Magnetic excitations in USn_3

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(Received 18 December 1989)

We report on inelastic-neutron-scattering studies of the paramagnetic response in polycrystalline samples of the heavy-electron compound USn_3. The magnetic scattering function, $S(Q,E)$, was determined over a wide range of momentum and energy transfer, $0.5 < Q < 6$ Å^{-1} and $0 < E < 200$ meV, at temperatures ranging from 1.5 to 300 K. We find that $S(Q,E)$ at $E > 2$ meV consists of only a broad quasielastic component characteristic relaxational dynamics of the U spins. The temperature dependence of the line width of this quasielastic peak exhibits a $T^{1/2}$-type power law with a large residual width at the lowest temperature. At $E < 2$ meV, on the other hand, there is evidence of an additional narrow component with a full width at half maximum of the order of 1 meV. Within experimental precision, we find no evidence of other inelastic peaks due to crystal-field excitations. The single-site magnetic susceptibility, $\chi(Q,T)$, obtained by a Kramers-Kronig analysis of the quasielastic spectra, is smaller than the bulk static susceptibility at low temperatures. At a given temperature, $\chi(Q)$ exhibits a Q dependence indicative of an instability towards antiferromagnetic ordering. The experimental results are compared with the spin dynamics observed in other heavy-f-electron compounds and the implication of s-f electronic hybridization is discussed.

I. INTRODUCTION

Hybridization between the f electrons and the conduction electrons in certain rare-earth and actinide intermetallic compounds called heavy-electron system gives rise to many interesting physical properties. For example, the electronic specific heat of these materials is anomalously large, the bulk magnetic susceptibility deviates markedly from the Curie-Weiss behavior at low temperatures, the magnetic moment is reduced from the ionic value, and often there is no long-range magnetic ordering down to very low temperatures. These phenomena are characteristic of strong spin fluctuations resulting from s-f electronic interactions in these materials.

In this paper we report a detailed inelastic-neutron-scattering (INS) study of the temperature dependence of the magnetic response in the heavy-electron material USn_3. USn_3 belongs to the series of intermetallic compounds UX_3 (X is a member of the set of III-group elements from Al to Tl, and IV-group elements from Si to Pb) that exhibit a variety of anomalous electronic and magnetic properties due to varying degrees of s-f hybridization. In these materials the U-U separation (4.0–4.8 Å) in the Cu_3Au-type lattice is significantly larger than the Hill limit[1] (3.25–3.5 Å) so that direct exchange due to U-U overlap is of secondary importance. Systematic studies[2] show that as X moves downward in the group III and IV columns of the periodic table, the extent of s-f hybridization decreases and reaches a rough border line separating itinerant and localized behavior between UGa_3 and UIn_3 in group III and at USn_3 in group IV. Beyond this the compounds become Curie-Weiss paramagnets and show magnetic order at low temperatures. In particular, the field-induced paramagnetic form factor[3] of UGe_3 is highly aspherical. This is indicative of bonding effects involving electron transfer from U to Ge, whereas the field-induced paramagnetic form factor of USn_3 shows[4] good agreement with an isotropic form factor of the U^{3+} free ion. At 0 K, $\gamma(0)$, the electronic specific-heat coefficient[5] of USn_3 (169–171 mJ/mol K^2) is about eight times larger than that of UGe_3 (20.4 mJ/mol K^2); this indicates an enhanced electronic density of states at the Fermi level. In addition, USn_3 is paramagnetic down to the lowest temperature (~ 1 K) whereas UPb_3, on the other hand, orders antiferromagnetically at 31 K. Studies[6] of $U(Sn,Pb)_3$ show that USn_3 is very close to a magnetic instability; a small substitution of Pb for Sn is sufficient to drive the system into a long-range magnetically ordered state. The temperature dependence of the electrical resistivity[7,8] and the electronic-heat[9] coefficient of USn_3 and other UX_3 compounds can also be analyzed in terms of localized spin fluctuations. The preceding properties suggest that the magnetic response in USn_3 is primarily of $5f$ character but correlation effects due to s-f hybridization and/or spin fluctuations may significantly affect the spin dynamics in a complex fashion.

