KFKI
17/1967

INELASTIC SCATTERING OF NEUTRONS BY VIRTUAL MAGNON STATES IN DILUTE ALLOYS

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Abstract

The effect of weakly bound magnetic impurity atoms /Mn,Er/ on the spin-wave spectrum of Fe has been studied by incoherent inelastic neutron scattering. Resonances of magnetic origin have been observed in both cases. In Fe/Mn/ the angular distribution of the total scattered intensity has a maximum, indicating that $S_{Mn} \neq 0$ and the density distribution of magnetic electrons of iron atoms near the Mn impurity has changed. In Fe/Er/ a low-lying virtual level of long lifetime was found.

The effect of magnetic impurities on the spin-wave spectrum of an ideal Heisenberg-ferromagnet has been investigated theoretically by many authors [1, 2] but very few experimental facts are known as yet. The calculations show that for weakly bound impurities, that is if the impurity-host exchange /J'/ is smaller than the host-host exchange /J/ an s-type virtual spin-wave state can be associated with the impurity. The energy of this state lies in the host spin-wave band. Since the lifetime of a virtual level is inversely proportional to the host density of states, the lower the energy of a virtual level, i.e. the smaller its $\mathcal{E} = J'/J$ value, the longer will be its lifetime.

The presence of magnetic impurities changes the neutron scattering properties of the system. The double differential scattering cross section has an incoherent part with a resonance around the energy E_o of the virtual state. The cross section, given by Izyumov [3] for neutron energy gain reads

$$\frac{d^2\sigma}{d\Omega dE} = \frac{1}{2}(r_o\gamma)^2 \frac{k'}{k_o}\left[n(E_o)\right]\left[F'(\kappa)\sqrt{S'} - F(\kappa)\sqrt{S}\right]^2\left[1+(\underline{e}.\underline{m})^2\right]\frac{1}{\pi}\frac{\Gamma}{\Gamma^2+(E-E_o)^2}$$

where $/\underline{\kappa} = \underline{k}' - \underline{k}_o$, $n/E_o/$ is the population factor, $F'(\kappa)\sqrt{S'} - F(\kappa)\sqrt{S}$ is an effective form-factor with S and $F(\kappa)$ giving the spin and form-factor unprimed for the host, primed for the impurity atoms respectively.

Unit vector e points in the direction of $\underline{\kappa}$, $\underline{m}$ into that of the magnetic field $\underline{H}$. Γ is the width of the resonant level.

To search for the existence and to study the properties of the virtual spin-wave states the Fe/Mn/ and Fe/Er/ alloys have been chosen. In Fe/Mn/ the NMR experiment of Jaccarino et al. [4] has already indicated the existence of a virtual level. In Fe/Er/ we expected a very low energy level with long lifetime, and a good agreement with existing theories, since the magnetic moments of rare earth atoms are assumed to be well localized.

The experiments were carried out on samples made from vacuum-melted Armco iron with 3 % Mn and 0,4 % Er impurities. The concentration of impurity atoms has been determined by activation analysis. The Er concentration is smaller than the solubility limit. For comparison pure Armco iron has been used.

The measurements were performed with a conventional type cold neutron time-of-flight spectrometer [5] with a liquid N_2 cooled Be-filter and a curved slit chopper before the sample. The spectrum of ingoing neutrons was centered around 4,25 Å with a wavelength spread $\Delta\lambda/\lambda = 12$ %. The scattering angles / $\vartheta = 7^o$, 12^o, 18^o, 26^o, 32^o, 41^o for Fe/Mn/ and 10^o, 16^o, 25^o, 35^o, 40^o for Fe/Er/ were chosen in the angular region where the coherent magnon scattering is not superimposed on the intensity of neutrons scattered by the virtual level. In Fig. 1 we have plotted the difference between the spectra measured at $\vartheta = 26^o$ in the alloy and in pure iron.

For the Fe/Er/ alloy the original spectrum at $\vartheta = 10^o$ is shown in Fig. 2., putting the existence of the virtual level beyond doubt. The effect of magnetic field on the excess intensity is also seen in Fig. 1. and 2. The about 20 % decrease in intensity in the case $\underline{e} \perp \underline{m}$ /$\underline{m} \parallel \underline{H}$/ shows the magnetic origin of the additional scattering.

