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Young Physicists in Helskinki

For the 7th EPS General Conference to be held in Helsinki from 10 to 14 August 1987, the EPS is able to offer a considerable number of scholarships to young physicists *i.e.* those below 30 years of age. This is because the Young Physicists Fund is in a healthy state, the local organizers have made big efforts to obtain funds and national societies are also helping.

Successful candidates from western countries will receive help towards travelling expenses of Sw.Fr. 400–800 depending on distance and the registration fee will be waived; those from eastern countries will have their full board and accommodation as well as their registration fee paid. Requests for an application form should be made now to the EPS Secretariat in Geneva. Also candidates should study straight away the most economical way of travelling. Different schemes apply in different countries and it is up to the traveller to find out what is available.

A special effort is being made in Helsinki to integrate the younger physicists into the programme. On the Monday evening, for example, (10 August) a beer party is being organised at which young physicists can meet each other and also their more celebrated colleagues. Astronauts, nobel prize winners and senior professors will be there in a grand informal mix.

Scholarships will be awarded in March so don't delay your application.

Neutron Spin Echo Spectroscopy

Applications in Magnetism

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High distinctions such as the EPS Hewlett-Packard Europhysics Prize are generally awarded to individuals rather than communities. However, the happy recipients mostly represent just the tip of the iceberg. Before turning to the subject of this paper, it is my privilege to acknowledge those groups and communities I was fortunate to belong to over the past nearly two decades I have spent in neutron scattering research.

First of all I am greatly indepted to the two people together with whom I built the first fully fledged Neutron Spin Echo (NSE) spectrometer, the "IN11" instrument at the Institut Laue Langevin (ILL) in Grenoble [1]). I shared the day-to-day work and the responsibility for the project from an early stage to completion and operation with John B. Hayter, a physicist from New Zealand, who also played a leading role in several applications of the NSE method, primarily in polymer science. Paul A. Dagleish, an engineer from Hull in England was a great companion in solving technical problems, in particular the development of the so called supermirrors, *i.e.* the multilayer interference devices, which provide the spectrometer with polarized neutrons.

In the first years of my work in the neutron field which culminated in 1972

Professor Mezei (right) receiving congratulations from the President of the EPS, Professor Buckel, following the presentation of the 1986 Europhysics Hewlett-Packard Prize, awarded by the EPS for "his invention and implementation of neutron spin echo spectroscopy". The ceremony took place in Stockholm during the 6th General CMD Conference; Professor Devreese, the retiring Chairman of the CMD Board looks on. (Photo: Bela Unger, Stockholm)

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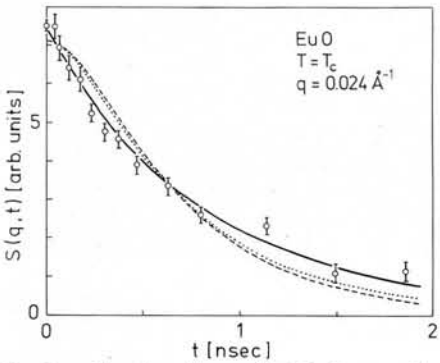


Fig. 1 — The time decay of critical magnetization fluctuations at a given wave number q in EuO at the Curie point [2]) as directly observed by NSE. The continuous line represents the exponential decay (best fit) and the other lines show line shapes predicted by more sophisticated approaches.

in the discovery and demonstration of the NSE method at the research reactor of the Central Research Institute for Physics (KFKI) in Budapest, I took great advantage of the first rate knowledge and equipment accumulated by my Hungarian predecessors in neutron scattering, and in particular of the expert advice by the late Imre Vizi in the practical work. The design and construction of the IN11 spectrometer at ILL (1972-1978) was a great experience in the inspiring atmosphere of the place, benefiting from the collaboration of the excellent ILL technical services, which turned neutron scattering instrumentation into a new art. I am particularly indepted to the directors of these two laboratories in this crucial period, Profs. L. Pal and R.L. Mössbauer, respectively, whose insight and support made the translation of the new idea into a research programme exceptionally straightforward.

Last, but not least, since the completion of the spectrometer in 1978 I had the privilege to work with a large number of colleagues from various areas of physics in applying and perfecting the new method. Their interest in the new approach helped to produce the real birth certificate of NSE spectroscopy: a bulk of useful experimental data with a spectrum ranging from protein dynamics to magnetism.

The principles of the NSE method and a few examples of its use have been described in a previous article in *Europhysics News* (April 1985), and the reader is referred to this for the fundamentals. For the present discussion, it will suffice to remember that the NSE method allows the direct observation of the time decay of (magnetization) fluctuations as a function of their range, *i.e.* of the wave number $\vec{q}$. Mathematically this is expressed by the so called intermediate correlation function $S^{\alpha,\beta}(\vec{q},t)$, where $\alpha,\beta = x, y$ or z define the magnetization components, $\vec{q}$ is the wavenumber and t the real physical time. $S^{\alpha\alpha}(\vec{q},t)$ corresponds to the decay of the α component of the magnetization, and actually in all the examples which follow we are concerned with the observation of this quantity with the direction α perpendicular to $\vec{q}$, *i.e.* with fluctuations transversal to the wavenumber. With this in mind we shall drop the indices in what follows.

