J. Phys. C: Solid State Phys., **15** (1982) 2709–2720. Printed in Great Britain

Impurity trapping effects in the localisation of muons in solids

Anne M Browne†‡ and A M Stoneham†
†Theoretical Physics Division, AERE Harwell, Didcot, Oxon OX11 0RA, UK
‡Department of Theoretical Physics, 1 Keble Road, Oxford OX1 3NP, UK

Received 4 June 1981, in final form 21 December 1981

Abstract. Muon spin rotation (μSR) experiments are now regularly used to study solids and solid-state processes. The interpretation of μSR data is usually based on a 'standard' picture in which the muons localise randomly in the solid, and then diffuse, possibly encountering impurities. There remain some important cases where no satisfactory interpretation results. For some of these anomalous systems we propose an alternative picture in which the two different factors are the importance of metastable (free muon) excited states, and the role of impurities in causing localisation. We show this allows a possible explanation of results for Al:Mn and we demonstrate that elastic strain fields of defects may be a major factor in influencing localisation. We also propose a new mechanism for delayed self-trapping.

1. Introduction

Muon spin rotation offers a special and flexible technique in the study of solids. It is a resonance method, in which the muon polarisation can be followed as a function of time. The relationship between the polarisation and physically-important quantities is discussed, for example, by Stoneham (1979a); comprehensive reviews and surveys are given by Brewer and Crowe (1978), Schenck (1976) and Seeger (1978).

Despite a number of successes, there remain some important problems of interpretation. These concern especially muons in metals at very low temperatures, and the role of impurities in small concentrations. These problems arise within what we shall call the 'standard picture', which we shall define shortly. It is our aim to argue that some of these results can be understood satisfactorily within an alternative picture. In this alternative, one important component is the view that, because of the finite muon lifetime (about 2 μs), the muon may not reach the thermodynamic ground state.

The 'standard' and 'alternative' pictures are most readily defined in terms of the three types of muon state in the solid. These states are (*a*) the 'free' state, i.e. the muon in its propogating state as when it enters the solid; (*b*) the 'self-trapped' state, in which the muon is effectively immobilised by the lattice distortion it causes itself, analogous to a small polaron or to hydrogen in metals; and (*c*) a localised state involving an impurity. It is useful to note that small-polaron theory predicts two distinct regimes in a perfect lattice, namely an incoherent hopping regime at higher temperatures, and a coherent propagation regime at lower temperatures. The coherent propagation state of state (*b*) is quite distinct from the free state (*a*).

0022-3719/82/122709 + 12 $01.50

The 'standard picture' invokes three physically-based assumptions:

(i) the 'free' state is never important: it lasts for a time too short to give significant consequences;

(ii) the rapid transition from the free to the self-trapped state occurs randomly in the solid;

(iii) once self-trapped, the muon diffuses through the lattice encountering impurities which affect its behaviour (see, e.g., Petzinger 1980, 1981, Kehr *et al* 1979).

It is probable that this picture is correct in many cases. Certainly the ideas agree with those accepted in other areas of solid-state science. One knows the muon will slow to thermal energies rapidly. One expects self-trapping to occur within a few lattice vibrational periods. There is no real doubt that the self-trapped state is the ground state (Hodges and Trinkaus 1976, Leung *et al* 1976). And the diffusion and trapping aspects are close to models of point defect motion following radiation damage.

The problems with this standard picture are ones which might be expected to be especially important at very low temperatures, where diffusion rates, detrapping rates, and any non-radiative transition rates may be expected to be slow. We mention four specific aspects.

(*a*) The range of diffusion should be very low. Estimated diffusion constants, whether measured directly when possible or whether extrapolated from data for hydrogen, correspond to about 10^{+5}–10^{+7} jumps s^{-1}. In 2 μs the muon would make 0.2 to 20 jumps, i.e. not enough to reach the nearest impurity in high-purity metals.

(*b*) Impurities appear to be very important even in high-purity metals. They show especially in the distinctive differences observed from one laboratory to another. Since so many authors mention effects of low impurity concentrations, we list a selection of the papers commenting on these effects in a separate Appendix.

(*c*) Quantitative fits to some of the best data fail to give an acceptable description of what is seen. Here we mean by 'acceptable' qualitative agreement with theoretical models and sensible quantitative values of any parameters. We shall discuss later the data on Al:Mn, where the careful analysis of Kehr *et al* (1981) makes just this point.

(*d*) For some systems, no interpretation is generally accepted, even at a qualitative level. These include the so-called anomalous metals (e.g. pure Al), where motional narrowing appears complete even at the lowest temperatures (e.g. Kehr *et al* 1981), and even the so-called normal metals (e.g. pure Cu) where the mean square internal field appears to change at very low temperatures (Hartmann *et al* 1981). However, the problems are not confined to metals, for the identifications of the normal and anomalous forms of muonium in diamond, silicon and germanium remain unsettled (Patterson *et al* 1978, Holzschuh *et al* 1979, 1981) and there are similar doubts about muon states in oxides. We shall mention all these cases in later sections.