Inelastic neutron scattering provides a direct measure of the spin-spin correlation function of a system; therefore, it has been applied to study the spin dynamics of many heavy-electron compounds. In many studies[10–13] including an earlier preliminary investigation[14] of USn_3,

the observed spectra show a broad quasielastic component with residual intensity extending to high energies (~ 100 meV) in contrast to the sharp crystal-field excitations expected for normal f-electron compounds with stable moments. In principle, the INS results can be analyzed in terms of the generalized dynamic magnetic susceptibility $\chi(\mathbf{q},E)$ (where $\mathbf{q}$ is the reduced wave vector and E is the energy) so as to be compared with theoretical calculations such as those obtained from solutions of the Anderson model. However, because of various limitations imposed both by experiments and theories, the observed spectra are often compared to a phenomenological function comprised of multiple Lorentzians. In spite of the fact that in many cases the data can be fitted qualitatively well to such functions, many questions concerning the nature of interaction between the f orbitals and the conduction bands remain unanswered. Furthermore, the Lorentzian form of the spectral function leads to a divergent magnetic moment thereby rendering such a simple picture of local spin relaxation unphysical. Therefore, it is important to pursue accurate INS measurements of the magnetic response of heavy-electron systems with the aim of identifying any discrepancies of the data from the spin-relaxation model. The systematics of these deviations may provide physical insight into the many-body effects on the dynamics of the f electrons that results from interactions with the conduction electrons.

Because of the unavailability of large enough single crystals, our INS measurements were made using polycrystalline samples. As a result, the scattered intensity at each energy is averaged over all $\mathbf{q}$ in the Brillouin zone and the scattering function is given by $S(Q,E)$ where Q is the polycrystal average of $\mathbf{Q}=\tau+\mathbf{q}$ (τ is a reciprocal vector). Thus any possible $\mathbf{q}$-dependent effects such as electronic coherence of the f electrons in a lattice cannot be studied in this experiment. Another limitation in INS using unpolarized neutrons is the subtraction of nuclear-scattering background (phonons, multiple scattering, etc.) from the total scattering so that a quantitative extraction of the magnetic component is possible. We find that this can be achieved if one explores the temperature-dependent scattering function over a wide range of (Q,E) space with good resolution. Then the nuclear scattering can be determined by a systematic self-consistent analysis of the Q and T dependence of the data, together with runs using nonmagnetic reference samples measured under similar conditions. In the case of USn_3, we have performed experiments in the temperature range of 1.5–300 K using three multidetector time-of-flight spectrometers at two neutron sources with incident-neutron energies ranging from 3 to 350 meV. The phonon and multiple scattering background was also checked by measurements made on the isostructural nonmagnetic sample $LaSn_3$. At the end, we find that the measured magnetic-excitation spectrum of USn_3 at low temperatures ($T < 100$ K) cannot be explained by simple spin relaxations of the $5f$ electrons. The central Lorentzian peak given by this interpretation fails to account fully for the bulk static magnetic susceptibility. In addition, there appear extra intensities in the inelastic region that cannot be described adequately by Lorentzian functions centered at finite energies. We shall briefly describe the neutron experiments, then present the results and compare the measured magnetic-response function with the spin relaxation model and the measured bulk magnetic susceptibility.

II. EXPERIMENTAL DETAILS

The INS experiments were performed using the high-resolution chopper spectrometer (HRCS) at the Intense Pulsed Neutron Source (IPNS) of Argonne National Laboratory, the IN4 and IN6 spectrometers at the high-flux reactor at the Institute Laue-Langevin (ILL) in Grenoble. These time-of-flight neutron spectrometers are equipped with wide-angle multidetector banks and thus enable measurements of inelastic scattering over a wide range of momentum and energy transfers ($\hbar Q,E$). Pulsed spallation neutron sources have large fluxes of epithermal neutrons and therefore are particularly suited for investigation of high-energy ($E > 100$ meV) excitations. To explore the fine structures in the quasielastic and near-elastic regions, on the other hand, the IN6 spectrometer, which provides an energy resolution [full width at half maximum (FWHM)] of ~ 0.1 meV, is more appropriate. We have also chosen the IN4 spectrometer for the exploration of excitation spectra in the 1–10 meV region. The important runs for the USn_3 measurements are given in Table I.

