"classical" critical indices $\eta = 0$ and $\nu = \frac{1}{2}$.

[7]Equation (4) is rigorous for $d = 2$, and confirmed numerically, but unproven, for $d = 3$. See Fisher and Burford, Ref. 3; and M. E. Fisher, in Critical Phenomena, edited by M. S. Green and J. V. Sengers (National Bureau of Standards, Washington, D. C., 1966).

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[10]For more distant sites the number of nonzero $q_n(\vec{r})$, $n \leq 12$, is insufficient for worthwhile extrapolation.

[11]Scaling depends only on the variation with temperature of $\kappa(T) = \kappa_0 \epsilon^{\nu}$. In drawing Fig. 1 we have used $\kappa_0 a = 2.30 \pm 0.03$, which consistently fits the exponential part of the large-r behavior, i.e., correctly gives the slope of $\ln[(r/a)\epsilon^{-\nu\eta}\Gamma(\vec{r}, T)]$ vs $-\epsilon^{\nu} r/a$ [see Eq. (2)].

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[14]Static scattering experiments measure $\chi(\vec{k}, T)$, the Fourier transform of $\Gamma(\vec{r}, T)$. Strong scaling predicts $\chi(\vec{k}, T) = F(k/\kappa)k^{2-\eta}$ for small k and κ regardless of the ratio k/κ. Reference 3 gives scattering approximants of this type. Our prediction is that there are small nonscaling departures from this behavior, notably at fixed k as $\epsilon \to 0$. It seems likely that recent scattering experiments on lattice systems do not have sufficient resolution to detect such effects. See L. Guttmann and H. C. Schnyders, Phys. Rev. Letters 22, 520 (1969); also, J. Als-Nielsen and O. W. Dietrich, Phys. Rev. 153, 706, 711, 717 (1967).

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SPIN-POLARIZED SPLITTINGS IN THE TEMPERATURE-DEPENDENT REFLECTANCE OF EuO†

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The reflectance of EuO from above the Curie point at 69°K down to 1.5°K shows splittings in the two main peaks near 1.5 and 4.7 eV. The first peak is a polarization-dependent triplet at 1.5°K and a doublet at 70°K. The data suggest that the 1.5-eV peak is associated with the absorption edge and arises from the transition $4f^7(^8S_{7/2}) \to 4f^6(^7F_J)5d$-($t_{2g}$). The narrow t_{2g} sub-band is exchange split by 0.25 eV at low temperatures.

Previous optical studies of the magnetic semiconductors, EuO and other europium chalcogenides, have shown unusually large magneto-optical effects[1] and an anomalous red shift of the absorption edge upon cooling through the Curie point.[2] These effects have been ascribed to transitions from the localized europium $4f$ electron states to $5d$ energy states.[3] We have further examined the effects of magnetic ordering on the band structure by optical reflection studies of EuO beyond the absorption edge in two sets of experiments: (1) measurement of the reflectance from 0.6 to 5.2 eV at several temperatures through the Curie point, $T_C = 69$°K, down to 1.5°K and (2) examination of the first peak in the reflectance with circularly polarized light and in a magnetic field at 70 and 1.5°K. We believe the splittings of the reflectivity peak observed in these measurements indicate that the transitions are to conduction-band states which spin split at low temperatures. To our knowledge, this is the first time such structure has been seen by direct reflectance measurements through the Curie point in any ferromagnetic material.

In the first set of experiments no polarized light or magnetic field was used. The results of these measurements appear in Fig. 1. E_1 centered at 1.44 eV at 80°K is the lowest energy structure near the absorption edge at 1.2 eV.[2,4-6] E_2 is centered at 4.65 eV at 80°K.

As the temperature is lowered through T_C several striking features appear in the spectrum.

(1) E_1 appears to narrow slightly with decreasing temperature above T_C but for $T < T_C$, E_1 broadens and a second peak E_1' splits off to lower energy. As noted later in our magneto-optical measurements, there is a third peak E_1'' splitting off to higher energies, not resolved in Fig. 1 (see Fig. 2), which also contributes to the broadening.