In Fe/Mn/ we found a virtual level at $E_o \approx 20$ meV, which corresponds to $\mathcal{E} = 0,16$ when using for J the value determined from the paramagnetic Curie-temperature and the formulas, given by Vashishta [6] for bcc host crystals. The width of the resonance is $2\Gamma \sim 12$ meV, equivalent to $\tau = 0,55.10^{-13}$ sec.

In Fe/Er/ the Er atoms are weakly bound and this leads to the $E_o \approx 0,6$ meV low energy virtual level. The corresponding $\mathcal{E}$ value is 0,04 and from the observed $2\Gamma = 0,35$ meV level width $\tau = 1,9.10^{-12}$ sec.

The angular distribution of the total intensity scattered by the virtual level can be seen in Figs. 3 and 4. for the Fe/Mn/ and Fe/Er/ alloys respectively.

It is interesting to note that in Fe/Mn/ around the scattering vector $\varkappa \sim 2{,}5$ Å^{-1} the angular distribution i.e. the effective form-factor has a maximum not appearing in Collins and Low's curve [7] . This is not very surprising, since their data pertain only to the $0 < \varkappa < 1{,}5$ Å^{-1} interval, under the $\varkappa$ -range of the present study. While the Collins-Low form-factor does not disagree with the assumption S'=0, our experimental data require a nonzero S' and an F/ $\varkappa$ / decreasing more strongly around $\varkappa \sim 2$ Å^{-1} than the form-factor of the Mn^{++}ion. This is very probably caused by the decrease of the magnetic electron density of the Fe atoms with Mn nearest neighbours. It would be desirable to determine the form-factor by diffraction technique at values of $\varkappa$ higher than 1,5 Å^{-1} in order to get more precise data in the $\varkappa$ -region of the observed maximum.

The angular distribution of the total intensity scattered by the virtual level in Fe/Er/ shown in Fig. 4 indicates the long range character of the magnetic electron density perturbation around the impurity atom.

The authors are indebted to Mr. G. Konczos for preparing the samples and to Dr. P. Quittner for the activation analysis.

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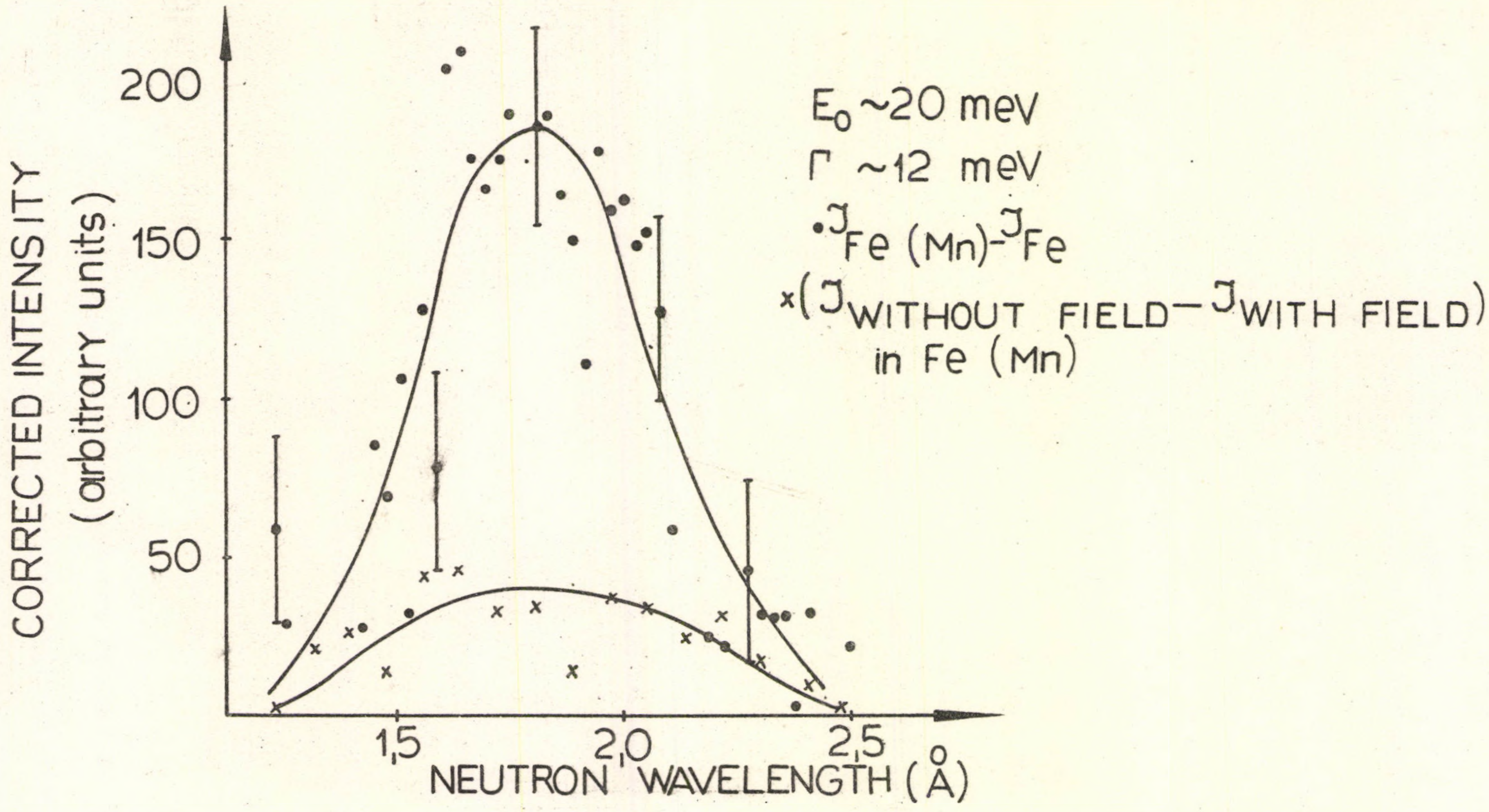

