZUO T, SHEN W Q. Nuclear Techniques, 1987, **12**: 4 (in Chinese)

7 Tadeusz Kulik. Journal of Non-Crystalline Solids, 2001, **287**: 145—161