In the simplest physical situation, the decay of fluctuations is characterized for any given wave number $\vec{q}$ by a well defined relaxation time τ_q, *i.e.*

$$S(\vec{q}, t) = S(\vec{q}) \exp(-t/\tau_q)$$

In fact from very general sum rule principles, the exponential decay cannot be exact for very short times, but it is often found to be an excellent approximation. For example, Fig. 1 shows the time decay of critical magnetization fluctuations in EuO at the ferromagnetic Curie point $T_C \cong 69.3$ K, as directly measured by NSE. The continuous line represents the exponential decay which, surprisingly, gives a better description of what is observed than the results of rather sophisticated mode-coupling theories (dashed and dotted lines).

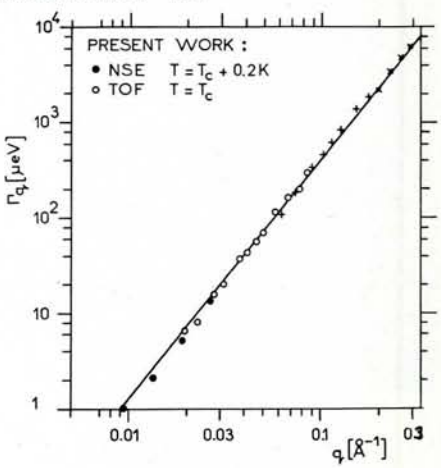
Once we established that the dynamics can be reasonably characterized by a relaxation rate $\Gamma_q = \tau_q^{-1}$, we can study the q dependence of this quantity. Results are given in Fig. 2 for Fe at the ferromagnetic Curie point. To a good approximation the $\Gamma_q \sim q^{5/2}$ law has been found (straight line) to apply in both Fe and EuO. This law corresponds to the predictions of scaling theories for the exchange model, neglecting dipolar and other kinds of interaction. The beautiful agreement in both cases is rather a puzzle. For example in Fe, the volume susceptibility χ_q is known to exceed the limit $1/4\ \pi$ for wavenumbers $q < q_d \cong 0.045$ Å^{-1} where demagnetization (*i.e.* dipolar) effects become dominant. Taking these dipolar interactions into account, the scaling theories would predict a cross-over to the $\Gamma_q \sim q^2$ law at q_d. And indeed, anomalies in the temperature dependence of the hyperfine field relaxation in Fe have been quite naturally interpreted as evidence for this cross-over. Thus there was an apparent contradiction between the neutron and hyperfine field results [4]).

The resolution of this contradiction is a good illustration of the unique significance of neutron scattering data in condensed matter research. Hyperfine field probes the fluctuations at the location of the nucleus, and does not allow us to single out fluctuations as a function of range (wave-number). Therefore the data can only be interpreted using a model assumption of the q dependence of Γ_q. By contrast, neutrons provide model independent results by giving access to both the space and the time (q and t) variables independently. The temperature dependent neutron data have revealed, that the anomalies in the hyperfine field relaxation are due to something other than the dipolar effects *viz.* to the occurrence of a strong temperature dependent uniform relaxation rate $\Gamma_q = 0$ (which vanishes at T_C), which can be explained neither by the exchange nor by the dipole interaction.

The contradiction between the results of the neutron experiments and dipolar theories, are not yet understood. One can speculate, that more sophisticated theories are needed, which take into account the strong demagnetization induced anisotroy of critical fluctuations with respect to the wavevector. Experimentally this anisotropy has only been observed recently [5]), but all the existing results on critical dynamics are only relevant to the magnetization components transversal with respect to $\vec{q}$. Very good quality single crystal samples will be needed in order to extend these experiments to fluctuations longitudinal with respect to the wavenumber $\vec{q}$.

Another example for the application of NSE is the investigation of the nature of the "freezing" phenomenon in spin glasses. The two very remarkable features of the NSE results are that, to the contrary of what we have just seen,
(a) $S(q, t)$ reveals no or little q-dependence and
(b) the time decay is strongly non-exponential.
Because of (a) the data obtained by experimental methods probing different length scales can be directly compared,

Fig. 2 — The relaxation rate of critical fluctuations in Fe at the Curie point as a function of the wave number [3]). The straight line represents the $q^{5/2}$ law.