Fig. 1 Intensity distribution in Fe/Mn/ at $\vartheta = 26^{o}$ due to incoherent scattering by a virtual level. The change when applying an $\underline{e} \perp \underline{m}$ magnetic field is also plotted.

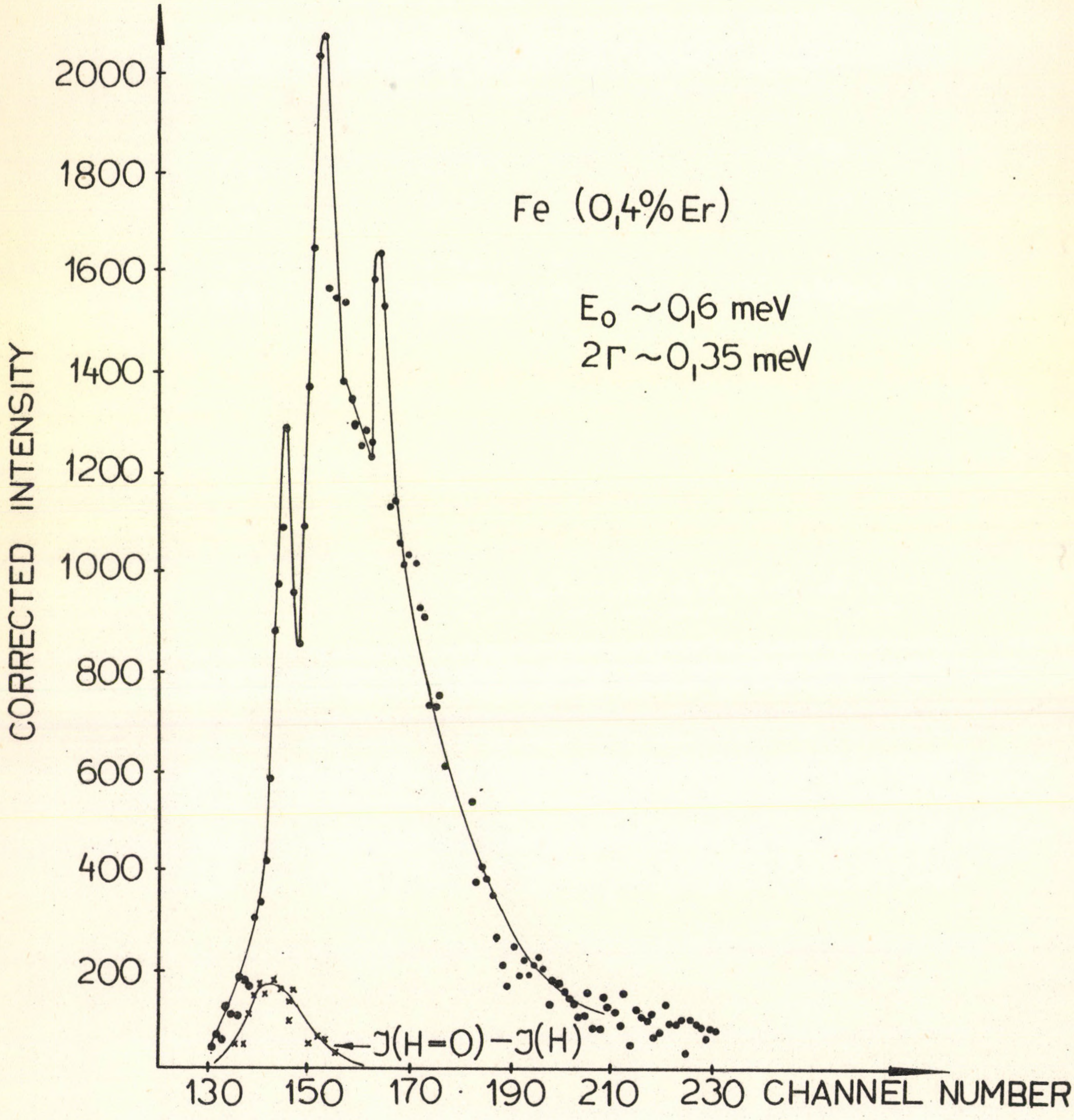

Fig. 2 Time of flight spectrum in Fe/Er/ at $\vartheta = 10^{o}$.

