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POSITIVE MUONS IN METAL PHYSICS

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1. INTRODUCTION

Positive muons have been used extensively during the last five years as probes of local fields, relaxation processes, diffusion, etc., in solid-state physics [1,2]. A new spectroscopy, called Muon Spin Rotation (μ SR) (in analogy with NMR and ESR) has been developed, which is based on the spin interaction of the muons. The properties of the μ^+ listed in Table 1 will help to elucidate the possibilities of μ SR as compared with other techniques.

Table 1

Muon properties

Mass	: $m_\mu = 206.8 m_e = 0.1126 m_p$
Spin	: $I_\mu = \frac{1}{2} \hbar$
Magnetic moment	: $\mu_\mu = 3.183 \mu_p$
Gyromagnetic factor	: $\gamma = 13.55 \text{ kHz/G}$
Lifetime	: $\tau_\mu = 2.199 \mu\text{s}$
Production	: $\pi^+ \rightarrow \mu^+ + \nu_\mu$
Decay	: $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$
Asymmetry of positron decay	: $W(\theta) = 1 + a_0 \cos \theta \quad (\bar{a}_0 = \frac{1}{3})^*$

*) Average over all positron energies

What is studied in μ SR is, basically, the reaction of the implantation medium to the introduction of an impurity charge. In a metal this charge is screened within a relatively short distance by the conduction electrons, whereas in semi-conductors and insulators the muon can bind an electron. The present review will deal only with the situation in metals. The muons settle down, after thermalization in interstitial positions in the pure lattice. Diffusion processes can be followed over the time scale of a few muonic lifetimes ($\approx 10 \mu\text{s}$). If impurity atoms, vacancies, or other imperfections are present in sufficient concentration the muons may reach regions which act as traps. Similarly, with a set of muons fixed at equivalent points in the lattice one can follow the relaxation of the muon spins over a time range which is important for many dynamic processes in metals and alloys.

The muons have a high initial polarization (70-90%) and the decay radiation is strongly anisotropic and easily detected because of its high energy (average 35 MeV positrons). The spin precession frequencies and the relaxation of the muonic spins can therefore be determined with very good accuracy after collecting a few million events of stopped muons. With modern machines this takes about 30 minutes.

The implantation conditions are such that virtually only one muon is present in the target at a given time. The total implantation doses are also sufficiently low that the risk of one muon interacting with radiation-damaged zones from another one is, in practice, negligible.

In materials research, muons can, therefore, be considered as ideal probes of properties connected with

- a) the response of the metallic electrons to a single positive test charge,
- b) the preferred sites for hydrogen-like interstitial atoms,
- c) diffusion rates and diffusion mechanisms for light interstitials,
- d) spin ordering and dynamics of spins in magnetic environments.

In addition to basic problems of these kinds, μ SR can be applied to questions of direct practical importance, such as the trap-limited diffusion in impure metals or radiation-damaged metals.

In the latter cases there is hope that the analogies of positive muon ($m_\mu = 1/9 m_H$) and hydrogen behaviour will turn out to be sufficiently strong to allow one to extract information on metal hydrides in the dilute limit, a topic which is otherwise difficult to approach experimentally.

2. EXPERIMENTAL METHODS

The experimental methods in μ SR are very similar to those used in perturbed angular correlations (PAC) of gamma-rays. There exist three different versions of μ SR which all have their counterparts in PAC:

i) The transverse field method

Here a magnetic field is applied perpendicular to the detector plane. The muon spin, which is initially oriented along the beam direction, precesses in the field with the characteristic frequency given in Table 1. The decay particles are detected in 2, 3, or 4 scintillator telescopes covering a large total solid angle. The timing system is started by the incoming muons with an anticoincidence condition on the forward detector (implying that the muon has stopped in the target). The precession curves from each telescope are analysed independently with respect to frequency and damping (Fig. 1).

Fig. 1 Transverse field μ SR. The data are corrected for the exponential decay. The lower curve is an on-line fit to the data.