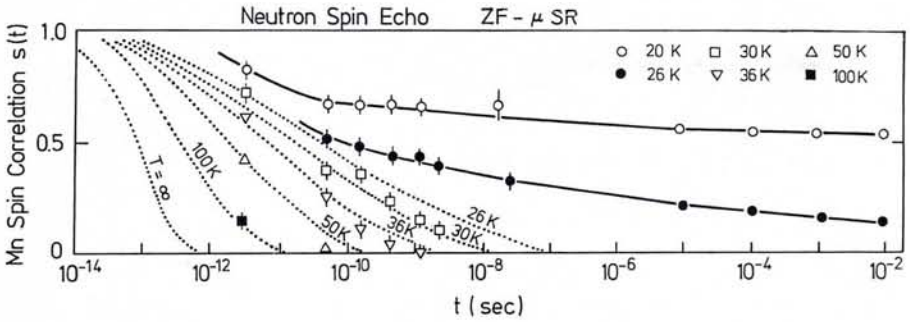


Fig. 3 — Spin relaxation in Cu (5% Mn) spin glass as determined by NSE, zero field muon spin rotation (ZF–μSR) and AC susceptibility measurements [6]. The dotted lines represent Eq. (1) with $\tau_o \simeq 1.2 \times 10^{-13}$ s. and $E_{max} \simeq 330$ K at various temperatures [7].

as shown in Fig. 3. The comination of NSE, muon spin rotation (μSR) and AC susceptibility results give a consistent picture of spin relaxation in the seminal Cu(Mn) spin glass system over a spectacularly wide range of $10^{-11} - 10^{-2}$ s. From the technical point of view however, the story is not so simple. μSR (and also ESR) measurements can only be evaluated by using a given model assumption for the functional form of the time decay, and the early μSR and ESR experiments have been misinterpreted because of the assumption of an exponential decay. Again, the model independence of the neutron data proved to be of great value, and the NSE results have allowed the correct quantitative interpretation of the μSR measurements to be made, as shown in Fig. 3.

The functional form of relaxation curves shown in Fig. 3 is a rather interesting question. The slowing down of the relaxation above the spin glass temperature $T_g \cong 27.5$ K can be described by the simple assumption that we have to do with a uniform distribution of activation energy barriers from zero up to a maximum value E_{max}, and this introduces a broad distribution of relaxation times [7]. Thus we can write

$$S(q,t) \sim \int_0^{E_{max}} dE \exp\left[-t/\tau_o \exp\left(E/kT\right)\right] \quad (1)$$

where τ_o and E_{max} are the only two free parameters. The dotted curves have been calculated from this equation, and they reproduce the observed behaviour remarkably well. Thus we find that the paramagnetic state above the spin glass transition temperature T_g, which appears to be a most ordinary paramagnet in all other experiments, is in reality a rather strange animal. Its q independent, Arrhenius type paramagnetic phase appears to be a precursor to the spin glass transition, and its understanding might contain some important clues to the spin glass phenomenon itself.

We can ask the question what the distribution of activation energies E in Eq. (1) corresponds to. Does it mean that various spin clusters in the sample see a different, but well defined barrier (inhomogeneous model)? Or that each spin or spin cluster in the sample sees an energy landscape characterized by small ripples between higher mountains within even higher peaks, and so on up to E_{max} (homogeneous model)? In other words, this latter scheme corresponds to a hierarchy of relaxation processes, consisting of frequent jumps over the small ripples interrupted more or less often by jumps over the higher barriers. Both pictures lead to the same experimental behaviour, Eq. (1), but there is some indirect evidence in favour of the hierarchical model, which has received recently quite a lot of theoretical attention. First, it would be a rather surprising accident, that a spatially inhomogeneous distribution of barrier heights leads to a q independent relaxation. One would expect that larger clusters relax more slowly than smaller ones, making the relaxation change with the length scale. Second, the average behaviour of an inhomogeneous model should be different in μSR from that in neutron scattering, (to the contrary of Fig. 3) since the coupling is linear to the magnetization in the first case and quadratic in the second [6].

Let us observe, that Eq. (1) breaks down near the spin glass transition T_g. (*cf* the 26 K calculated line and the experimental points). This might be an indication of the collective nature of the transition.

Of course, Eq. (1) is not the only possible mathematical form for the description of the data. As a matter of fact the "stretched exponential" form

$$S(q,t) \sim \exp\left(-t/\tau\right)^{\beta} \quad (2)$$

is a good approximation to Eq. (1) with $\beta = 1$ at $T \to \infty$ and $\beta \cong 1/4$ at $T = 30$ K in our example (where τ in Eq. (2) also changes with temperature). Actually, the NSE data in Fig. 3 are the first evidence for the recently much investigated "stretched exponential" behaviour in spin glasses — preceding theoretical interest by several years.

These two examples are meant to illustrate the potentials of the NSE method in the investigation of magnetism. In both cases the point was that we were able to produce model independent data in an extended time domain up to $10^{-9} - 10^{-8}$ s, compared with the usual $10^{-14} - 10^{-11}$ s range of traditional neutron scattering spectroscopy. Keeping in mind, that the characteristic atomic collision times are of the order of $10^{-13} - 10^{-12}$ s, this suggests an important clue to the significance of NSE spectroscopy.

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