The direct evidence for the standard picture is rather limited. In particular, properties like the Knight shift depend mainly on the spatial region within the unit cell that is sampled by the muon, and are not too sensitive to the kinetic aspects as concentrated on here.

2. The alternative picture

We propose that, for some systems, the usual assumptions (i)–(iii) of § 1 are replaced by these:

(i) metastable excited states may be important: in particular, there are circumstances in which the free state cannot be ignored;

(ii) the direct transition from the free state to a self-trapped state can be very slow in a perfect (i.e. defect- and impurity-free) crystal;

(iii) the impurities or defects affect the muons in three ways:

(*a*) they may scatter free muons;

(*b*) they may catalyse the free to self-trapped muon transition, i.e. they may speed the formation of self-trapped muons relative to that in the perfect crystal. An important consequence is that *muons will localise initially preferentially near defects*, not at random;

(*c*) they may trap muons, exactly as in the conventional picture.

In several respects this alternative view for muons resembles the usual view of positrons in solids: positrons do not appear to have a self-trapped state in perfect metal crystals, so localisation is inevitably associated with defects or impurities. The distinctions are illustrated in figure 1. This model was mentioned briefly in Stoneham (1979b) and a preliminary account was given of a similar model in Browne and Stoneham (1980).

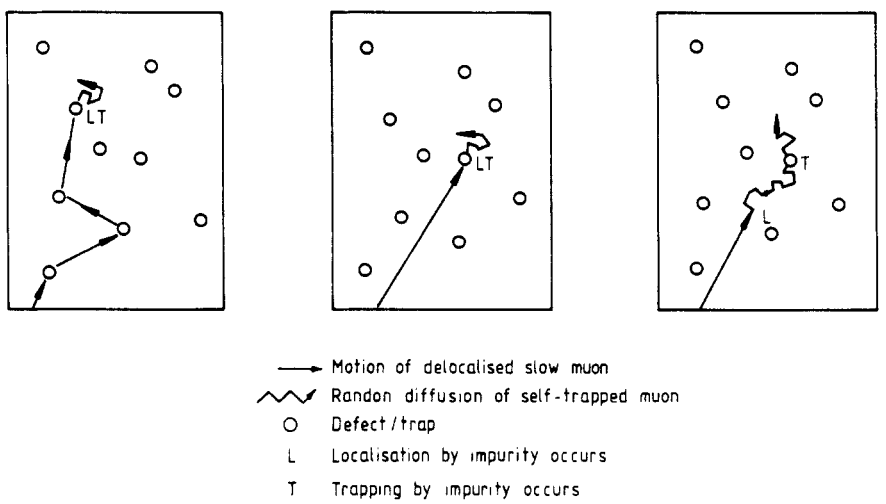


Figure 1. This figure contrasts schematically three different types of behaviour:
(*a*) a thermalised muon scattered and finally localised by impurities;
(*b*) here self-trapping occurs at defects without significant thermal diffusion;
(*c*) the 'standard' picture, in which there is random self-trapping and diffusion involving traps.

2.1. Metastable excited state

The most direct evidence for metastable excited states is for muons in Fe_2O_3 and Cr_2O_3, where extra spectral lines appear at low temperatures. The most likely explanation (C Boekema and W C Mackrodt, private communication) is that the extra lines come from muons at different sites in the unit cell, where there is a local minimum in the energy. Muons at these sites are in metastable excited states. A rather similar interpretation of the two signals ('anomalous' and 'normal') in diamond, silicon and germanium has been advanced by Estle (1981). In metals, the change in mean square field seen in Cu at 0.8 K presumably corresponds to some (as yet undetermined) excited state.

There is a general problem of interpretation in the case of muon excited states, and this arises from the finite lifetime. Do reaction kinetics or thermodynamic equilibrium considerations determine the populations of states? At low temperatures, thermodyn-

amic considerations favour the *lowest* energy state being populated. Kinetics aspects, since transition rates fall at low temperatures, may favour enhanced occupation of an *excited* state: there may not be time in the muon lifetime to achieve the ground state. This situation is, of course, also met in exciton systems. It means that, in the muon case, one cannot be sure whether the lower temperature signal corresponds to the upper or lower of the two states involved.

2.2. Other general aspects

The essence of the alternative picture is that at short timescales muons behave like positrons in solids, and that at longer timescales muons behave like hydrogen. We are specifically concerned with systems where the short-time behaviour holds for most of the muon lifetime.

The first obvious consequence of the alternative picture is that the effects of trace impurities are easily understood. The muon does not have to *diffuse* to the defect; instead it localises preferentially *at* the imperfection.