The damping is due to the dephasing of muon spins because of interaction with random local fields (T_2 -relaxation). For a muon fixed in the lattice it is described by

$$P(t) = P_0 \exp(-\sigma^2 t^2), \quad (1)$$

where $\sigma^2 = 1/2 \gamma^2 \langle B_{\text{dip}}^2 \rangle$, corresponding to the second moment in NMR line broadening, due to nearby nuclear dipoles. For a muon jumping quickly between such sites one would have instead

$$P(t) = P_0 \exp(-2\sigma^2 \tau_c t) = P_0 \exp(-\lambda t), \quad (2)$$

where τ_c is a correlation time related to the jump time τ of the muons. In the intermediate region, for $\tau_c \approx \tau_\mu$, the formula

$$P(t) = P_0 \exp\{-2\sigma^2 \tau_c^2 [\exp(-t/\tau_c) - 1 + t/\tau_c]\} \quad (3)$$

is used to fit the data. In this case it is useful to describe the damping by specifying the time required for the polarization to decay to $1/e$ of its initial value. The inverse of this time is called Λ , a parameter to be used later.

ii) The longitudinal field (or zero field) arrangement

β detectors are placed in forward and backward directions and the ratio

$$\frac{N_f - N_b}{N_f + N_b} = A P_z(t) \quad (4)$$

is formed for each time interval. The corresponding damping curves (Fig. 2a) measure the depolarization of the spin components along the initial orientation axis, that is the T_1 relaxation.

Already in zero field, part of the polarization is maintained at long times if the reorientation is due to static fields at the muonic sites. If the local fields are due to random nuclear dipoles (a few gauss) the precession period is of the order of $10 \mu\text{s}$ and $1/3$ of the initial polarization

Fig. 2 a) G_z : longitudinal, zero-field, results for muons in ZrHf_2 [6]. G_x : corresponding transverse attenuation. b) Stroboscopic resonances (from Ref. [14]).

is conserved on the average after this time, corresponding to precession along the polarization axis (z axis). A similar phenomenon is observed in PAC for nuclei in static field gradients [3].

Likewise, the precession in internal fields in non-magnetized ferromagnets (of the order of 1 kG) can be followed in zero field using this geometry. There will then appear a precession amplitude of $\frac{2}{3} a_0$, since only the x- and y-components of the fields are effective in this geometry.

In the case of fluctuating fields the $G_z(t)$ function is monotonously decreasing but there exist intermediate cases, in which, for instance, the history of muon diffusion out from a trap or into a trap can, in principle, be followed in $G_z(t)$ [4].

When a magnetic field is applied longitudinally, the polarization can be wholly or partially restored and the field dependence of relaxation processes can be studied [5].

iii) The stroboscopic method

The stroboscopic method has been described in several works on PAC [6]. In principle, several precession curves, starting at times t_0 , $t_0 + t_1$, $t_0 + 2t_1$, ... $t_0 + nt_1$ (where t_1 is the pulse repetition time of short muon pulses produced by the accelerator) are superimposed. When the magnetic field is changed so that the muon precession frequency coincides with $1/t_1$, all precession curves will be added in phase, which can be detected as a peak in the amplitude of the oscillating component (Fig. 2b).

The application of stroboscopy to μ SR allows very high data-collection rates, since it is not limited by the overlap of muon decay signals within 0-10 μ s as in the time-differential methods. It is used in cases where frequencies must be determined with very high accuracy (of the order of $1:10^6$).

The production of muons requires accelerators with proton energies of about 500 MeV. Such machines exist at SIN and CERN (Switzerland), LAMPF (USA), TRIUMF (Canada), Dubna and Gatchina (USSR) and KEK (Japan). The μ SR technique has been applied in all these institutes, and further experiments are planned for Rutherford Laboratory (UK) and IKO (The Netherlands).

The polarization of the muon beams follows from the weak decay of the pions produced initially [7]. Both high-momentum (≈ 200 MeV/c) beams and low-momentum (≈ 30 MeV/c) beams are used for μ SR. The latter, so-called "surface beams", make it possible to work with smaller amounts of target material. The penetration of the muons is still reasonably high and the implantation materials can be conveniently cooled, heated, or even (for high-energy beams) introduced into pressure cells.