(2) E_1 has a red shift upon cooling similar to that of the absorption edge.[6] However, the peak shift is not as great as that of the edge, the peak shifting about 0.2 eV and the edge about 0.3 eV

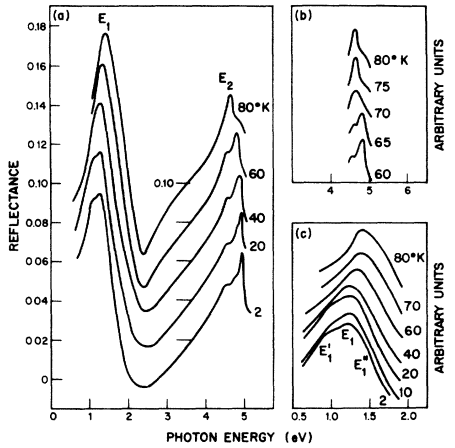

FIG. 1. (a) Reflectance versus photon energy at selected temperatures above and below the Curie point $T_C = 69°K$. Each curve is arbitrarily displaced 0.02 from the one above. (b) Detail of E_2 near the Curie point. (c) Detail of E_1.

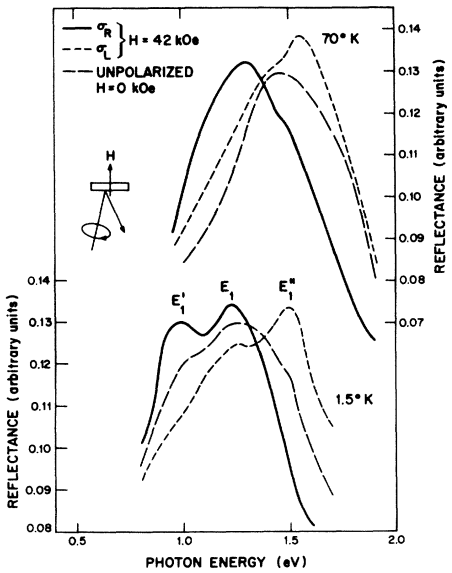

FIG. 2. Reflectance versus photon energy for right and left circularly polarized light at 70 and 1.5°K. The unpolarized reflectance is also shown.

between 80 and 10°K. It thus appears that if the low-energy tail of E_1 is giving rise to the absorption edge as we believe, then the additional red shift of the absorption edge is caused by the splitting off of the transition E_1'.

(3) E_2 does not appear to have a red shift as does E_1. However, there are distinct changes in it on cooling below T_C, as shown in Figs. 1(a) and 1(b). The peak at 4.65 eV and the high-energy shoulder resolve into a remarkably sharp peak at 4.95 eV with at least two lower energy shoulders.

In our second set of experiments the reflectance around E_1 was examined using right and left circularly polarized light in a magnetic field. For measurements at 1.5°K, the sample was immersed in pumped liquid He with the magnetic field applied perpendicular to the reflecting face of the sample. In this configuration, a minimum field of 25 kOe is required to remove the domain structure. In our experiments, 42 kOe were used. The results are shown in Fig. 2. The structure of E_1 in the ferromagnetic state is clearly resolved into three components. The central E_1 peak is seen for both polarizations, E_1' is seen only in σ_R polarization and E_1'' only in σ_L polarization. The convention used is that σ_R corresponds to a magnetic quantum number change $\Delta m = -1$ while σ_L corresponds to $\Delta m = +1$. The energy splittings of E_1' and E_1'' from the central E_1 peak are equal and have the value $\Delta E_1 = 0.25$ eV.

Similar measurements were made near T_C at 70°K. With 42 kOe applied, E_1 is split into a doublet with a total separation of 0.25 eV compared with the total separation of 0.5 eV at 1.5°K. We confirmed that the unpolarized peak is considerably broader at 1.5°K than at 70°K because of the increased splittings due to magnetic exchange.