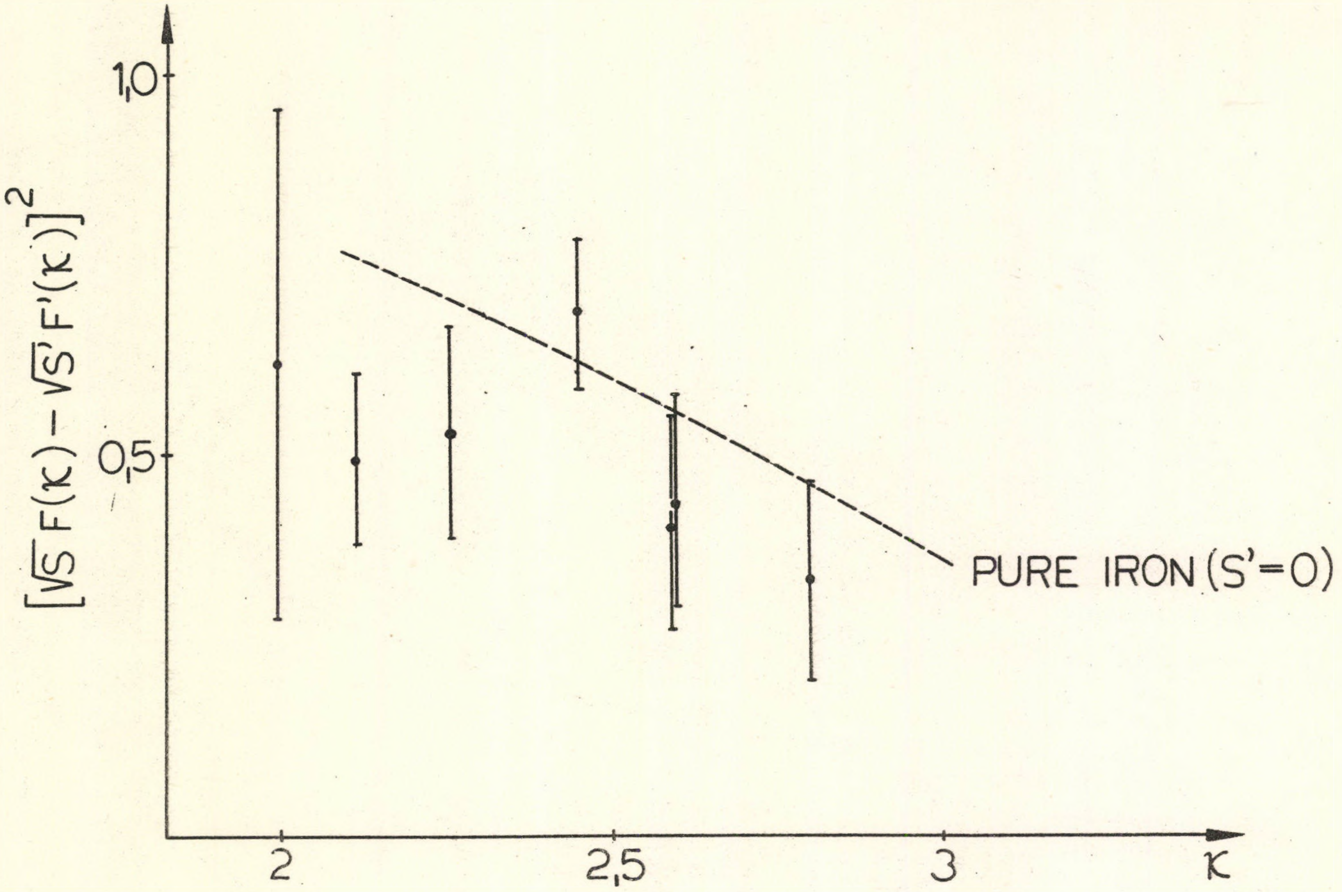

Fig. 3 Angular distribution of the total intensity of neutrons scattered by the virtual level in Fe/Mn/. The corresponding function of pure iron is also shown.

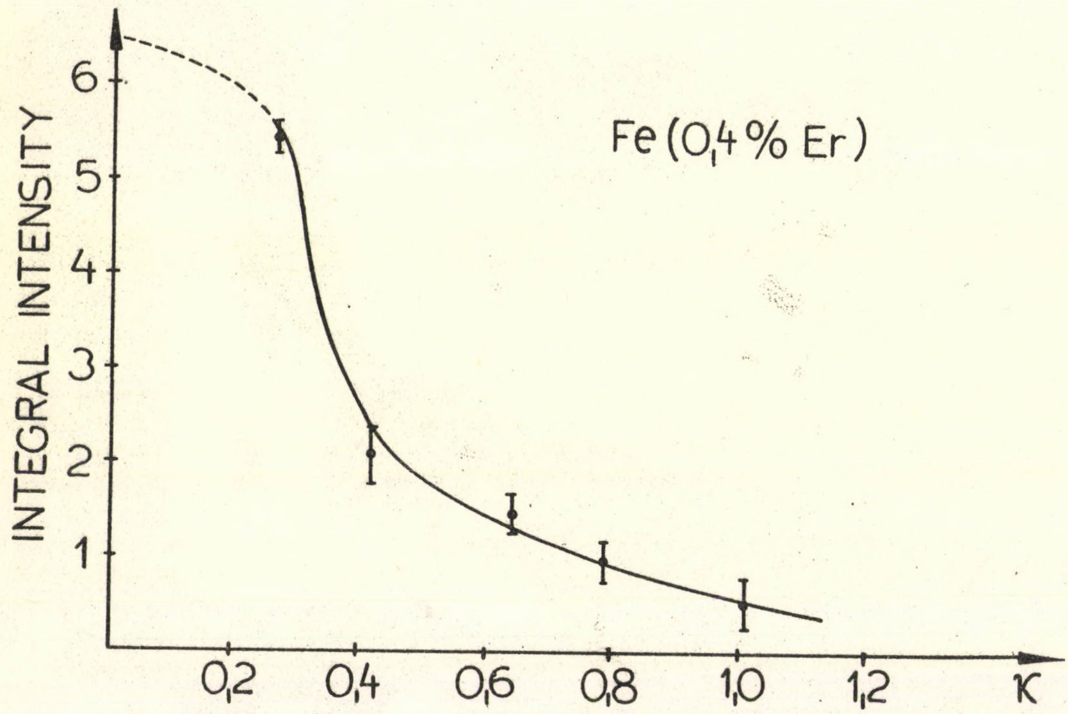

Fig. 4 Angular distribution of the total intensity in Fe/Er/.

61.767

Printed in the Central Research Institute for Physics, Budapest
Kiadja a KFKI Könyvtár- és Kiadói Osztály
o.v. dr. Farkas Istvánné
Példányszám: 115 Munkaszám: 3204 Budapest, 1967 október 10.
Készült a KFKI házi sokszorositójában
F.v.: Gyenes Imre