3. LOCAL ELECTRONIC STRUCTURE

In a metal, a positive muon is expected to come to rest in an interstitial position, or possibly a vacancy. If the metal nuclei have large enough nuclear moments it is possible to determine the symmetry of these sites simply by measuring $\langle B_{dip,z}^2 \rangle$, i.e. the σ values, with the external field applied along different axes of a single crystal target. Owing to the different geometrical arrangements of the dipoles with respect to the field axes, muons in f.c.c. Cu, for instance, are expected to have the following σ values [in $(\mu s)^{-1}$] for sites of octahedral (O) and tetrahedral (T) symmetry (compare Fig. 3)

Field along [100]	O site: $\sigma = 0.307$	T site: $\sigma = 0.077$
[110]	$= 0.164$	$= 0.279$
[111]	$= 0.067$	$= 0.319$

Fig. 3 Interstitial sites in an f.c.c. lattice

Fig. 4 Calculated potentials and energy levels for muons and protons in Cu [8]

In a strong field, values close to those calculated for 0 sites are found experimentally, at least over a large temperature range, which establishes the preferred occupation of these sites for muons in Cu. For this example, this is in accordance with a calculation by Teichler [8], whose result is shown in Fig. 4.

When the muon settles down in an interstitial position, the following changes are expected in the immediate surroundings:

- i) The lattice is expanded locally.
- ii) A screening charge is formed around the muon. The lattice expansion is determined by the elastic forces, which in turn are modified strongly by the screening electrons.
- iii) The potential models predict the energy levels and the activation energy for diffusion on the basis of the screening. The relation between the force g exerted on the lattice by the muon, the average elastic force constant α_1 , and the activation energy E_a , is expected to be [8]

$$E_a = 0.258 g^2 / \alpha_1 . \quad (5)$$

- iv) The muonic charge gives rise to an electric field gradient (EFG) acting on the neighbour nuclei. This EFG is also screened by the local conduction electrons.
- v) In a magnetic field the electrons are polarized to some extent. The electrons within the screening charge are expected to show an enhanced polarization as compared with the bulk electrons. This enhancement factor is called η [9].

All these local properties can, in favourable circumstances, be experimentally determined in μ SR, which therefore provides a comprehensive check on the local electronic structure around these simple point defects in a metal.

The *lattice expansion* is determined by the deviation of the σ values from those calculated for a rigid lattice. In the case of Cu it amounts to $\Delta R/(a/2) = 4.9\%$, where a is the lattice constant.

The *activation energy* for diffusion is determined in the temperature range where the muons start to get released from their equilibrium positions, which in the example of Cu occurs above ≈ 100 K. Assuming a simple Arrhenius law for the jump rate

$$1/\tau_c = 1/\tau_0 \exp(-E_a/kT), \quad (6)$$

one obtains $E_a \approx 50$ meV. A more elaborate formula [8] gives $E_a = 79(3)$ meV.

The relation (5) gives $g = 2.7(1)$ eV/a [10] and $\Delta R(a/2) = 5.6\%$ in good agreement with the result from the σ values.

The EFG produced on the nearest neighbour nuclei can be estimated in the following way: the total interaction of the nuclei close to the muon sites is a combined magnetic (dipole interaction with the applied field) and an electric one (quadrupole interaction with the EFG from the muon and for non-cubic sites also from the lattice asymmetry), i.e.

$$\mathcal{H}_{\text{nuclei}} = \mathcal{H}_{\text{magn}} + \mathcal{H}_{\text{el}}. \quad (7)$$

The observed quantity in μ SR is the $\langle B_{\text{dip},z}^2 \rangle$ of the nuclei, acting back on the muon, which is given by the expectation value of the nuclear spins I_z along the field axis. When these quantities are evaluated as a function of applied field, as done by Hartmann [11] it turns out that it takes a certain strength of magnetic field to overcome the action of $\mathcal{H}_{\text{el}}$ and produce the strong-field values (quoted above for Cu). These decoupling curves (see Fig. 16 for an example) can be fitted by the parameter $x = \omega_B/\omega_E$, which contains the product (quadrupole moment) $\times$ (EFG). For the case of Cu the quadrupole moments are not accurately known and the EFG parameter q comes out with a fairly large error [12]

$$q = 0.27 \pm 0.15 \text{ \AA}^{-3}.$$

This value has been discussed by Jena et al., who find agreement with the results of a treatment based on a screening model for the EFG [13].

