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Magnetic moments of ^{76}As and ^{77}As

T. Ohtsubo, K. Mizushima, and S. Ohya
Department of Physics, Niigata University, 8050, Ikarashi-2, Niigata, 950-2181, Japan

S. Muto
National Laboratory for High Energy Physics, Tsukuba 350, Japan

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The nuclear magnetic moments of the ground states of ^{76}As and ^{77}As were measured using nuclear magnetic resonance on oriented nuclei (NMR-ON) by detecting γ rays and β rays. The magnetic hyperfine splitting frequencies of ^{76}AsFe and ^{77}AsFe in a zero external magnetic field are 117.99(8) MHz and 225.58(8) MHz, respectively. With the known hyperfine field of $B_{\mathrm{hf}}(^{75}\mathrm{As}Fe)=34.29(3)$ T the magnetic moments have been determined as $\mu(^{76}\mathrm{As},2^-)=(-)0.9028(10)\mu_N$ and $\mu(^{77}\mathrm{As},3/2^-)=+1.2946(13)\mu_N$. The effective spin-lattice relaxation time for ^{76}AsFe has been measured to be 5.2(8) m and 11.2(16) m at the external magnetic field of 0.2 T and 0.6 T, respectively. The observed magnetic moments are discussed in the framework of the configuration mixing model. [S0556-2813(99)05602-2]

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I. INTRODUCTION

Electromagnetic properties of nuclei play an instrumental role in the critical evaluation of various nuclear models and can thus significantly enhance our understanding of nuclear structure. Magnetic moments of the ground states are particularly sensitive to the single-particle, proton-neutron composition of the corresponding levels. The description of the isotopes of arsenic is complicated because of the large number of nucleons outside the closed neutron and proton shells $Z=N=28$. Outside the closed shells the shell model states $2p_{3/2}$, $1f_{5/2}$, $2p_{1/2}$, and $1g_{9/2}$ can be occupied by the 5 extra protons and many extra neutrons of the arsenic nuclei. Experimental results of this region are important for testing the applicability of various nuclear models. The technique of nuclear magnetic resonance of oriented nuclei (NMR-ON) is a powerful method in the study of nuclear magnetic moments and hyperfine interactions of dilute impurities in ferromagnetic host metals. The magnetic moments of the ground states of arsenic isotopes of ^{71}As($5/2^-$), ^{72}As(2^-) [1], and ^{74}As(2^-) [2] have been measured by the NMR-ON method. Using the radio-frequency nuclear orientation method the magnetic moment of ^{76}As(2^-) was determined [3]. Those of the lighter isotope nuclei of ^{69,71}As($5/2^-$), ^{70}As(4^+), and ^{72}As(2^-) were measured in an atomic magnetic resonance experiment [4]. The magnetic moment of the stable nucleus ^{75}As($3/2^-$) has been measured by conventional NMR [5]. The deviation of these magnetic moments from the simple shell model were explained by configuration mixing. However, up to now, no measurement of the magnetic moment of ^{77}As($3/2^-$) has been performed. Figure 1 shows the partial decay scheme of ^{77}As. Most of the β decays feed the ground state of ^{77}Se and γ transitions are very weak. A large asymmetry of the pure Gamow-Teller type β transition is expected from the oriented ^{77}As. Therefore, in order to study the magnetic moment of ^{77}As, we observed NMR-ON spectra by detecting β rays. We also observed the NMR-ON spectra and the effective relaxation time of ^{76}AsFe. The experimental values of the magnetic moments are compared with values calculated with the shell model.

II. EXPERIMENTAL PROCEDURES

The samples of ^{76}AsFe and ^{77}AsFe were prepared by recoil implantation using ^{76}Ge($\alpha,p3n$)^{76}As and ^{76}Ge($\alpha,p2n$)^{77}As reactions. Targets of ^{76}Ge were made by evaporating the enriched isotope (89%) onto thin Al foils. Stacks of alternating targets and pure Fe foils ($\sim$1.5 μm) were irradiated with 60-MeV and 50-MeV α beams ($\sim$1.5 μA) for 20 h at the SF cyclotron at the Institute for Nuclear Study, University of Tokyo. After irradiation, samples were annealed at 500 °C for 30 m in vacuum. The activated part of the foils was soft soldered to the copper cold finger of a ^{3}He/^{4}He dilution refrigerator and cooled to about 8 mK. The temperature was monitored using a ^{56}Co source produced simultaneously in the Fe foil by irradiation. In order to polarize the Fe foil, an external magnetic field B_0 was applied to the sample. An inhomogeneity of B_0 at a sample is smaller than 2%.