In an INS experiment, polycrystalline samples of USn_3 (of 50–160 g depending on the instrument in use), contained in an aluminum cell in the shape of a thin slab were mounted either perpendicular or at a 45° angle to the incident beam. Such a geometry limits the neutron path length traversing the material to less than 0.8 cm for all detector angles (3°–120°), thereby reducing multiple scattering of neutrons in the sample. The effective transmission of the sample was 90–95 %. Either a closed-cycle helium refrigerator or a conventional helium cryostat was employed to cool the sample, and the sample temperature was controlled to within 0.5 K throughout the measurement. Since neutrons are scat-

TABLE I. Neutron-scattering measurements on USn_3.

HRCS		IN4		IN6	
E_0 (ΔE)[a] (meV)	T (K)	E_0 (ΔE) (meV)	T (K)	E_0 (ΔE) (meV)	T (K)
70(2.5)	15	12(0.6)	5	3(0.1)	1.5
	100		50		5
	200		125		14.5
	296		200		29
					50
					80
					118
					190
					243
250(7.5)	10	50(3)	120		
350(10.5)	12				

[a] E_0 and ΔE are the incident-neutron energy and the mean energy resolution (FWHM), respectively.

tered by (magnetic) electrons as well as by nuclei in the sample, a reliable extraction of the magnetic scattering from the observed intensity is very important in these measurements. To obtain information about elastic and inelastic contributions from nuclear scattering, we have also measured the energy spectrum of the isostructural but nonmagnetic compound $LaSn_3$ (150 g) on HRCS with incident energies 70 and 350 meV. The container and absorber runs were used to correct for background scattering and to assess the effect of sample attenuation. Measurements of elastic incoherent scattering from a vanadium standard provided detector calibration and intensity normalization to absolute units of scattering cross section. In general, we find good agreement (less than 10% discrepancy) among the measured absolute intensities obtained using different instruments under similar conditions.

III. RESULTS AND ANALYSIS

The measured scattering functions $S(Q,E)$ for USn_3 obtained from the HRCS ($E_0=70$ meV) runs are shown in Fig. 1. Additional data from some IN4 and IN6 measurements and the HRCS $LaSn_3$ spectrum at 296 K are also given in this figure. For definitions of scattering functions and their relations with the Lorentzian spectral functions and the bulk static susceptibility, see, for example, Refs. 11 and 15. In general, there are broad peaks at about ± 7, ± 15, and ± 30 meV. The negative-energy peaks arising from neutron-energy-gain processes are broader due to the lower E resolution in this region, and their intensities diminish at low temperatures because of the detailed balance factor. As it can be seen from the $LaSn_3$ data [Fig. 1(d)], these features actually arise mainly from single- and double-phonon scattering. The phonon peaks at 7 and 15 meV resemble the features in the $LaSn_3$ one-phonon density of states.[16] Here we except the nuclear scattering (phonons, multiple scattering, etc.) from USn_3 to be very close to that from $LaSn_3$ because of their same crystal structure and the nearly identical coherent-scattering amplitudes of U and La. Small effects due to the difference in atomic mass ($M_U=238$, $M_{La}=139$) and in lattice constant ($a_{USn_3}=4.626$ Å, $a_{LaSn_3}=4.768$ Å) are negligible under the present instrumental resolution. Thus we may represent the nuclear-scattering intensity in USn_3 by Gaussian functions fitted to the measured $LaSn_3$ spectra. The estimated phonon component can further be checked for self-consistency through its Q dependence: $Q^2\exp(-\alpha Q^2)$ for a given E (where α is the coefficient for the Debye-Waller factor), and its temperature dependence: the Boltzmann factor. Note that in the low-Q region, say, below 3 $Å^{-1}$, phonon contribution is small and magnetic scattering is strong because of the large magnetic form factor. Once the nuclear contributions are determined, they are used together with an additional magnetic spectral function to fit the measured spectra of USn_3 in the low-Q region. The fitted results (solid curves) for the HRCS data, assuming a Lorentzian quasielastic function together with the deduced nuclear scattering convoluted with the instrumental resolution, are shown in Fig. 1. Alternatively, we may compute the magnetic scattering in USn_3 by subtracting off the corresponding $LaSn_3$ data from the total scattering. The result of such procedure for the case of $T=296$ K is shown in Fig. 1(e), in which we find good agreement with results obtained by the first method. Thus it provides additional credence to the extraction of magnetic components out of the total measured intensities. These schemes of analysis have yielded satisfactory results[17,15] also in the cases of heavy-electron materials UAl_2 and $Ce_{0.74}Th_{0.26}$.