The second consequence is that, since transition probabilities involving lattice vibrations usually decrease rapidly with temperature, we expect the low-temperature features to be particularly sensitive to the differences between the two pictures. At high temperatures there is rapid diffusive motion, and kinetic limits should be less important. In particular, therefore, we expect that in metals the differences of picture will matter most in the so-called intrinsic regime of behaviour.

In the following two sections we discuss specific aspects in more detail. First, can this model give an explanation of the best-documented and most confusing of systems, Al:Mn? Secondly, are defect strain fields an important part of the catalytic process by which self-trapping is enhanced? We shall postpone any detailed analyses of kinetics to a separate report. Thirdly, we propose a new mechanism by which delayed self-trapping can occur, and one which does not appear within the standard 'molecular crystal' model of small-polaron theory.

3. Motion of muons in Al

In pure aluminium, no damping is seen in the μSR signal down to about 0.1 K. Many workers have noted the dramatic effects of small impurity concentrations or of lattice defects. We shall discuss specifically the comprehensive data on Al:Mn published recently by Kehr *et al* (1981). Their results fall into two broad regimes. Above about 2 K, a consistent and sensible interpretation emerges in terms of the trapping of muons by the strain fields of the Mn impurities. We shall not discuss this further. Below 2 K, Kehr *et al* discuss many explanations, and cast doubts on all of them.

In experiments, the measured quantities are counts in detectors at a particular time after the muon has entered the sample. The expression for the count in a particular detector contains a factor $\exp(-\Gamma(t))$ which describes dephasing of the muon's spin in its motion. If the mean square variation of precession frequency $\omega(t)$ is σ^2, then (subject to certain general assumptions which are not too restrictive) $\Gamma(t)$ takes the form $2\sigma^2\tau_c t$, where τ_c is a correlation time defined by $\langle\omega(t)\omega(0)\rangle = \sigma^2 \exp(-t/\tau_c)$. As τ_c becomes shorter the depolarisation rate (measured by Γ) decreases, giving the familiar motional narrowing phenomenon.

The correlation time is determined by muon behaviour. If the muon is diffusing freely with diffusion constant D, then

$$\tau_c^{\text{Diff}} = G_d d^2/D \tag{1}$$

where d is the lattice spacing and G_d is a purely geometric factor defined by the sites involved. Note that *slower* diffusion increases Γ. If, however, the depolarisation is determined by the fraction of muons captured, then Γ will *increase* with faster muon motion. This situation has been discussed very clearly for positrons by Hodges (1974), who notes two particular limits. If the capture event itself is rate-determining, then one has $\Gamma(t) \equiv t\Gamma_c^{\text{cap}}$ with

$$\Gamma_c^{\text{cap}} = v_\mu c_T \pi r_c^2 \xi \tag{2}$$

where capture is presumed at a surface of radius r_c, with ξ an absorption or penetration coefficient; $\pi r_c^2 \xi$ is thus a cross-section, and ξ is related to the sticking probability used to describe carrier capture in semiconductors. The muon velocity is v_μ; c_T is the trap concentration. If diffusion to the trap is rate-determining, the expression becomes instead $4\pi r_c D c_T$. Hodges' analysis suggests capture is rate-determining for positrons, and we shall assume this holds for muons too.

In comparing with observation, it is convenient to adopt specific units: $\theta \equiv$ temperature in mK, and $f \equiv$ trap concentration in atomic parts per million. Since c_T is defined per unit volume, we introduce $\frac{4}{3}\pi R^3$ as an atomic volume. From Kehr *et al*, using $\Gamma \equiv 2\sigma_0^2 \tau_c$ with their quoted values, we find:

$$\Gamma_K = (2.3 \times 10^5\,\text{s}^{-1})\, f^{0.69} \theta^{-0.57}. \tag{3}$$

Expression (2), with the assumption the muons have thermalised, so that $\frac{1}{2} m_\mu v_\mu^2 \equiv \frac{3}{2} kT$, gives us:

$$\Gamma_c^{\text{cap}} = (1.1 \times 10^5\,\text{s}^{-1})\, f \theta^{1/2} \frac{\xi}{(R/1\text{Å})} \left(\frac{r_c}{R}\right)^2. \tag{4}$$

The two expressions are clearly broadly similar in magnitude for a reasonable cross-section $\pi r_c^2 \xi$. The expressions would be equal if one had:

$$\pi r_c^2 \xi / \pi R^2 = 2.1\,(R/1\text{Å})\, f^{-0.31} \theta^{-1.07}. \tag{5}$$

Clearly the concentration dependence is not exact, though the discrepancy may be within the limits of experiment. The temperature dependence implies a cross-section inversely proportional to temperature, $\sigma \sim T^{-1}$. Hodges argues that, for positrons, capture by vacancies is inversely proportional to velocity ($\sigma \sim T^{-1/2}$). This is surely correct for the strong, short-range interactions of positron and vacancy. For muon–impurity systems, the position is less certain. For Al : Mn (though less clearly for Al : Li) there will be a longer-range elastic interaction, and it is possible that there are several excited states of muon and impurity. The parallels are then closer with some semiconductor systems (see e.g. Stoneham 1975, Abakumov *et al* 1978) where several situations occur with $\sigma \sim T^{-1}$.

