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THE HYPERFINE FIELD OF XENON NUCLEI AT LATTICE SITES IN IRON

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Résumé. — Le champ hyperfin du noyau Xe aux sites du réseau dans le fer a été déterminé à partir d'expériences d'orientation nucléaire, à des températures variant entre 11 mK et 80 mK obtenues avec un cryostat à dilution ^3He - ^4He . De la variation avec la température des anisotropies du rayonnement γ M4 de $^{133\text{m}}\text{Xe}$ et $^{131\text{m}}\text{Xe}$ implantés dans le fer par séparateur isotopique, le pourcentage des noyaux Xe aux sites haut-champ est déterminé et une valeur du champ hyperfin $H_{\text{hf}} = 1\,510 \pm 160$ kG est déduite.

Abstract. — The hyperfine field of xenon nuclei at lattice sites in iron has been determined from nuclear orientation experiments at temperatures between 11 mK and 80 mK obtained with a ^3He - ^4He dilution refrigerator. From the temperature dependence of the M4 γ -ray anisotropies of $^{133\text{m}}\text{Xe}$ and $^{131\text{m}}\text{Xe}$ implanted in iron by isotope separator, the fractions of xenon nuclei at high-field sites were determined, and a value $H_{\text{hf}} = 1\,510 \pm 160$ kG was deduced.

1. **Introduction.** — Recent heavy-ion channeling experiments [1], correlated with Mössbauer-spectroscopy data [2], did prove the relationship between high-field sites and substitutional ions of xenon implanted in iron by isotope separator. As the fraction of substitutionally implanted nuclei differs considerably from unity, also at rather low xenon concentrations, a determination of the hyperfine field of xenon at lattice sites in iron cannot be done without measuring this fraction. The value $H = 1\,010 \pm 40$ kG obtained by Niesen *et al.* [3], [2] from nuclear orientation of $^{133\text{g}}\text{Xe}$ implanted in iron, by neglecting the low-field fraction, therefore can only be regarded as a lower limit. A determination of the hyperfine field of substitutional xenon nuclei in iron is interesting for solid-state physicists trying to describe these large hyperfine fields in terms of complex polarization phenomena. On the other hand, nuclear physicists can use these fields to study magnetic moments of excited nuclear states. Therefore, a method to determine the hyperfine field of xenon nuclei at lattice sites in iron with a simultaneous determination of the low-field fraction became highly desirable.

In a recent paper [4], we demonstrated the possibility of extracting precise values for the hyperfine interaction energies of the $11/2^-$ isomeric states of odd-mass spherical nuclei implanted in iron, by observation of the anisotropy of M4 γ -rays emitted by these nuclei in nuclear orientation experiments. In the odd-xenon nuclei, long-living isomeric states

and corresponding deexciting M4 γ -rays are present in ^{129}Xe , ^{131}Xe and ^{133}Xe . The temperature dependence of the angular distribution of M4 γ -rays ($11/2^- \rightarrow 3/2^+$) from oriented nuclei with magnetic moment μ in the presence of a magnetic field is given by

$$W(\theta, T) = 1 + \sum_i \alpha_i \sum_{k=2,4} F_k \left(44 \frac{11}{2} \frac{3}{2} \right) \times \\ \times B_k \left(\frac{\mu H_i}{T} \right) Q_k P_k(\cos \theta).$$

In this expression, we introduced the parameters α_i , being the fractions of nuclei at a certain site (substitutional lattice site or different possible interstitial ones) with corresponding hyperfine fields H_i .

We now make the assumption — based on Mössbauer-experiments on the ^{133}Cs daughter nuclei of implanted ^{133}Xe [2] — that the substitutional xenon nuclei do feel a much higher field than xenon nuclei in any other position. Using the fact that the anisotropy detected in a nuclear orientation experiment decreases rapidly with μH , we can neglect the small degree of alignment of the xenon nuclei at non-substitutional sites, thereby introducing an error in the substitutional fraction α and the corresponding hyperfine field H which is only of the order of a few percent. Due to the big directional distribution coefficient $F_2(44(11/2)(3/2)) = -0.889$, the M4 γ -transition is very favourable to determine both α and the product μH by a careful measurement of the temperature dependence of the M4 γ -ray anisotropies. This was done in a series of nuclear orientation experiments.