In a recent review paper,[7] Methfessel and Mattis have documented the various extensive experimental results and conclude that the absorption edge in the Eu-chalcogenide semiconductors arises from a $4f$-$5d$ transition. The basic energy-band scheme is one in which the fundamental energy gap occurs between the predominantly anion p band and a europium $5d$-$6s$ conduction band. The $4f$ levels are highly localized and the ground state may be placed in this gap.

Using this model of localized $4f$ states and $5d$ bands for the electrons, as shown in Fig. 3, we have calculated, for right and left circularly polarized radiation, the transition probabilities for transitions from an all-spin-up ground state consisting of a $4f^7(^8S_{7/2})$ configuration to excited states corresponding to the spin-up components of the $4f^6(^7F_J)5d(t_{2g})$ states for the $J = 0$, 1, 2, 3, 4, 5, and 6 configurations using essentially the same procedure as Freiser, Methfessel, and Holtzberg.[8] Our calculation differs from theirs in that they considered an e_g final state corresponding to the lowest $5d$ state in EuF_2 with a fluorite structure, while we have made the calculation for a t_{2g} final state corresponding to the lowest $5d$ state in ferromagnetic EuO with rock-salt structure.[6] Also, instead of averaging over all

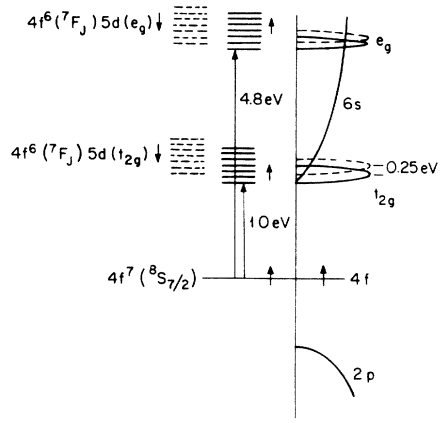

FIG. 3. Schematic band structure of ferromagnetic EuO. The right side shows the fundamental energy gap and the narrow $5d$ bands. The left side shows the E_1 and E_2 reflectance structure as transitions from the localized $4f^7$ ground state to a final state consisting of the ladder structure of a $4f^6$ excited state and an electron in a spin-split component of the d bands.

M_S quantum numbers as they did, we have considered only $M_S = -3$ corresponding to the fully spin-polarized bands. When this is done, we find that the transitions to the higher J-value states are dominantly left circularly polarized while the transitions to the lower and intermediate J-value states are dominantly right circularly polarized. Consequently, simply due to the energy separations of these final-state configurations, we obtain a resolution of the transition into right and left circularly polarized components. The amount of this resolution can be estimated from the data on EuF_2 to be approximately 0.3 eV. We believe that this value corresponds to the doublet splitting of 0.25 eV we observe near T_C. It should be recognized that the resolution into these polarized components depends on our considering only the $M_S = -3$ state and that it disappears if one averages over all M_S values. In the model, then, the polarization effects near T_C are due to a preferential population of the spin-up $^8S_{7/2}$ ground state in the presence of the magnetic field. The exchange splitting of the $5d$ conduction-band state is assumed to be small when the temperature is near T_C. When full magnetic saturation is reached at low temperature, the resolved doublet at 70°K is further split, the various components corresponding to transitions to each of the two spin-split states of the $5d$ band. Four transitions are expected, but because the exchange splitting is also ~0.25 eV, the two central components of the quartet overlap giving a triplet. Thus, we obtain pure polarized components for the extrema and a mixed central component, as observed experimentally. Although the model is obviously a simplified representation, it does give an adequate interpretation of the data.