We note that, in principle at least, there are experimental possibilities for verifying capture-limited behaviour. A high concentration c_S of defects which do not trap muons (possibly Si) could possibly change the capture-limited regime to a diffusion-limited regime, giving a concentration dependence $c_T c_S^{-1}$ for Γ. However, as Hodges notes, this requires a muon mean free path smaller than r_c, and the concentration needed may be

excessive. Alternatively, since equation (5) suggests trapping involves more than a strong, short-range interaction, one might hope to modify this interaction by pairing the Mn impurity with another impurity species. Hydrogen presumably binds to Mn, just as muons do, and would be a possibility. However, one would have to ensure almost all the hydrogen was paired with Mn to avoid confusing influences of isolated hydrogens.

In most of this analysis it makes no significant difference whether we assume the muon moves as a 'free' muon or as a large polaron, or with some intermediate character. The calculations of Hodges and Trinkaus and of Leung *et al* both strongly suggest a small polaron ground state for Al and other 'anomalous' muon–metal systems, and the main feature needed is just a delay in attaining the small polaron form. We return to this point in § 5.

We see from this section that the assumptions of the alternative picture appear to give an acceptable interpretation of the Al : Mn data, unlike the 'standard' picture. At this point it is convenient to comment on an earlier proposal of ours, which also proposed delayed localisation (Browne and Stoneham 1980). In the earlier model the emphasis was more on the capture event. Kehr *et al* rejected the earlier model, but on grounds which appear to confuse the self-trapping energy and the binding energy of a self-trapped muon to the impurity which catalyses localisation. Nevertheless, we agree with their conclusion that the earlier description did not offer an obvious interpretation of their data.

4. Intrinsic or extrinsic localisation?

The first component of the alternative picture concerns the importance of metastable excited states. The second essential component concerns the way in which impurities can influence behaviour, for example by encouraging transitions from 'free' to localised (self-trapped or impurity-trapped) states. Since the influence of impurities is apparent in quite a few systems, and since there seems no reason to associate this influence with a unique chemical or defect species, we examine here the question 'Can the strain fields of point defects cause free muons to localise?'. We do not discount the chemical interactions, which may be strong, nor the influence of line defects. However, suitable chemical impurities are unlikely to be so common in nature as those with significant strain fields, so we shall ignore chemical effects in the first instance.

The idea of a barrier to self-trapping is quite old (Rashba 1957, Toyozawa 1962). The energy gain from self-trapping is only achieved after an initial critical distortion, and the strain energy associated with this constitutes a barrier. The implications of this have been developed in two ways. On the one hand, there are questions of large versus small polaron stability in their lowest-energy states, the possible coexistence of the two, and the consequences for transport. These features have been studied almost exclusively in tight-binding, one-band models (Emin 1973, Emin and Holstein 1976, Sumi 1972). Emin's review covers in detail these questions and their relation to steady-state transport, whilst explicitly excluding the dynamics of the adjustment of the lattice deformation to carriers that are injected. Emin and Holstein's scaling analysis shows with clarity many of the qualitative features which underly our own analysis. It is principally questions of the kinetics (rather than the dynamics) of self-trapping and the observable consequences which are our present concern. These issues have been touched on by many workers and surveyed by Mott and Stoneham (1977); in the context of muons there are recent discussions by Browne and Stoneham (1980) and by Emin (1981). We shall take over

from the earlier papers the important idea that a critical strain is necessary for localisation to occur, and we shall look at the thermal and defect contributions to this strain. This type of picture is also used in other areas, such as electron solvation in aqueous solutions (Walker 1967). It is necessary for us to use the relatively simple idea of a critical strain principally because the treatments in small polaron theory make rather restrictive assumptions: they use one-band models, ignoring the higher-energy bands, and they concentrate on thermodynamic equilibrium, rather than on the transient states which are important in kinetics.

Here we shall quote results from our earlier report (Browne and Stoneham 1980), with some generalisation. To be specific we concentrate on a locally tetragonal critical strain, rather than simply dilatation, to avoid the well-known feature that a spherical inclusion in an elastically isotropic lattice gives only a uniform dilation. Our conclusions should be qualitatively correct for strains of any symmetry.