We note that although we accomplish an overall reasonable fit to the data at all temperatures by assuming a Lorentzian quasielastic magnetic-response function (see Fig. 1), closer scrutinization of the low-temperature data [e.g., see Fig. 1(a)] suggests that there exist extra intensities at energies below ~ 2 meV that cannot be accounted for accurately by the fitting functions. However, since phonon and multiple scattering constitute a substantial

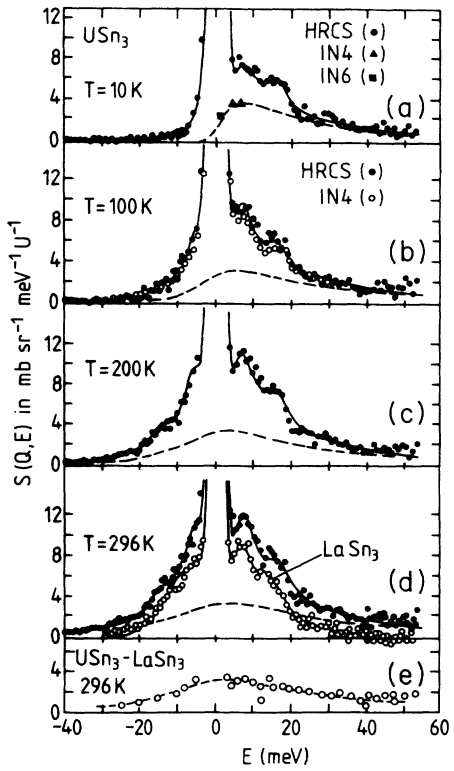

FIG. 1. Measured scattering functions $S(Q,E)$ (solid circles) of USn_3 in units of mb sr^{-1} meV^{-1} per uranium atom from HRCS with incident energy 70 meV. Q varies from 0.9 at the elastic position to 2 $Å^{-1}$ near the ends of the spectra. The solid curves were obtained from fits to the data with a nuclear-scattering component (Gaussians, not shown) and a magnetic component (a Lorentzian spectral function, dashed curves) (see the text). Additional data from IN4 and IN6 at comparable Q but with much smaller E_0 are also given in (a). In (b) the IN4 data (open circles) were collected with $E_0=50$ meV at 120 K. The Q value at a given E for the IN4 data is slightly smaller than that of HRCS, therefore, it can be seen that the IN4 data are slightly below the HRCS data because of less phonon scattering.

part of the observed intensity, examination of detailed structures in the underlying magnetic contribution is extremely difficult. Consequently, a high-resolution low-nuclear-scattering-background experimental configuration is needed to investigate the magnetic response at low energies. This was achieved by using the cold-neutron spectrometers IN4 and IN6 at ILL (see Table I). By combining the employment of low-energy incident neutrons with much improved (Q,E) resolutions and a reduction of sample size, a significant suppression of phonon and multiple scattering was realized. This can be seen in Fig. 1(a) in which the IN4 and IN6 data points are just slightly above the deduced magnetic component. These data sets help clarify the temperature dependence and Q dependence of the low-energy magnetic excitations in USn_3.

The Q dependence of the magnetic scattering of USn_3 at 5 K and the temperature dependence at a Q range of 0.7–1.9 $Å^{-1}$ are shown in Figs. 2 and 3, respectively.