These results, along with optical rotation measurements near the absorption edge[1] and photoconductivity measurements,[9] strongly suggest that we are indeed observing transitions to the spin-polarized conduction-band structure. In ferromagnetic metals, reflectance structure associated with the spin-split bands is not readily observed because transitions to the Fermi surface do not usually give resolvable structure which can be followed through T_C. However, in the ferromagnetic semiconductor EuO, these transitions are observed because they occur at critical points in the joint density of states at the conduction-band minima and also because the $5d$ conduction band is apparently quite narrow.

Cho's[10] latest band calculation for the Eu chalcogenides shows essentially the same features as this model except that there is a broad $5d$ conduction band. However, our data as well as other results are more consistent with narrower, well separated, t_{2g} and e_g sub-bands. This is seen by comparing the two prominent features in the EuF_2 absorption spectra.[6]

In EuF_2, sharp ladder structure in the lower energy peak is associated with transitions to the lower e_g component of the d band, while the well separated but less structured high-energy peak is associated with transitions to the t_{2g} state.[8] In EuO, this ladder structure appears in E_2, since t_{2g} and e_g are expected to be reversed.[6] Structure in the t_{2g} transitions is not resolved because of spin-orbit broadening which is absent in e_g transitions.[8] Thus, we believe E_2 is due to transitions $4f^7(^8S_{7/2}) \rightarrow 4f^6(^7F_J)5d(e_g)$ although broader structure from other interband transitions ($p \rightarrow 5d$ and $6s$) may be superimposed. The sharp structure of E_2, and the isolation of E_1 which shows up more markedly in a plot of the imaginary part of the dielectric constant,[5] therefore lead us to believe that the transitions are to narrow, well separated t_{2g} and e_g states. We have not yet studied E_2 in polarized light to determine if exchange splittings are also involved here.

Although spin-orbit effects were considered only for the $4f$ states in our model, the spin-orbit splitting of the narrow t_{2g} band by ~0.3 eV[11] should also contribute to the polarized doublet structure at $T \sim T_C$ in much the same way that this effect causes the magnetic rotation in

$CrBr_3$.[12] The origin of the triplet structure for $T < T_C$ including this spin-orbit effect is still the splitting of the final $5d$ conduction-band states by the exchange interaction as we described.

One must also consider the possibility that in EuO the $5d$ levels do not form itinerant bands, but are localized since optical rotation effects in ferromagnetic insulators, such as $CrBr_3$,[12] are due to transitions between localized states. In addition, the red shift of the absorption edge above the Curie point is most easily explained by localized short-range spin-split interactions.[13] However, we feel that if our model for the splitting of the E_1 transition is valid, the change we observe from a doublet structure near T_C to a triplet structure at low temperatures requires the $5d$ state to have delocalized character. Very simply, in a strongly coupled model, the energy state of the d electron will be lowest when aligned with the $4f$ spin on the same ion. Therefore a spin splitting of a localized $5d$ state should exist both above and below T_C. In the delocalized model, the d electron sees an average spin which is zero for $T > T_C$ but is polarized for $T < T_C$. Therefore an exchange splitting will be seen only in the magnetic state, as we observe. Transport measurements[14] and photoconductivity[9] associated with the absorption edge also suggest a conducting d band. However, we have not ruled out the possibility that a broad $6s$ band, degenerate with the $5d$ band at the bottom, may be important for the transport measurements. Extension of this work to other Eu chalcogenides can help elucidate this problem.

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PRODUCTION OF ^{11}B AND ^{10}B BY PROTON SPALLATION OF ^{12}C†

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Measurements of the ^{10}B and ^{11}B spallation production in ^{12}C are presented. These cross sections are related to theories on the origin of the elements lithium, beryllium, and boron.

The nucleosynthesis of the light elements lithium, beryllium, and boron (LiBeB) is a problem of great astrophysical interest.[1-3] Since these elements have very short lifetimes for destruction by stellar thermal protons, they will not survive if produced in the inner regions of stars. It is generally believed that they are produced in a cool stellar environment by the proton-induced spallation of abundant heavier nuclei. The fast protons, with energies of several MeV and high-