Muonic *Knight shifts* have been studied extensively by Schenck and collaborators [14], using the stroboscopic method. They measure the polarizability of the local electrons through their hyperfine interaction with the muon. If all of this effect should be due to the contact interaction between the nucleus and conduction electrons one would expect the Knight shift to be

$$K = -\frac{8\pi}{3} \mu_B \eta(0)(n_0^\uparrow - n_0^\downarrow), \quad (8)$$

where the n_0 's are conduction electron densities for spin-up and spin-down in the pure metal and $\eta(0)$ is the spin-enhancement factor for electrons in scattering states making up the screening charge.

The data [15] on the simple metals (Li, Na, K, Rb, Cs and Be, Mg, Ca, Sr, Ba) do not seem to vary with free electron density in the systematic way expected in the screening models [9] and more sophisticated calculations, of cluster type or including details of the band structure, have therefore been started recently. The latter calculations indicate that muon-metal bonding states may form, which can lead to diamagnetic shielding and core-polarization contributions. This recent detailed experimental work on the electron structure around the muons in metals will also shed light on the corresponding problem of isolated hydrogen ions in metals.

In metals of h.c.p. structure a strong anisotropy (for Cd single crystals) and strong temperature dependencies (for Zn) have been found. The former reflects a non-spherically symmetric charge distribution around the muon.

Passing from normal metals to the semi-metals (As, Sb, Bi) means a decrease of conduction electron density by a factor of 10^2 - 10^5 . Experiments on Sb single crystals by the CERN group [16] showed a very large Knight shift (about 1% instead of 10-100 ppm for simple metals). This Knight shift

Fig. 5 Knight-shift data for semi-metallic Sb [16]. a) Magnetic field in a plane containing the c axis. b) Magnetic field in a plane perpendicular to the c axis.

is also strongly anisotropic in the plane containing the c-axis (Fig. 5) and is fully developed only below 20 K. No detailed explanation has so far been given in terms of the local electron structure of hydrogen-like point defects in this class of materials.

4. MUONS IN MAGNETIC MATERIALS

The muonic impurity problem can be studied conveniently in ordered magnetic materials by the zero-field method, which gives directly the local field(s) at the muon sites

$$B_{\text{loc}} = B_{\text{dip}} + B_{\text{contact}} \quad (9)$$

In *ferromagnetic metals*, both terms may be of the order of kilogauss. The dipolar term disappears for both types of interstitial sites in the f.c.c. lattice (Ni), but should take two different values for octahedral as well as tetrahedral sites of b.c.c. metals (Fe). However, if there is a fast jump process between magnetically non-equivalent sites in Fe, the dipolar fields are expected to average out in this case also, whereas the contact field remains. This fast averaging is working even at relatively low temperatures in Fe, where diffusion seems to be fast even at $T = 2$ K.

In the simplest theories the local spin polarization to be put into Eq. (9) for the contact field is the pure metal value ($n_{\uparrow}^0 - n_{\downarrow}^0$), multiplied by an enhancement factor $\eta(0)$ calculable from theory in the scattering models. The unperturbed interstitial spin densities are then taken from neutron scattering data. The measured fields are not well reproduced by this method, however, and one has to realize, as in the Knight shift case, that the muon is not just a passive probe of spin density, but perturbs the electronic structure in its own characteristic way.