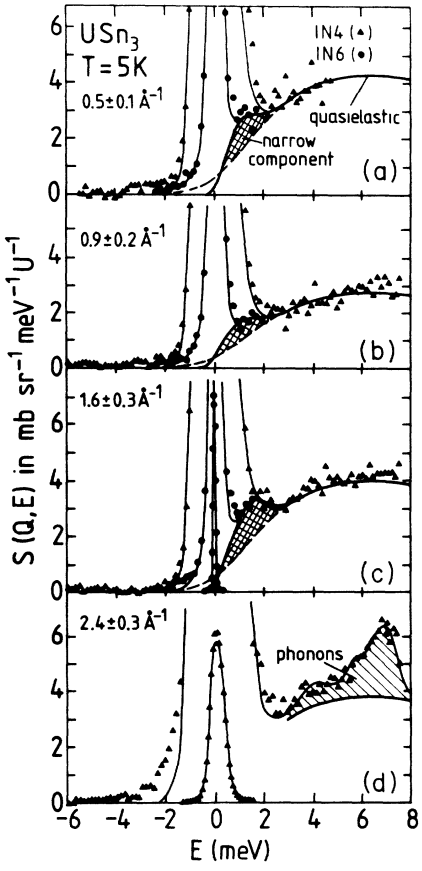

FIG. 2. The measured $S(Q,E)$ at $T=5$ K for USn_3 from IN4 (triangles) and IN6 (circles) measurements. Data of a fixed Q interval are shown in each panel. The solid curves tracing the data points represent the results of the fits (see the text). The sharp peaks centered at zero energy in (c) and (d) are the resolution-limited elastic peaks of IN6 and IN4, respectively, scaled down by a factor (typically ~1000 and ~100 for IN6 and IN4, respectively).

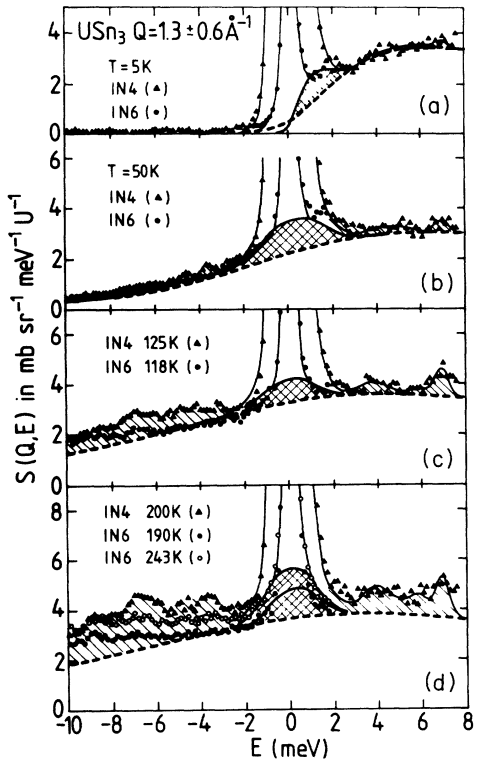

FIG. 3. The temperature dependence of $S(Q,E)$ for USn_3 where Q varies from 0.7 to 1.9 $Å^{-1}$. The hatched areas represent the phonon contributions and the cross-hatched areas represent the estimated narrow component (see the text). The dashed curve denote the underlying quasielastic magnetic components at each group of temperatures in (a)–(d).

Here the observed spectra are dominated by magnetic scattering, and the fluctuations of the data points above the broad magnetic quasielastic component represent the phonon scattering that can be seen increasing with Q (Fig. 2) and with temperature (Fig. 3), as expected. First, because of the small nuclear-scattering background, the amplitudes of the quasielastic magnetic component can be established more accurately, and they agree very well with those deduced from the HRCS data (Fig. 1). The half widths Γ, of the quasielastic Lorentzian, which increases from 7 to 20 meV monotonically with temperature, on the other hand, are better determined by the HRCS results because of the availability of high-energy data. Second, we observe a drop of the magnetic intensity around $Q=0.9\pm0.2$ $Å^{-1}$ [Fig. 2(b)] in spite of the nearly constant U^{3+} magnetic factor in the Q range of 0.5–2 $Å^{-1}$. Third, because of the high energy resolution of the IN6 data, the extra magnetic intensity below 2 meV is well resolved. We find that this narrow component is of inelastic nature, centered at about 1 meV at $T=5$ K [Figs 2(a)–2(c) and 3(a)], and it rapidly moves towards the elastic region, becoming quasielasticlike at $T\geq 50$ K (Fig. 3). Unfortunately, due to effects of polycrystal averaging, we feel that further quantization of

these narrow components by analytical functions is not warranted at this stage.

In addition to the IN4 and IN6 measurements aiming at the determination of fine structures in $S(Q,E)$ at low energies, we also attempted to characterize the magnetic-excitation spectrum of USn_3 at high energies by the HRCS spectrometer with incident energies of 250 and 350 meV (see Table I). Within experimental precision, we find no evidence of additional inelastic features of magnetic origin in the energy range of 50–200 meV. The observed intensity falls off monotonically with increasing energy. However, due to uncertainties in multiphonon- and multiple-scattering background, we were not able to quantitatively determine the energy dependence of the magnetic intensity to examine whether it obeys the $1/E$ behavior imposed by the purely relaxational spin dynamics.