The radio frequency (rf) field was applied in the foil plane and perpendicular to B_0. The rf was modulated at a rate of 300 Hz. The β rays were detected with two Si detectors mounted in the refrigerator placed at 0° and 180° with respect to B_0. The γ rays were detected with four pure Ge-

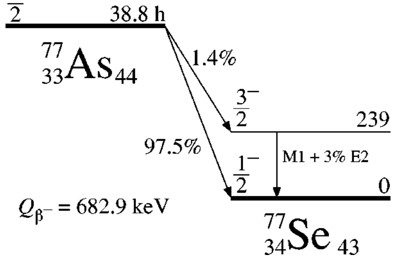

FIG. 1. The partial decay scheme of ^{77}As.

detectors at 0°, 90°, 180°, and 270°. The details of the apparatus have been described in Ref. [6].

III. RESULTS AND DISCUSSION

A. ^{77}As

The angular distribution of β rays from oriented nuclei is given by

$$W_\beta(\theta)=1+B_1A_1\cos\theta,$$

where B_1 is the orientation parameter and A_1 is the angular distribution coefficient [7]. $A_1=1.09$ is expected if we assume that the β decays are pure Gamow-Teller transitions. The ratio of β-ray counts R, at 0° and 180° is described as

$$R=N(0°)/N(180°)=\epsilon(1+B_1A_1)/(1-B_1A_1).$$

Here N is the β-ray counts and ϵ is the geometrical asymmetry of the β-ray detection system. If the orientation is destroyed by the applied rf field, the resonance is detected by the change of the ratio R. The sign of the hyperfine interaction of ^{77}As in Fe (the product of the nuclear magnetic moment and the hyperfine field) can be also deduced from the sign of the change of R.

The continuous β-ray spectra measured with the Si detectors were analyzed for several energy regions. The β-ray spectrum contains some contaminants from the activities produced simultaneously by the recoil implantation. From the analysis of the γ-ray spectrum, the contamination involves β rays from ^{57}Ni, ^{71}As, and ^{72}As, which the resonance frequencies are already known [1,6]. More than 70% of the spectrum was from ^{77}As.

At first, the NMR-ON search was performed with a wide frequency modulation (FM) width of 2 MHz and a resonance was found at about 228 MHz. The effective relaxation time of ^{77}AsFe for $B_0=0.6$ T was estimated to be $T_1'=180(30)$ s from the empirical relation of the relaxation time between the isotope nuclei. The observed relaxation time of ^{76}AsFe will be described later. For precise measurements an interval of 300 s was taken between frequency steps to allow complete relaxation. The resonance spectra were measured for $B_0=0.2$, 0.4, and 0.6 T as shown in Fig. 2. The solid curves in Fig. 2 are the results of a least-squares fit assuming a resonance with a Gaussian shape. The resonance frequencies ν versus B_0 are shown in Fig. 3. For a pure magnetic hyperfine interaction, the resonance frequency is given by

$$\nu=|g(B_{\rm hf}+(1+K)B_0)|\mu_N/h$$

and

$$d\nu/dB_0=\mathrm{sgn}(B_{\rm hf})|g(1+K)|\mu_N/h,$$

where g is the nuclear g-factor, $B_{\rm hf}$ is the magnetic hyperfine field, and K is the Knight shift factor. From least-squares fits, the following results were obtained:

$$\nu(^{77}\mathrm{As}Fe,B_0=0)=225.58(8)\ \ \mathrm{MHz}$$

and

$$d\nu/dB_0(^{77}\mathrm{As}Fe)=6.5(3)\ \ \mathrm{MHz/T}.$$

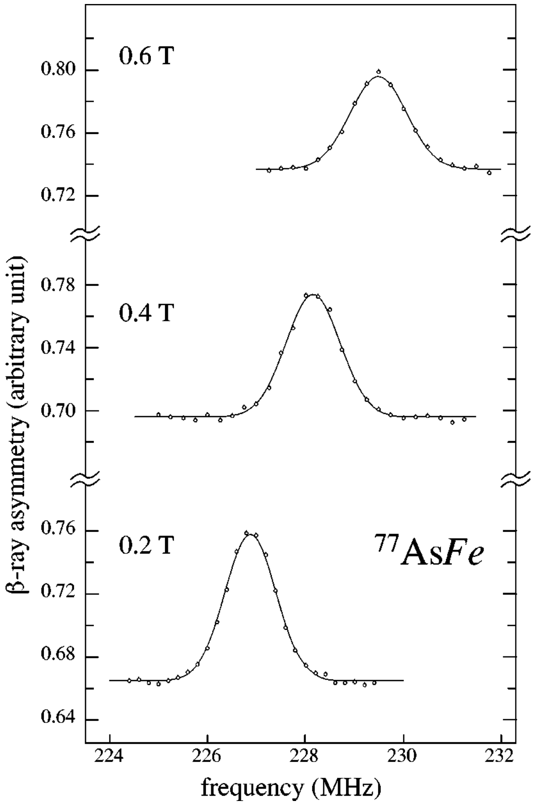

FIG. 2. NMR-ON resonances of ^{77}AsFe measured by detecting the asymmetry of β rays at $B_0=0.2$, 0.4, and 0.6 T.

We neglected a possible hyperfine anomaly $^{75}\Delta^{77}$ because these states have similar configurations [8]. Using the known value of $B_{\rm hf}(^{75}\mathrm{As}Fe)=+34.29(3)$ T [2], the magnetic moment of ^{77}As and Knight shift factor K were deduced as

$$\mu(^{77}\mathrm{As},3/2^-)=+1.2946(13)\mu_N,$$

$$K(^{77}\mathrm{As}Fe)=-0.01(3).$$

The positive sign of the magnetic moment of ^{77}As was deduced from the sign of the β asymmetry destruction on resonance and the sign of the hyperfine field.

The magnetic moment of ^{77}As is comparable with the known magnetic moment of $\mu(^{75}\mathrm{As},3/2^-)=+1.439475(65)\mu_N$ [5]. Both values are smaller than the Schmidt value of the $p_{3/2}$ proton state of $+3.79\mu_N$. The

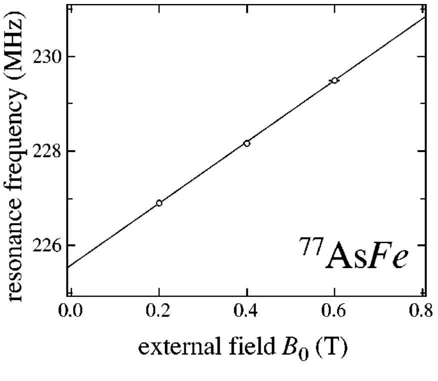

FIG. 3. NMR-ON resonance-frequency shift with B_0 for ^{77}AsFe.