(i) *Thermal strain.* The conditional probability that the strain exceeds a particular critical value ε_c is given by:

$$\tilde{P}_T(\varepsilon > \varepsilon_c) = \operatorname{erfc}(\varepsilon_c/\varepsilon_T) \tag{6}$$

where ε_T is a constant of the material. For copper ε_T is 0.05 at 0 K and 0.08 at 300 K; for aluminium, the corresponding values are 0.14 and 0.16.

(ii) *Defect-induced strain.* In the absence of a thermal component the conditional probability can be written:

$$\tilde{P}_R(\varepsilon > \varepsilon_c) = 1 - \frac{2}{\pi}\tan^{-1}\left(\frac{\varepsilon_c + \alpha\Delta v\rho}{\beta\Delta v\rho}\right) \tag{7}$$

where we have written the materials-dependent factors as α and β; for Cu $\alpha = 0.04$ and $\beta = 0.27$. The density of defects is ρ and Δv is the volume dilatation per defect; it is often found that Δv is of the order of the atomic volume, and we shall use this value in making rough estimates.

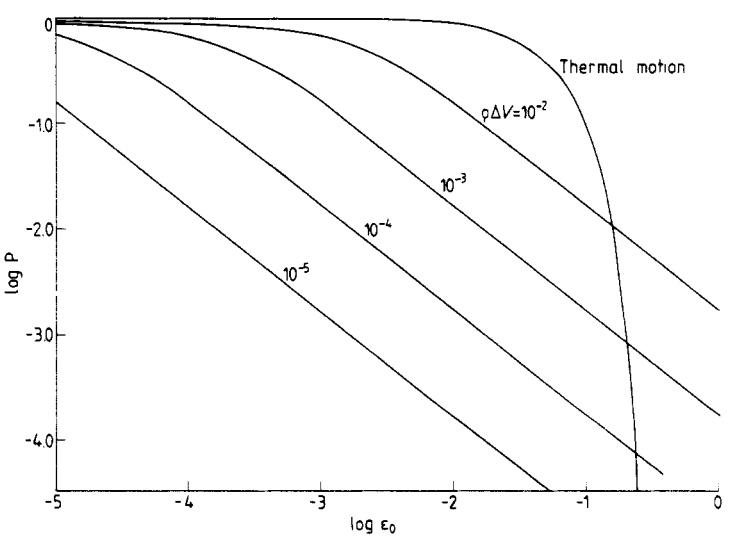


Figure 2. Probability P that the strain from a particular source ε exceeds a particular value ε_0. Values are for tetragonal strains in Cu. The defect contribution is given for different values of the defect density ρ and the dilatation ΔV per defect.

(iii) *Defect and thermal strains simultaneously present.* The distribution of strains is here a convolution of the Gaussian thermal distribution with the Lorentzian component from point defects. Such distributions have been discussed by Posener (1959). Explicit numerical evaluations confirm that the conditional probability lies above the two limiting cases of thermal broadening alone or strain broadening alone, and it interpolates smoothly between these extremes. From these calculations one finds (see figure 2) that whenever the critical strain is at all large (i.e. greater than 5–10%) the regions close to defects will dominate for point defect concentrations greater than about 100 ppm. Further, the high-strain sites are almost exclusively near to the defects: this implies preferential localisation at point defects.

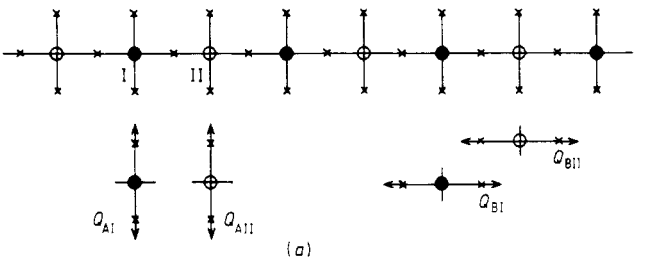
5. Why is localisation delayed?

Within the usual polaron models, delayed self-trapping occurs only for restricted ranges of parameters. There is a barrier only in the so-called 'coexistence' regime in which both small and large polarons may occur. For parameters outside this range the small polarons, if stable at all, should relax within a few periods of lattice vibrations. In a metal–muon system, ignoring for the moment the finite muon lifetime, there are surely excited states forming large-polaron bands. Even for the lower-energy states the parameters may lie outside the restricted regimes needed for the coexistence of large and small polarons. It is hard to be convinced that there is really an effective barrier to self-trapping of the form usually discussed in any but very special circumstances.