The results of μ SR related to ferromagnets have been reviewed recently in a comprehensive paper by Denison et al. [17]. Here, the treatment will be limited to one particular example, studied at CERN by Butz et al. [18]. Figures 6a and b illustrate the temperature and pressure dependence of the contact field in Ni and Fe. The temperature dependence of the contact field is expressed in terms of the parameter

$$\frac{B_c(T)}{B_c(0)} = A(T) \frac{M(T)}{M(0)}, \quad (10)$$

Fig. 6 a) Temperature and b) pressure dependence of B_{contact} for muons in Ni and Fe [18]

where $M(T)$ is the host metal magnetization. In Fig. 6a the full curve is a theoretical prediction for Ni by Katayama et al. [19], based on a more advanced treatment where the local spin density is the result of a hybridization of $1s$ electrons on the μ^+ sites (assumed to be octahedral) and d -electron states from Ni, calculated with muffin-tin potentials. It can reproduce the absolute value of B_{contact} reasonably well. The temperature dependence follows from the rearrangement of spin-up and spin-down electrons near the Fermi level.

The high pressure experiment (up to 7 kbar) was performed at room temperature in order to pick out a possible direct dependence on the volume. Using these data it was found, for the case of Ni that about half of the variation of $A(T)$ could be explained by thermal expansion of the Ni lattice, which brings the theory into better agreement with experiment. Another reason for temperature variations of the local field could be changes in the amplitude of the zero-point motion of the muon, which is large because of the small muon mass (see Fig. 4). It is hoped that the fairly detailed data from μSR experiments can help in the understanding of the structure of hydrogen-like impurities even in transition metals.

Spin glasses are systems which are not yet well understood. A muon spin in such an environment relaxes by direct interaction with the dipoles of the magnetic atoms rather than via local conduction electrons (RKKY) and can therefore serve as a probe of the dynamics in the bulk material.

The zero-field longitudinal method is ideally suited to this problem, since it can distinguish between static inhomogeneous field broadening and dynamic field modulation. Primary data obtained for $\text{AuFe}_{0.01}$ by Uemura

Fig. 7 a) $P_z(t)$ data for AuFe spin glass [20]. b) The Fe spin correlation time for $\text{AuFe}_{0.01}$ as a function of temperature.

et al. [20] are shown in Fig. 7a. The correlation times for the Fe moments derived from these curves are shown in Fig. 7b. It is seen that they vary very fast, but smoothly, over the freezing temperature (as defined by susceptibility data) and four orders of magnitude in τ_c can be covered. These data form a valuable complement to those of neutron diffraction and EPR and more detailed work is expected in this area.

5. DIFFUSION

Hydrogen diffusion is known to be very fast in metals and the state of hydrogen above a certain temperature is sometimes referred to as a "lattice gas".

The positive muons are expected to be even more mobile, because of their smaller masses. Muon jump rates, $1/\tau_c$, can be conveniently studied in the range 10^5 – 10^7 s^{-1} , since the μSR pattern (Fig. 1) then changes from the strongly damped limit valid for muons in fixed positions ($\tau_c \gg \tau_\mu$) to the limit where the dipolar fields are averaged out by many jumps ($\tau_c \ll \tau_\mu$, motional narrowing case), giving an undamped signal. In this range, the jump rates can be fitted with an Arrhenius function [Eq. (6)] for diffusion.

Using again Cu metal as an example, such a free diffusion sets in between 100–250 K and the activation energy comes out as discussed above to be about 80 meV, whereas the corresponding value for hydrogen is 400 meV (studied in the range 500–1000 K). The pre-exponential factor $1/\tau_0$ is $10^{7.5}\text{ s}^{-1}$ for muons and 10^{12} s^{-1} for protons. A series of fits to the formula of Teichler [8] is shown in Fig. 8 with experimental data from ref. 10.

The diffusion mechanisms for light interstitials in metals are of considerable interest both from a theoretical and a practical point of view. The muon pre-exponential factor clearly indicates a sub-barrier diffusion. The mechanisms proposed are illustrated schematically in Fig. 9.

Fig. 8 Diffusion data for muons in a Cu single crystal [10]

Fig. 9 Suggested diffusion mechanisms for muons in metals

The processes to be considered for muons below room temperature are:

a) The phonon-assisted tunnelling is an incoherent tunnelling process, by which the particle plus its surrounding lattice deformation moves one step forward. The so-called small polaron theory by Holstein [21] and Flynn-Stoneham [22] then predicts the following expression:

$$\frac{1}{\tau_0} = \left[\frac{\pi}{4\hbar^2 E_a kT} \right]^{1/2} J^2, \quad (11)$$

where J is a tunnelling matrix element (with a value of 32 μeV for our example of Cu).