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(**) Bevoegdverklaard navorser NFWO.

periments on $^{133m+g}\text{Xe}$ and ^{131m}Xe implanted in iron by isotope separator.

2. Source preparation and nuclear orientation measurements.

— The xenon activity was produced by irradiation of natural xenon gas during one week in a neutron flux of $1.8 \times 10^{14} \text{ n.cm}^{-2} \text{ s}^{-1}$. The activities were implanted with the aid of an isotope separator, at an acceleration voltage of 75 kV, into high-purity and electropolished iron foils. The beam was continuously swept in both directions in order to achieve maximum homogeneity. The implantation dose, determined from the total current on the foil itself, was $3.6 \times 10^{13} \text{ at.cm}^{-2}$ for the $^{133m+g}\text{Xe(Fe)}$ source and $3.5 \times 10^{15} \text{ at.cm}^{-2}$ for the $^{131m+g}\text{Xe(Fe)}$ source. The latter value is mainly due to the stable ^{131}Xe . Both doses are comparable to the xenon concentrations used in the experiments described in references [1] and [2].

The nuclear orientation experiments are performed using a high-power $^3\text{He-}^4\text{He}$ dilution refrigerator; the γ -radiation was detected with 30 cm^3 high-resolution Ge(Li) detectors. A description of the complete apparatus is given in reference [4]. The temperature, ranging from 80 mK to 11 mK, was continuously monitored by the anisotropy of the 136 keV γ -ray of $^{57}\text{Co(Fe)}$.

In a first run, the $10 \mu\text{Ci}^{131m}\text{Xe(Fe)}$ source was oriented and the temperature dependence of the anisotropy of the 164 keV γ -ray was measured.

A least squares fit through the data, with both α and the product $\mu_{11/2} H$ as free parameters, resulted in :

$$|\mu_{11/2} H| = 1\,200 \pm 100 \mu_N \times \text{kG}$$

and

$$\alpha = 0.45 \pm 0.05.$$

Figure 1 clearly demonstrates the possibility to determine the substitutional fraction from the temperature dependence of the M4 γ -ray anisotropy.

The $^{133}\text{Xe(Fe)}$ source contained about $10 \mu\text{Ci}$ of ^{133m}Xe activity ($T_{1/2} = 2.26 \text{ d}$) and about $100 \mu\text{Ci}$ of ^{133g}Xe activity ($T_{1/2} = 5.27 \text{ d}$). This source was oriented in two different runs. During the first run, the detection of the strong 81 keV γ -ray from the decay of ^{133g}Xe was diminished by absorbers placed between the source and the detectors in order to improve the detection of the 232.8 keV M4 γ -ray. A least squares fit through the experimental data resulted in

$$|\mu_{11/2} H| = 1\,300 \pm 110 \mu_N \times \text{kG}$$

and

$$\alpha = 0.65 \pm 0.08.$$

In the next run, the anisotropy of the 81 keV M1 ($E 2$) γ -ray in the decay of the $3/2^+$ ground state of ^{133}Xe was observed. As the substitutional fraction for this source is known from the M4 γ -rays analysis, the