IV. DISCUSSION

We have performed INS study of the paramagnetic response in the polycrystalline heavy-electron compound USn_3 over a wide range of temperatures, momentum and energy transfer. Here we first discuss the overall features of the excitation spectrum. The observed magnetic scattering function at all temperatures consists mainly of a broad *quasielastic* component. Within experimental precision, we find no evidence of well-defined inelastic peaks characteristic of crystal-field excitations. This suggests that exchange interactions arising from spin fluctuations and/or s-f hybridization are strong so that transitions within the crystal-field-split ground-state multiplet are damped out completely. A complete determination of $S(\mathbf{q},E)$ would, in principle, provide detailed information on the nature of the s-f exchange interactions in the vicinity of the Fermi level. In the case of polycrystalline measurements, $S(Q,E)$ provides a measure of the joint density of electronic states, for which there is currently no simple analytical form available from any theoretical treatment. Therefore, as in many other works, we resort to the characterization of the magnetic response by an over-simplified picture of purely relaxational dynamics of the $5f$ moments. In such a model the spin dynamics is characterized by an energy scale for the relaxational motions, $\Gamma(T)$, which corresponds to the half width at half maximum of the Lorentzian quasielastic function used to describe the measured-scattering function. We find that this function describes our data for the magnetic scattering reasonably well at all temperatures over the energy range of 2–150 meV (see also Figs. 1–3). The values of Γ as a function of temperature obtained from least-squares fits to all the data are shown in Fig. 4. As it can be seen (Fig. 4), $\Gamma(T)$ follows a $A+BT^{1/2}$ behavior over the temperature range from 0 to 300 K. $A=60$ K and $B=9$ $K^{1/2}$ were obtained from a fit to the data.

The observed large residual width [$\Gamma(0)\simeq 60$ K (5.2 meV), see Fig. 4] of the *quasielastic* peak in USn_3 suggests that at low temperatures the energy scale for the many-body s-f interactions is significantly larger than the thermal energy. In fact, the $\Gamma(0)$ for USn_3 is comparable to those[12] for other heavy-electron systems, although it has been pointed out[12] that cerium compounds in general exhibit a smaller line width than the uranium compounds. The linewidth at low temperature is often compared with the spin-fluctuation temperature, T_{SF}. In USn_3 $\Gamma(0)$ agree very well with T_{SF} obtained[6] from magnetic-susceptibility measurements (58 K) and from electrical-resistivity data (60 K). It has been argued[9] that the onset of spin fluctuations, which was not taken into account by the ground-state band calculation, is responsible for the enhancement of the electronic specific heat below 30 K. The $T^{1/2}$-like dependence of the quasielastic linewidth is similar to those[18,19] observed in some rare-earth heavy-electron compounds. It also agrees qualitatively with the results of several theoretical studies.[19–23] However, at this stage neither the model calculations nor our data are extensive enough to afford a detailed comparison between theory and experiment so as to identify the physical origins of this type of behavior.

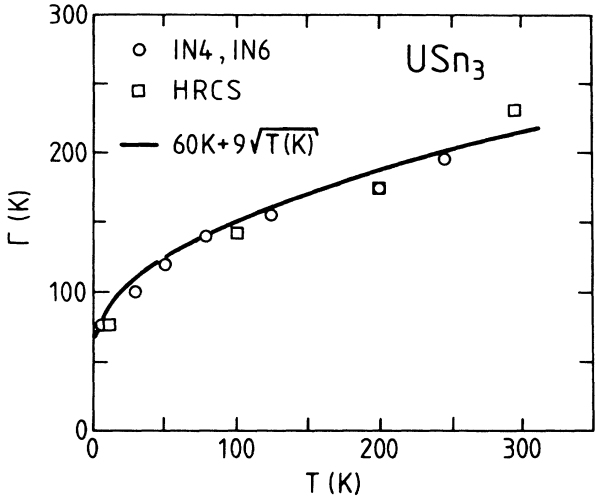

FIG. 4. The temperature dependence of the half width Γ of the magnetic quasielastic Lorentzian spectral function. The solid curve is a fit to the data assuming an $A+BT^{1/2}$ temperature dependence.