The expression [Eq. (11)] is based on multiphonon processes. It breaks down at low temperatures (where a T^7 -dependence of the jump rate is expected), but another possibility, the so-called one-phonon process which has a linear T -dependence, has recently been discussed. It is expected to work only in cases where strains destroy the symmetry of the pure lattice.

b) The coherent tunnelling, or band-like motion, would take place without phonon interaction -- and would indeed be destroyed by the presence of phonons already at relatively low temperatures.

Coherent motion is expected to be easily destroyed also by static perturbations of the energy levels at different sites, since a delocalization can develop only if the effective matrix element for tunnelling is greater than the energy spread of the neighbouring levels (Anderson condition [23]). It is therefore a process that can be expected to occur only in very pure materials, with little elastic strains from impurity atoms and at low temperatures (Fig. 9). The very fast diffusion ($\tau_c^{-1} > 10^7 \text{ s}^{-1}$ at 0.03 K) in Al metal has been ascribed to coherent diffusion, since phonon-induced processes are hard to imagine at such low temperatures [24].

Fig. 10 Damping factor Λ versus temperature for Nb. Sample 1: 3700 ppm N. Sample 2: ≈ 60 ppm N. Sample 3: 15 ± 5 N [25]. Lowest circles are valid for a very pure Nb sample.

In the following we shall discuss a few examples of muon diffusion, the experimental evidence for phonon-assisted tunnelling, and the possible transition from incoherent to coherent tunnelling at low temperatures. The different processes can, in principle, be distinguished by their characteristic temperature dependences. Experiments of this kind have been performed for practically all metals which have large enough dipole moments to make $\sigma(T)$ or $\Lambda(T)$ curves easily measurable.

The results seem, at first, confusing. For the f.c.c. metals there is a large difference between muon diffusion in Cu, which sets in only above 100 K in all samples studied so far, and diffusion in Al, which is fast at all temperatures down to 0.03 K in pure samples. In the b.c.c. metals, V, Nb, Ta, one finds complicated T-dependences like those of samples 1, 2, and 3 of Fig. 10.

Some of these results are now reasonably well understood in terms of *trapping phenomena*. In the example of Fig. 10 from work at CERN, for instance, it was found that added N-atoms act as traps for muon diffusion in the temperature range 30-60 K [25]. The curves are fits to a mathematical model [26], which assumes a certain correlation time τ_c for jumps out of initial sites occupied at low T, a time τ_1 (inversely proportional to the N-concentration) to reach the traps, and a time τ_0 before the muons are released from the traps. Activation energies associated with τ_c and τ_0 can be calculated and compared with corresponding values for hydrogen, which also exist in the case of Nb. A very pure sample of Nb (< 1 ppm substitutional and < 2 ppm interstitial impurities [27]); lowest points in Fig. 10 give completely different results which means that the study of intrinsic diffusion in metals requires a purity of the order of 6 N (all impurity elements considered).

The sensitivity to trapping can, however, be used to advantage, both in studies of the diffusion mechanisms and in applied materials studies, where trap-limited diffusion would certainly be dominating. The symmetry of the trapping sites and trap depths can be determined and possibly also some features of their electronic structure.

The intrinsic diffusion has been studied recently by the introduction of various types of imperfections:

i) A study has been made on Al-metal using *electron-irradiated samples*, which contain a high concentration of vacancies (Herlach et al. [28]). At a dose of $2 \times 10^{18} \text{ e}^-/\text{cm}^2$ of 3 MeV electrons the vacancy concentration is estimated to be of the order of 10^{-6} . The experimental curves for $\Gamma(T)$ [= $\sigma(T)$ in our notation] shows an almost complete trapping for $T > 200 \text{ K}$ and site determinations verify the substitutional sites for the muons occupying the vacancies.