There is, however, an alternative. Suppose one regards the muon's low-lying delocalised states as tight-binding band states, built from local states centred on interstitial sites. Normally a single type of site will dominate completely. In some hosts there may be significant contributions from more than one interstitial site (say I and II) to these low-lying, delocalised states. In aluminium, for example, the several calculations suggest that the octahedral site is only slightly more stable than the tetrahedral site (Popovic and Stott 1974, Popovic *et al* 1976, Mainwood 1976, Jena and Singwi 1978, Prakash *et al* 1979, Taylor 1980, Kahn *et al* 1980). The source of delay in localisation is now apparent: if the muon becomes (metastably) associated with sites II, its ultimate self-trapping on sites I will be delayed.

We may describe this more formally, noting that the self-trapping distortions are 'driven' by the forces the muon exerts on the surrounding lattice. The stronger these forces, the more rapidly localisation occurs and the more stable it will be. Thus, if the muon, whilst slowing, cools into low-lying states principally on sites II, the inhibition of the ultimate self-trapping distortion of sites I can be attributed to the reduction in the force driving the self-trapping distortion on site I (Q_I, say). This is most easily seen for a specific example, such as the one-dimensional model of figure 3, which illustrates two distinct effects. The first is that, roughly speaking, the force F_I driving the distortion Q_I depends on the fraction f_I of muon charge at site I. If the local distortions caused by muons entirely at one site or the other are entirely independent degrees of freedom (Q_{AI} or Q_{AII} in figure 3), then the relaxation energy becomes $E_R \equiv (f_I^2 E_I + f_{II}^2 E_{II})$. Even if E_I and E_{II}, the individual relaxation energies, are equal, E_R is lower than either because there is no cross-term in $f_I f_{II}$. The mere existence of the alternative site reduces the driving force for self-trapping, and so may delay the process. However, a second effect may be seen if the self-trapping distortions are not independent (Q_{BI} or Q_{BII} in figure 3),

when the effect is more dramatic still. In the case illustrated, $Q_{BI} = -Q_{BII}$, i.e. the (large polaron) distortions from the amplitude at site II are opposite to those giving the ultimate localisation on site I. There will be an increased delay because the lattice has to make a very large readjustment in going from the low-lying excited states, based on sites II, to the lowest states based on sites I. Moreover, one can note the possibility of several different coexistence regimes: two types of small polaron, one associated with each type of site (this could correspond to the oxide systems discussed in §2.1), or site II large polarons coexisting with site I small polarons. In both cases there would be energy barriers between the two species.



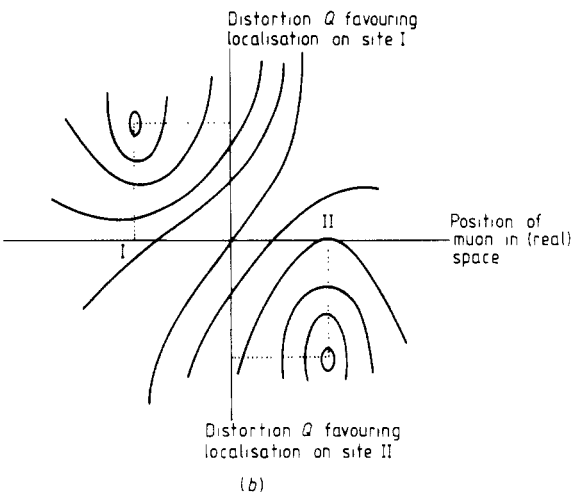


Figure 3. (*a*) Model system showing a mechanism for delayed localisation. Q_A and Q_B are distortions which may give rise to localisation. × host lattice atom; ● interstitial sites I; ○ interstitial sites II.

(*b*) Energy contours illustrating the way a barrier can appear when there is competition between the localising distortions for different interstitial sites.

The situation described leads to a delay in localisation involving conditions quite distinct from the usual mechanism. It seems likely, in particular, that there will be a delay irrespective of whether or not a distinct small polaron can be formed at the higher-energy site. We suggest that there may be a fairly general rule that, for 'normal' host metals, only a single interstitial site is important, whereas for 'anomalous' metals there may be distinct interstitial sites close in energy.

6. Conclusions

We have proposed an alternative picture of muon behaviour in solids, and one which appears to cover those cases which are anomalous in the standard picture. It achieves this without any major reinterpretation of those results which fit the standard picture, apart from a possible re-identification of some of the lowest-temperature regimes (region I in the 'model trapping behaviour' as described in Stoneham (1979a, b)) as extrinsic rather than intrinsic.

The main features of the alternative picture are the recognition of the importance of metastable excited states and the recognition of the role of impurities in accelerating evolution towards the expected ground state. We have shown that the results of the most detailed study of an anomalous system, Al:Mn, fit a model like ours satisfactorily. Further, we have shown that strain fields of defects can account for much of the impurities' influence. What we have not discussed is the kinetic behaviour preceding and during self-trapping. This is still an area of active research where little is settled, even for model polaron systems. Apart from some general points made in our earlier report (Browne and Stoneham 1980), the extent to which these results apply to muon systems is less well defined. Nevertheless, our arguments require only simple general features, notably some feature which inhibits localisation and which loses its effect when there is a large enough local perturbation.