The *static single-site* magnetic susceptibility $\chi_0(T)$ is connected to the magnetic-response function by the Kramers-Kronig relation. In the case of a purely relaxation model, $\chi_0(T)$ is simply proportional to the amplitude of the Lorentzian spectral function. Therefore, it is of interest to compare $\chi_0(T)$, obtained from the neutron data averaged over different $|\mathbf{Q}|$ intervals, with the bulk magnetic susceptibility, χ_{bulk}. As we mentioned in the preceding section, at all temperatures the observed magnetic intensity is reduced beyond experimental error in the Q interval of 0.9 ± 0.2 Å^{-1} as compared to those in 0.5 ± 0.1 and 1.6 ± 0.3 Å^{-1}. The corresponding χ_O and χ_{bulk} as a function of T is shown in Fig. 5. We find that the single-site susceptibility is smaller than the bulk susceptibility at all temperatures, and the discrepancy increases with decreasing temperature. It should be pointed out that if the f sites are interacting, the bulk susceptibility per atom is not the same as the average single-site

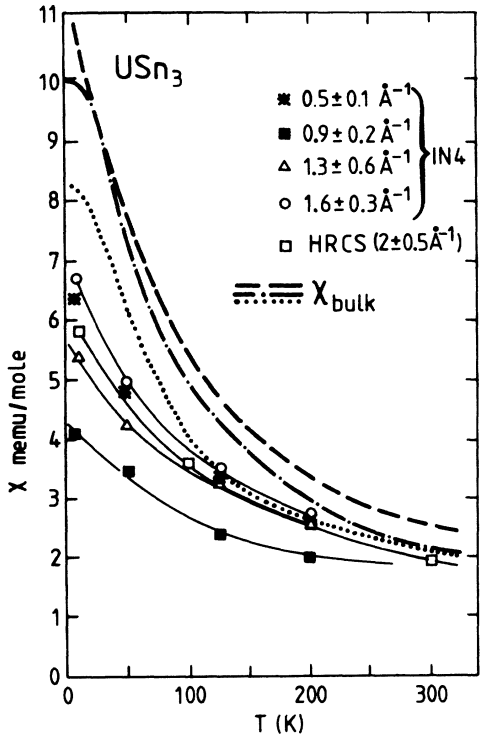

FIG. 5. A comparison of the static single-site magnetic susceptibility obtained from the neutron data over various Q intervals with the bulk magnetic susceptibility (the dashed curve is the present sample, dotted curve is from Ref. 6, and dashed-dotted curve is from Ref. 7). The solid curves passing through the neutron data are guides to the eye. The estimated absolute uncertainty for the neutron data is ~10%, whereas the relative uncertainty between data of a fixed temperature is ~5%.

susceptibility. The former is given by $\lim_{q\to 0}\chi(\mathbf{q},0,T)$, while the latter is obtained by averaging over all $\mathbf{q}$. In addition, we note that the Q values centered around 0.5 and 0.9 are close to the moduli of reciprocal points $(\frac{1}{2},0,0)$ and $(\frac{1}{2},\frac{1}{2},0)$, respectively. Therefore, it is tempting to associate these features to the presence of frustrations of the f moments by opposing effects of spin fluctuations and antiferromagnetic ordering. However, it should be borne in mind that our measurements using polycrystalline specimen inherently obscure the manifestation of such effects, if any. Single-crystal experiments are needed to clarify this situation.

Finally, we comment on the extra narrow component observed at energies below 2 meV (Figs. 2 and 3). At $T \leq 5$ K it centers at about 1 meV and evolves rapidly into a quasielastic peak at higher temperatures. The intensity is too weak to be modeled by an analytic function, and it is unlikely to contribute in any significant way to the static single-site susceptibility at any temperature. At present it is not clear whether this feature is the remnant of crystal-field transitions, or it is of exotic origins such as arising from electronic excitations across hybridization gaps.[24,25] We should point out that in a recent INS measurements[26] of the spin-fluctuation spectra of single-crystal, heavy-electron compound $CePd_3$ an inelastic response was found in addition to the quasielastic Lorentzian component. We believe that in USn_3 the true magnetic response, $S(\mathbf{q},E)$, is probably much more complex than the global features derived from this experiment. Clarification of the situation has to await detailed INS studies using single crystals.