The vacancies were formed at 150 K. A series of annealings at 213 K, 237 K, and 245 K shows the gradual decrease of vacancy concentration (Fig. 11). From the trapping rates at different concentrations it was possible to derive a T-dependence of the diffusion coefficient (Fig. 12). It follows very well the small-polaron theory in the range investigated.

ii) Another series of studies was carried out on aluminium, where only a lower limit ($1/\tau_c > 10^7 \text{ s}^{-1}$) can be obtained for materials with 6 N purity because of the fast diffusion even at low T. Experiments have been done at CERN on *materials doped with impurity elements* like Mn, Mg, Li, and Ag [29]. The interpretation of such data is reasonably clear for the range above 2 K where the T- and c (concentration)-dependences can be fitted to a trapping rate (Fig. 13)

$$1/\tau_1 \propto c \cdot T^{0.89(3)}, \quad (12)$$

using the same model as for muons in Nb [26]. This T-dependence speaks in favour of one-phonon assisted tunnelling at these temperatures.

Fig. 11 Diffusion in electron-irradiated Al, for various annealing temperatures [28]

Fig. 12 Diffusion coefficient D derived from the data of Fig. 11

Fig. 13 Diffusion studies in AlMn alloys for temperatures above 2 K [29]

Fig. 14 Correlation times for diffusion in AlMn-alloys in the temperature range below 2 K [31]

In the low-T range (Fig. 14), the situation is more unclear at the moment: one can either assume some initial starting sites at $T < 0.1$ K, between which the muons jump with $1/\tau_c$ proportional to $T^{0.6}c^{-0.7}$ (after which they reach the traps around 15 K), or one can assume that there is another diffusion process acting below 2 K, which works faster at lower T and leads to a *trapping* rate $1/\tau_1 \propto T^{-0.6}c^{0.7}$, after a random implantation in the lattice. The concentration dependence can be explained in the first version as increased strain limitation on the mobility with c (but Li and Mn impurities should be very different in this respect because of their different long-range elastic effects) and in the second version simply as an increased probability of finding the traps. A distinction between these two cases can possibly be made by zero-field longitudinal measurements as mentioned in Section 2. Such experiments are now in progress.

The obvious candidate for an inverse T-dependence of the diffusion rate is the coherent type of process. It may be operative at low concentration of impurities, but at a level of $c = 1000$ ppm it can be calculated that the average strain fields from Mn atoms should prevent any coherent motion. This is also in agreement with observations. The quantitative explanation of such a power law is still missing, but parallel cases seem to occur in other cases of narrow-band motion in slightly disordered materials.

iii) As a third example of diffusion experiments using impurities, we may mention the *dopings with paramagnetic atoms*, like Gd and Er, which form localized moments in metals like Al, Cu, Ag, and Au at low concentrations. Such large dipole moments give a strong damping on the μ SR pattern if the muons enter certain regions around them. Heffner and collaborators [30] have used this technique to study diffusion rates in Ag and Au, where nuclear dipoles are too weak to produce a measurable damping.

6. CONCLUDING REMARKS

In the foregoing, we have described some contributions from positive muons to the study of the fundamental problem of the isolated point defect in a metal. Several puzzles remain in this area and we may mention two of them: the first is the T-dependence of σ for Cu samples [31] at $T < 2$ K (Fig. 15), where the state of the muon is not understood at the moment: site occupation determinations by the $\sigma(B)$ method described in Section 3 indicate O-site preference in both cases (Fig. 16). The second example is that of Fe metal, where the damping data below 50 K [32] are still a matter of discussion.

Fig. 15 $\sigma(T)$ curve for a Cu single crystal of high purity [32]

Fig. 16 $\sigma(B)$ curves for the same crystal as in Fig. 15

Problems relevant to applied material science which are studied at present include the possible formation of muon-impurity complexes in the metals and of so-called tunnel-split states including 4T, 6T, etc. sites. Another application area is to be found among the saturated metal hydrides, where a muon probably can jump only when a proton jumps and the muon therefore can be said to act as a spectator transmitting information to the observer.

Although the μ SR technique seems to be too expensive to apply as a routine method in metallurgy, it can help to solve a number of fundamental questions concerning impurity interactions in metals and alloys.

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