We have discussed the alternative picture in the context of scientific solid-state applications of Muon spin rotation. However, the implications are especially important if muon spin rotation is to be used in materials technology. If the standard picture applies, intrinsic host behaviour is monitored in a straightforward way. When the alternative picture applies, it is the behaviour of muon excited states (possibly ill-defined) and interactions with trace impurities (possibly unintentionally present) which one monitors, a situation of more restricted practical value.

Appendix

We list here papers which describe experiments in which either trace impurity effects are mentioned or apparent. In the case of copper there are indications of metastable excited states. The list is in order of increasing atomic number.

Host	Reference
Be	Metz H *et al* 1979 *Hyp. Int.* **6** 271
Al	Hartmann O, Karlsson E, Norlin L-O, Richter D and Niinikoski J O 1978 *Phys. Rev. Lett.* **41** 1055
	Hartmann O, Karlsson E, Norlin L-O, Niinikoski J O, Kehr K W, Richter D, Welter J-M, Yaouanc A and le Hericy J 1980 *Phys. Rev. Lett.* **44** 337
	Hartmann O *et al Solid State Commun.*, to be published
	Kehr K W, Richter D, Welter J-M, Hartmann O, Norlin L-O, Karlsson E, Niinikoski J O, Chappert J and Yaouanc A 1981 *Hyp. Int.* **8** 681
	Kohn S, Brown J A, Heffner R H, Huang C Y, Kitchens J A Jr, Leon M, Olsen C E, Schillaci M E and Gauster W B 1979 *Hyp. Int.* **6** 283
	Kossler W J, Fiory A J, Lankford W F, Lindemuth J, Lynn K G, Mahajan S, Minnich R P, Petzinger K G and Stronach C E 1978 *Phys. Rev. Lett.* **41** 1558
V	Fiory A J, Lynn K G, Parkin D M, Kossler W J, Lankford W F and Stronach C E 1978 *Phys. Rev. Lett.* **40** 968
	Hartmann O, Karlsson E, Norlin L-O, Pernestal K, Borghini M, Niinikoski J O and Walker E 1978 *Hyp. Int.* **4** 824

Heffner R H, Brown J A, Hutson R L, Leon M, Parkin D M, Schillaci M E, Gauster W B, Carlson O N, Rehbein D K and Fiory A J 1979 *Hyp. Int.* **6** 237
Metz H *et al* 1979 *Hyp. Int.* **6** 271
Nikolskü B A 1977 *Meson Chemistry and Mesomolecular Processes in Matter Conf., Dubna, USSR* p 246

Cr Grebinnik V G *et al* 1979 *Hyp. Int.* **6** 103
Kossler W J, Fiory A J, Murnick D E, Stronach C E and Lankford W F 1977 *Hyp. Int.* **3** 287
Weidinger A, Balzer G, Graf H, Möslang J, Recknagel E, Wichert Th, Bigot J and Grynszpan R I 1981 *Hyp. Int.* **8** 543

Fe Graf H, Kündig W, Patterson B D, Reichart W, Roggwiller P, Camani M, Gygax F N, Rüegg W, Schenck A and Schilling H 1976 *Helv. Phys. Acta.* **49** 730
Graf H, Balzer G, Recknagel E, Weidinger A and Grynszpan R I 1980 *Phys. Rev. Lett.* **44** 1333
Nishida N, Hayano R S, Nagamine K, Yamazaki J, Brewer J H, Garner D M, Fleming D G, Jakeguchi J and Ishikawa Y 1977 *Solid State Commun.* **22** 235
Yagi E, Bossy H, Döring K P, Gladisch M, Herlach D, Matsui H, Orth H, zu Pulitz G, Seeger A and Vetter J 1981 *Hyp. Int.* **8** 553
Yaouanc A, Chappert, J, Hartmann O, Norlin L-O and Karlsson E 1981 *Hyp. Int.* **8** 667

Cu Hartmann O, Karlsson E, Norlin L-O, Niinikoski J O, Kehr K W, Richter D, Welter J-M, Yaouanc A and le Hericy J 1980 *Phys. Rev. Lett.* **44** 337
Hartmann O, Norlin L-O, Yaouanc A, le Hericy J, Karlsson E and Niinikoski J O 1981 *Hyp. Int.* **8** 533

