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PROPOSAL

FORMAIION AND INTERACTION OF MUONIUM IN INSULATORS AND SEMICONDUCTORS

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In order to use muonium as a probe in solids, the first step is to identify the processes of formation of this hydrogen-like atom in the so-called "muon spur"

By muon spur, we refer to the volume at the end of the track of the particle which normally consists of some excess electrons and the corresponding positive ions Within this area, very probably, the muon and/or the muonium will participate in the recombination process in competition with the positive ions[1] At the moment, no clear data are available either on the muonium formation yield in insulators and semiconductors, or on their mobility within the host lattice A preliminary study of the muonium formation yield in insulators and in semiconductors as a function of the temperature and the external field for both transverse and longitudinal configuration will give us the necessary information to choose the best experimental conditions The second step is to investigate where the muonium is trapped in the lattice Extending the similarity between Mu (muonium) and H, the most likely place is an interstitial site This type of "centre" formed by H has been extensively studied with ESR and ENDOR techniques in alkali halides The results have shown a strong interaction of the trapped H atom with the nuclear spin of the surrounding shell[2] The presence of an analogous interaction for Mu would also explain the results obtained in SiO_2, KCl and Al_2O_3 [3-5] with experiments in longitudinal configuration where the muon polarization was measured as a function of an external magnetic field SiO_2 shows a regular behaviour while KCl and Al_2O_3 present a steep rise in the muon residual polarization by increasing the external magnetic field from a few to about 20 G In fact, K, Cl, and Al have a 100% abundance of isotopes with nuclear spin (to be compared with the 4 71% of Si), and it is to be expected that at a sufficiently low field, the coherent precession is destroyed by the randomly oriented magnetic field of the nucleus surrounding the Mu Weaker interaction can be expected if the Mu is trapped in lattice defects such as dislocations and vacancies

In general, a Mu atom in a solid can be described by the following Hamiltonian:

$$\mathcal{H} = H_{hf} + H_{ze} + H_{zn} + H_{dep\ e} + H_{dep\ \mu},$$

where

$$H_{hf} = \sum_{n=1}^{N} A_{i,n}\, \vec{S} \cdot \vec{I}_n + \sum_{n=1}^{N} \vec{S}\, A_{a,n}\, \vec{I}_n$$

is the isotropic (i) and anisotropic (a) hyperfine interaction (N being the number of interacting nuclei including the muon); H_{ze} and H_{zn} are the electron and the nuclear Zeeman term, respectively; $H_{dep\ e} = g_e\, \mu_B\, \hbar\, S_e \cdot B'_L$ is the electron depolarization term, where B'_L is the average magnetic field experienced by the electron owing to the surrounding nuclei except those participating in the hyperfine interaction; $H_{dep\ \mu} = g_\mu\ \mu_B \hbar\ \vec{I}_\mu \vec{B}_L$ is the muon perturbation term, where B_L is the average local field at the muon site generated by the neighbouring nucleus The first term H_{hf} will give the usual Breit-Rabi level diagram when N = 1 and $I_1 = \frac{1}{2}$, while $H_{dep\ e}$ and $H_{dep\ \mu}$ will mix the levels and will be responsible for the broadening of the spectra In general we can distinguish two types of Mu:

1) Free muonium

By free Mu we mean a muonium atom weakly interacting with the electronic structure of the host lattice, such as in ice or SiO_2 In these types of crystals the hyperfine coupling is close to the expected coupling in vacuum (4 46 × 10^9 Hz) In this condition the presence of a non-zero $H_{dep\ \mu}$ term will greatly affect the actual possibility of detecting a Mu coherent precession A minimum jumping frequency for the Mu of the order of 10^9/sec can be estimated for $B_L \sim 10$ G to have a detectable Mu signal in normal experimental conditions (motional narrowing)

2) "Paramagnetic" muonium

In paramagnetic Mu the electron wave function is shared with the first neighbouring atoms As a first consequence the hyperfine coupling is greatly reduced in this second type The Mu atoms will also be sensitive to the lattice or the electronic structure anisotropy, as is the case for the Mu* in Si(6) In such system the Paschen-Bach region is in the order of the kG Calculations on a model with (N + 2) spins have shown that at these fields the γ for the muon spin reversal is very close to the γ_μ of the free muon (13 5 kHz/G instead of 1 395 MHz/G) It is therefore expected to have a much smaller depolarization effect from the $H_{dep\ \mu}$ term in the Hamiltonian

PROPOSED MEASUREMENTS

1 Alkali halides

In alkali halides, Mu has not been seen in transverse field measurements However, depolarization measurements in the longitudinal field have given indications of Mu formation It is most likely that the first type of Mu is formed in these crystals: it therefore becomes imperative to make measurements at several temperatures in the longitudinal and the transverse fields in order to find the optimum conditions between the Mu formation yield and motional narrowing, as mentioned before The Mu trapping sites will also be investigated

The measurements will be made on KCl and NaCl single crystals So that they will be free of impurities, the samples will be grown and controlled at the University of Parma where such facilities are available Non-stoichiometric samples will also be grown

2 Semiconductors

Si and Ge have been tested since the beginning of the μ^+SR technique, not only because they are the "semiconductors" but also because they have a low content of isotopes with nuclear spins Both types of Mu have been detected[6,7] at low temperature (LNT to 20 K) The first type shows a spherical symmetry, while the second has cylindical symmetry along the ⟨111⟩ direction However, the polarization of the free muons and of the muoniums accounts for only about 60% of the total polarization available: either other types of Mu, not yet detected, are created, or there is a fast depolarization which has not been accounted for Measurements at very low temperature (1-20 K) may give an answer to the question

GaAs is a semiconductor which is very similar to Si and Ge, both in lattice structure and energy gap However, in this compound, both elements have a 100% abundance of isotopes with nuclear spins Careful experiments will be made in longitudinal fields to detect Mu formation Eventually, attempts will be made in transverse fields to evaluate the hyperfine coupling

MACHINE TIME

Between April and December 1979, 40 shifts will be necessary to carry out the program: about 20 for the alkali halides and about 20 for the semiconductors

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