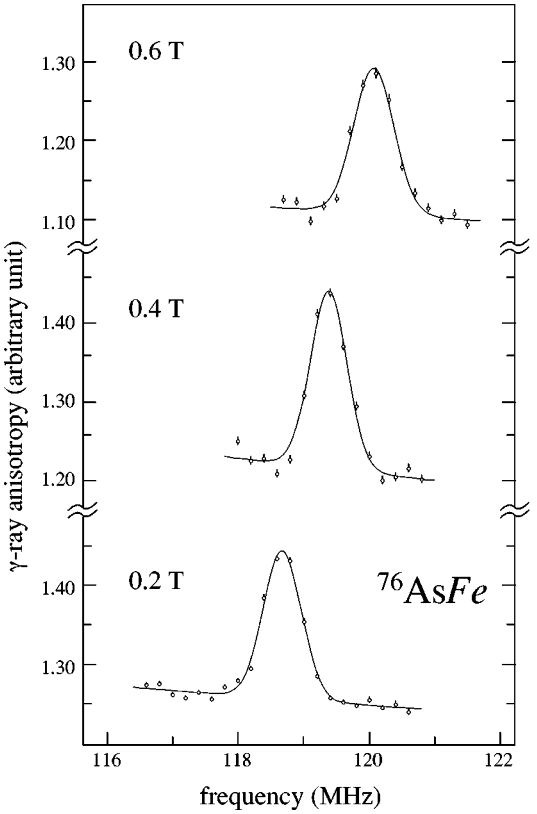

FIG. 4. NMR-ON resonances of ^{76}As*Fe* measured by detecting the 559-keV γ transition at $B_0 = 0.2$, 0.4, and 0.6 T.

large deviation of the magnetic moment from the Schmidt value may be explained by the core-polarization formula [9] as well as the previous discussion on other isotopes [1,2,4]. Outside the closed $Z = N = 28$ shells the shell model states $2p_{3/2}$, $1f_{5/2}$, $2p_{1/2}$, and $1g_{9/2}$ are available to the 5 extra protons and 14 or 16 neutrons of ^{75,77}As, respectively. With the proton configurations of $(2p_{3/2})^3(1f_{5/2})^2$ or $(2p_{3/2})^3(1g_{9/2})^2$ and the neutron configuration of $(1g_{9/2})^n$, the calculated value is $+1.96\mu_N$ or $+1.54\mu_N$ for ^{75}As and $+1.92\mu_N$ or $+1.50\mu_N$ for ^{77}As, respectively. Here, the parameter set of the harmonic-oscillator potential with $C = 40$ MeV was used in the calculation. With the configuration of $(2p_{3/2})^3(1g_{9/2})^2$ the calculated values are closer to the experimental values than those with the $(2p_{3/2})^3(1f_{5/2})^2$ configuration. It shows that the contribution of $g_{9/2}$ shell is important to the ground state of $3/2^-$ arsenic isotopes. It is interesting that the low-lying $9/2^+$ levels are found in ^{75,77}As.

In ^{75,77}As there is another low-lying $3/2^-$ state which could be a three-quasi-particle state of $(f_{5/2})^3 3/2^-$ or a phonon coupling state. The magnetic moment of the three-quasi-particle state can be estimated to be $+1.00\mu_N$ from the value of the ground state of ^{71}As$(5/2^-)$. This value is in good agreement with that of the first $3/2^-$ excited state (265 keV) of ^{75}As $(+0.98(19)\mu_N)$ [5]. In case of ^{77}As, the energy of the first $3/2^-$ excited state (216 keV) is lower than that of ^{75}As. Therefore the mixing configurations of such states may be taken into account in more detailed calculation of ^{77}As.

B. ^{76}As

The angular distribution of γ rays from the oriented nuclei is given by

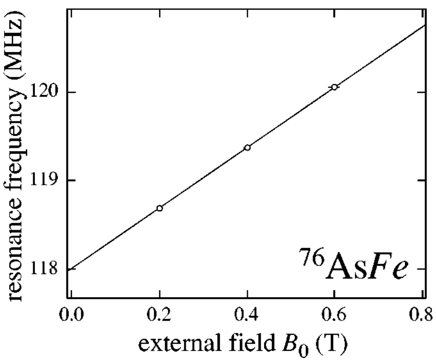

FIG. 5. NMR-ON resonance-frequency shift with B_0 for ^{76}As*Fe*.

$$W_\gamma(\theta) = 1 + \sum B_\lambda A_\lambda U_\lambda Q_\lambda P_\lambda(\cos\theta),$$

where B_λ are the orientation parameters, A_λ the angular distribution coefficients, U_λ the deorientation parameters, Q_λ the solid angle correction factors, and P_λ is Legendre polynomials [7]. The angular distributions of the γ rays were already measured by nuclear orientation [10]. The strong 559-keV γ ray, having a large anisotropy, was used to detect resonances.