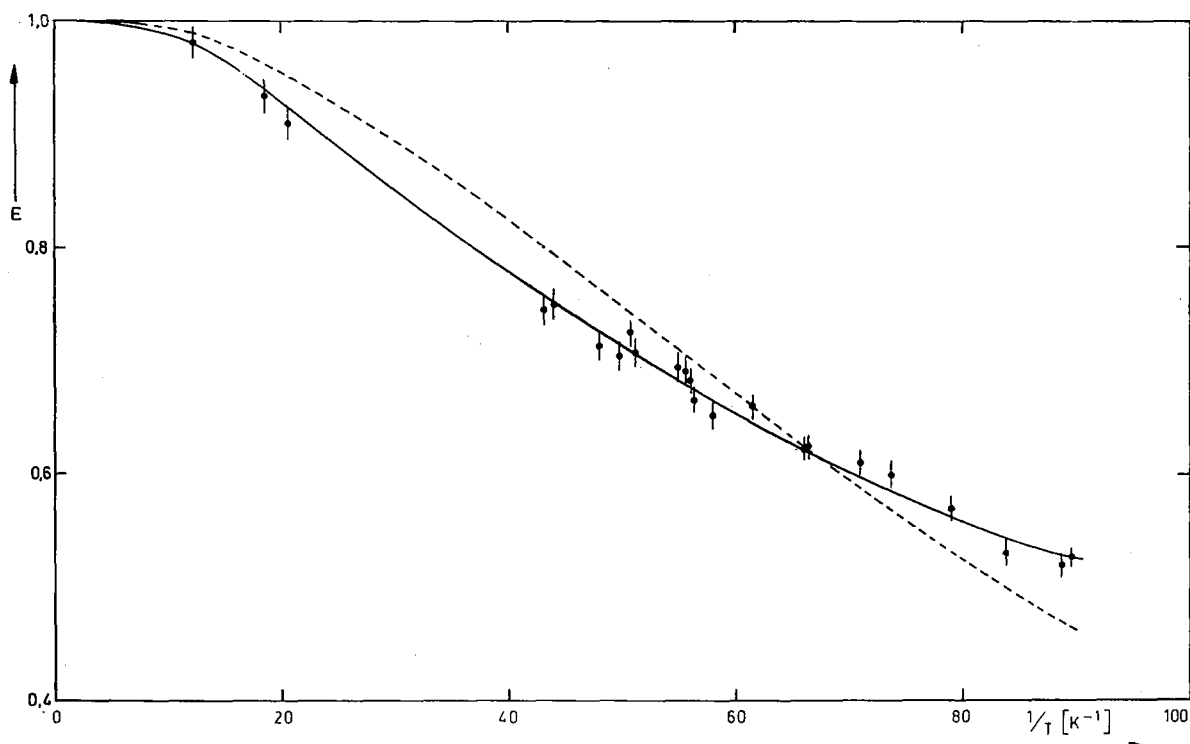


FIG. 1. — The function $W(0)/W(\pi/2)$ vs. $1/T$ for the 164 keV M4 γ -ray of ^{131m}Xe . The solid line represents the best fit : substitutional fraction $\alpha = 0.45$, whereas the broken line represents the best fit if all xenon nuclei are supposed to be substitutional.

product $\mu_{3/2} H$ was determined by a least squares fit with only one free parameter. For the $E2/M1$ mixing ratio of the 81 keV γ -ray, the value $\delta = 0.153 \pm 0.006$ from reference [5] has been used. This resulted in

$$|\mu_{3/2} H| = 1\,100 \pm 120 \mu_N \times \text{kG}.$$

3. **Discussion.** — A recent paper [6] on the magnetic moments of the $3/2^+$ low-lying states in odd-neutron spherical nuclei shows that the variation in these magnetic moments is well reproduced by spin-polarization calculations using wave functions from pairing-plus-quadrupole theory [7]. $\mu_{3/2}$ of ^{131}Xe is known with good accuracy ($\mu_{3/2} = 0.691 \mu_N$ from reference [8]) and as theory predicts an increase of $\mu_{3/2}$ with $0.03 \mu_N$ when adding a pair of neutrons, $\mu_{3/2}(^{133}\text{Xe}) = 0.72 \pm 0.05 \mu_N$ can be regarded as a safe estimate. This can then be used to obtain a hyperfine field of substitutional xenon in iron; we find:

$$H = 1\,510 \pm 160 \text{ kG}.$$

A positive sign is assumed on the basis of systematics of hyperfine fields of neighbouring elements in iron. At the same time the magnetic moments

of the $11/2^-$ isomeric states of ^{131}Xe and ^{133}Xe can be derived

$$^{131}\text{Xe}: |\mu_{11/2^-}| = 0.80 \pm 0.10 \mu_N$$

and

$$^{133}\text{Xe}: |\mu_{11/2^-}| = 0.87 \pm 0.12 \mu_N.$$

The fact that these values do agree with the theoretical predictions based on calculations outlined in reference [7] ($0.91 \mu_N$ and $0.92 \mu_N$ for ^{131}Xe and ^{133}Xe respectively) — which were shown to agree well with other experimental $\mu_{11/2^-}$ values — can be considered as a consistency test of this analysis.

As the substitutional fractions depend on the implantation dose, the acceleration voltage and probably also on other physical conditions such as the temperature of the iron foil at the time of implantation and subsequent heat treatment, no reliable comparison can be made between the values derived by us and those obtained in references [1] and [2]. The variety of results however stresses the need for a determination of the substitutional fraction each time an implanted xenon source is used.

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