Nb Birnbaum H K, Camani M, Fiory A J, Gygax F N, Kossler W J, Rüegg W, Schenck A and Schilling H 1978 *Phys. Rev.* B **17** 4143
—— 1978 *Phys. Lett.* **65**A 435
Borghini M, Niinikoski J O, Soulié J C, Hartmann O, Karlsson E, Norlin L-O, Pernestal K, Kehr K W, Richter D and Walker E 1978 *Phys. Rev. Lett.* **40** 1723
Brown J A *et al* 1979 *Hyp. Int.* **6** 233
Metz H *et al* 1979 *Hyp. Int.* **6** 271
Niinikoski J O, Hartmann O, Karlsson E, Norlin L-O, Pernestal K, Kehr K W, Richter D, Walker E and Schulze K 1979 *Hyp. Int.* **6** 229

Ta Borghini M, Niinikoski J O, Soulié J C, Hartmann O, Karlsson E, Norlin L-O, Pernestal K, Kehr K W, Richter D and Walker E 1978 *Phys. Rev. Lett.* **40** 1723
Brown J A *et al* 1979 *Hyp. Int.* **6** 233
Metz H *et al* 1979 *Hyp. Int.* **6** 271
Niinikoski J O, Hartmann O, Karlsson E, Norlin L-O, Pernestal K, Kehr K W, Richter D, Walker E and Schulze K 1979 *Hyp. Int.* **6** 229
Schilling H, Camani M, Cygax F N, Rüegg W and Schenck A 1978 *Phys. Lett.* **67**A 231

References

Abakumov V N, Perel V I and Yasievich I N 1978 *Sov. Phys.–Semicond.* **12** 1
Brewer J H and Crowe K M 1978 *Ann. Rev. Nucl. Part. Sci.* **28** 239
Browne A M and Stoneham A M 1980 *AERE Report.* TP.880
Emin D 1973 *Adv. Phys.* **22** 57
—— 1981 *Hyp. Int.* **8** 515
Emin D and Holstein J 1976 *Phys. Rev. Lett.* **36** 323
Estle T 1981 *Hyp. Int.* **8** 365
Hartmann O, Norlin L O, Yaouanc A, le Hericy J, Karlsson E and Niinikoski J O 1981 *Hyp. Int.* **8** 533
Hodges C H 1974 *J. Phys. F: Met. Phys.* **4** L230
Hodges C H and Trinkaus H 1976 *Solid State Commun.* **18** 857
Holzschuh E, Graf H, Recknagel E, Weidinger A, Wichert Th and Meier P 1979 *Phys. Rev.* B **20** 4391
Holzschuh E, Kündig W and Patterson B D 1981 *Hyp. Int.* **8** 819
Jena P and Singwi K S 1978 *Phys. Rev.* B **17** 1592
Kahn L M, Perrot F and Rasolt M 1980 *Phys. Rev.* B **21** 5594
Kehr K W, Richter D and Honig G 1979 *Hyp. Int.* **6** 219

Kehr K W, Richter D, Welter J M, Hartmann O, Norlin L-O, Karlsson E, Niinikoski J O, Chappert J and Yaouanc A 1981 *Hyp. Int.* **8** 681
Leung C H, McMullen J and Stott M J 1976 *J. Phys. F: Met. Phys.* **6** 1063
Mainwood A M 1976 *AERE Rep.* TP.684
Mott N F and Stoneham A M 1977 *J. Phys. C: Solid State Phys.* **10** 3391
Patterson B D, Hintermann A, Kündig W, Meier P F, Waldner F, Graf H, Recknagel E, Weidinger A and Wichert Th 1978 *Phys. Rev. Lett.* **40** 1347
Petzinger K 1980 *Phys. Rev. Lett.* **75**A 225
—— 1981 *Hyp. Int.* **8** 647
Popovic Z D and Stott M J 1974 *Phys. Rev. Lett.* **33** 1164
Popovic Z D, Stott M J, Carbotte J P and Piercy G P 1976 *Phys. Rev.* B **13** 590
Posener D 1959 *Aust. J. Phys.* **12** 184
Prakash S, Bonnet J and Lucasson P 1979 *Phys. Rev.* B **19** 1976
Rashba E I 1957 *Opt. Spektrosk.* **2** 75
Schenck A 1976 *Nuclear and Particle Physics at Intermediate Energies* ed. J B Warren (New York: Plenum) pp 159–297
Seeger A 1978 *Topics in Applied Physics* **28** ed. G Alefeld and J Vökl p 349
Stoneham A M 1975 *Theory of Defects in Solids* (Oxford: Oxford University Press)
—— 1979a *Comments Solid State Phys.* **9** 77
—— 1979b *Hyp. Int.* **6** 211
Sumi H 1972 *J. Phys. Soc. Japan* **33** 327
Taylor D W 1980 *Phys. Rev.* B **21** 5096
Toyozawa Y 1962 *Scottish Univ. Summer School: 'Polarons and Excitons'* ed. C G Kuper and G D Whitfield (Edinburgh: Oliver and Boyd) p 211
Walker D C 1967 *Q. Rev. Chem. Soc.* **21** 79