The resonance spectra for $B_0 = 0.2$, 0.4, and 0.6 T are shown in Fig. 4. An interval of 900 s was allowed between each frequency step for full spin-lattice relaxation. The solid curves in figure are Gaussian line least squares fit. The resonance frequencies ν versus B_0 are shown in Fig. 5. From least-squares fits, the following results were obtained:

$$\nu(^{76}\mathrm{As}Fe, B_0 = 0) = 117.99(8)\ \ \mathrm{MHz}$$

and

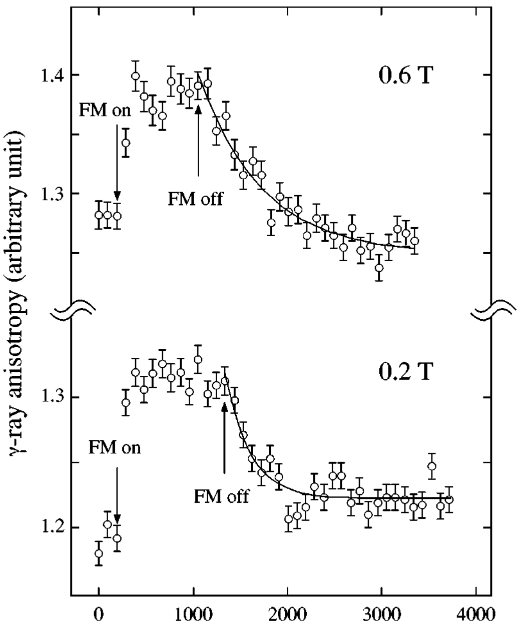

FIG. 6. The time-dependent γ anisotropy of ^{76}As*Fe* at 8 mK and $B_0 = 0.2$ T and 0.6 T.

$$\frac{d\nu}{dB_0}(^{76}\mathrm{As}Fe)=3.5(2)\ \ \mathrm{MHz/T}.$$

Taking the hyperfine field as before and again neglecting any possible hyperfine anomaly, the magnetic moment of ^{76}As and Knight shift factor K were deduced as

$$|\mu(^{76}\mathrm{As},2^-)|=0.9028(10)\mu_N,$$

$$K(^{76}\mathrm{As}Fe)=0.02(3).$$

The present value of the magnetic moment agrees with that of $-0.906(5)\mu_N$ [5] measured by the radio-frequency nuclear orientation method [3]. The magnetic moments of the 2^- ground states of other As isotopes are $\mu(^{72}\mathrm{As})=-2.1566(3)\mu_N$ [5], $\mu(^{74}\mathrm{As})=-1.597(3)\mu_N$ [2]. The nuclear spin values can be explained by a coupling of single proton state of ^{71,73,75}As and neutron states. The magnetic moment of ^{71,73,75}As is coupled to the magnetic moment of the last unpaired neutron to give the total moment. Using empirical g factors derived from neighboring even-odd $9/2^+$ state (^{73}Se) and odd-even $5/2^-$ state (^{71,73,75}As) nuclei [5], the calculated values for ^{72}As, ^{74}As, and ^{76}As were $-1.82\mu_N$, $-1.79\mu_N$, and $-1.24\mu_N$, respectively. In another case, using empirical g factors derived from even-odd $7/2^+$ state (^{79}Se) and odd-even $3/2^-$ state (^{75}As) nucleus [5] the calculated value was $-1.03\mu_N$. Comparing the experimental values with these calculated ones, the main configuration of ground states of ^{72,76}As are the $(\pi_{5/2^-},\nu_{9/2^+})2^-$ configuration and the $(\pi_{3/2^-},\nu_{7/2^+})2^-$ configuration, respectively. The configuration of ^{74}As is probably a mixture of the $(\pi_{5/2^-},\nu_{9/2^+})2^-$ and $(\pi_{3/2^-},\nu_{7/2^+})2^-$ configurations.

The effective relaxation times were also measured for $B_0=0.2$ and 0.6 T by turning the frequency modulation (FM) signal on and off at the center frequency. Figure 6 shows the time-dependent γ anisotropy of $^{76}\mathrm{As}Fe$ at $B_0=0.2$ and 0.6 T. The solid curves in the figure are the results of a least-squares fit assuming with a single exponential shape of $\exp(-t/T_1')$. The effective relaxation time T_1' were measured as 5.2(8) m and 11.2(16) m for $B_0=0.2$ and 0.6 T, respectively.

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