ACKNOWLEDGMENTS

We thank Dr. Stassis (Ames Laboratory) and Mr H. Knott (Argonne) for providing, respectively, the $LaSn_3$ and USn_3 samples used in the experiment. We are also grateful to Dr. G. H. Lander for many helpful discussions. The support from NATO Grant No. RG 85/0156 is gratefully acknowledged. Work at Argonne National Laboratory was supported by the U.S. Department of Energy, Basic Energy Sciences (BES)-Materials Sciences, under Contract No. W-31-109-Eng-38.

[1]H. H. Hill, in *Plutonium 1970 and other Actinides,* edited by W. N. Miner (The Metallurgical Society of the AIME, New York, 1970), p. 2.

[2]D. D. Koelling, B. D. Dunlap, and G. W. Crabtree, Phys. Rev. B **31**, 4966 (1985).

[3]G. H. Lander, J. F. Reddy, A. Delapalme, and P. J. Brown, Phys. Rev. Lett. **44**, 603 (1980).

[4]G. H. Lander and A. Delapalme, in Institute Laue-Langevin Annual Report 1985, p. 221.

[5]M. H. van Maaren, H. J. van Daal, K. H. J. Buschow, and C. J. Schinkel, Solid State Commun. **14**, 145 (1974).

[6]G. L. Lin, L. W. Zhou, J. E. Crow, and R. P. Guertin, J. Appl. Phys. **57**, 3146 (1985).

[7]K. H. J. Buschow and J. J. van Daal, in *Magnetism and Magnetic Materials (Chicago, 1971),* Proceedings of the 17th Annual Conference on Magnetism and Magnetic Materials, AIP Conf. Proc. No. 5, edited by D. C. Graham and J. J. Rhyne (AIP, New York, 1972), p. 1464.

[8]M. B. Brodsky, Phys. Rev. B **9**, 1381 (1974).

[9]M. R. Norman, S. D. Bader, and H. A. Kierstead, Phys. Rev. B **33**, 8035 (1986).

[10]W. J. L. Buyers and T. M. Holden, in *Handbook of Physics and Chemistry of the Actinides,* edited by A. J. Freeman and G. H. Lander (North-Holland, Amsterdam, 1985), Vol. 2, p. 239.

[11]G. H. Lander, Phys. Scr. **T13**, 60 (1986).

[12]S. M. Shapiro, Physica **136B**, 365 (1986).

[13]*Moment Formation in Solids,* edited by W. J. Buyers (Plenum, New York, 1984).

[14]M. Loewenhaupt, S. Horn, F. Steglich, E. Holland-Moritz, and G. H. Lander, J. Phys. C **4**, 142 (1979).

[15]C.-K. Loong, B. H. Grier, S. M. Shapiro, J. M. Lawrence, R.

D. Parks, and S. K. Sinha, Phys. Rev. B **35**, 3092 (1987).
[16]C. Stassis, J. Zarestky, C.-K. Loong, O. D. McMasters, and R. M. Nicklow, Phys. Rev. B **23**, 2227 (1981).
[17]C.-K. Loong, M. Loewenhaupt, and M. L. Vrtis, Physica **136B**, 413 (1986).
[18]A. P. Murani, K. Knorr, K. H. J. Buschow, A. Benoit, and J. Flouquet, Solid State Commun. **36**, 523 (1980).
[19]L. C. Lopes, Y. Lassailly, R. Jullien, and B. Coqblin, J. Magn. Magn. Mater. **31 – 34**, 251 (1983).
[20]C. M. Varma (unpublished).
[21]N. E. Bickers, D. L. Cox, and J. W. Wilkins, Phys. Rev. Lett. **54**, 230 (1985).
[22]Sadamichi Maekawa, Saburo Takahashi, Shin-ichi Kashiba, and Masashi Tachiki, J. Phys. Soc. Jpn. **54**, 1955 (1985).
[23]B. Jin (unpublished).
[24]A. J. Fedro and S. K. Sinha, in *Valence Fluctuations in Solids,* edited by L. M. Falicov, W. Hanke, and M. B. Maple (North-Holland, Amsterdam, 1981), p. 321; *Moment Formation in Solids,* Ref. 13, p. 135.
[25]D. L. Huber, Phys. Rev. B **28**, 860 (1983).
[26]S. M. Shapiro, C. Stassis, and G. Aeppli, Phys. Rev. Lett. **62**, 94 (1989).