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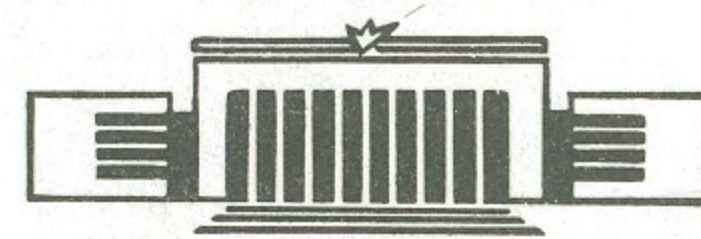


ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

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DOES P-ODD ENERGY DIFFERENCE BETWEEN
HELICOIDAL SPIN STRUCTURES EXIST?

PREPRINT 85-15



НОВОСИБИРСК

DOES P-ODD ENERGY DIFFERENCE BETWEEN
HELICOIDAL SPIN STRUCTURES EXIST?

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Abstract

Parity nonconserving energy difference between crystals with right- and left-hand helicoidal spin structures is shown to exist, contrary to the arguments of Ref. [4]. A simple estimate for the magnitude of the effect is given.

In Refs. [1,2] we have shown that when parity is violated, a static P-odd potential of the type

$$U(\vec{R}_{ij}) = (\vec{J}_i \times \vec{J}_j) \cdot \vec{R}_{ij} \cdot f(R_{ij}) \quad (1)$$

arises between atoms or ions. Here \vec{J}_i is the angular momentum of an atom or ion located at the point \vec{R}_i , and the function f decreases like a power of the distance $R_{ij} = |\vec{R}_{ij}| = |\vec{R}_i - \vec{R}_j|$. For ions in metals the effect was shown to arise mainly due to the weak interaction between the conduction electrons and the nuclei. An explicit expression was obtained for this potential in the indirect exchange model (here oscillations may be imposed on the power-like decrease of the potential). In such a way P-odd energy difference between crystals with right- and left-hand helicoidal spin structures arises. Its order of magnitude reaches ~ 100 Hz per ion in rare-earth metals. As it was emphasized in Ref. [2], this estimate allows one to be optimistic about the possibility to observe experimentally the discussed effect. The corresponding experiments are going on already [3].

But some time ago we have come across a recent paper [4] where P-odd effects in metals are also considered. In particular, the influence of parity nonconservation on the phenomena caused by the indirect exchange are discussed. The authors of Ref. [4] contend that the energy difference between right- and left-hand spin structures in rare-earths, predicted by us, does not arise at all in first order in P-odd electron-nucleus interaction*).

This assertion seems at once to be somewhat surprising by the following reason. A crystal with a helicoidal spin structure is a kind of a giant chiral molecule. And the existence of the P-odd energy difference between optical isomers

*) Moreover, it is said in Ref. [4] that this difference arises in second order in P-odd interaction. It is quite clear however that a pseudoscalar correction to energy cannot in principle be quadratic in a pseudoscalar perturbation.

is now firmly established theoretically. (By the way, there was a time when this fact was also questioned repeatedly although in a folklore form only).

In the present note we wish to consider the corresponding arguments of Ref. [4] and to show that they do not disprove our conclusion about the existence of the effect.

We start from some sufficiently general considerations. In the absence of the weak interaction, the energy of a crystal with a helicoidal spin structure is described by an even periodic function $F_0(\alpha)$ of the angle α through which the spins of ions are rotated on going from one basal plane to another. This function has minima of equal depth at $\alpha = \pm \alpha_0$, and of course at the angles differing from $\pm \alpha_0$ by $2\pi n$. Due to parity nonconservation, a term in the energy of a crystal arises described by an odd periodic function $F_1(\alpha)$. Such a correction naturally makes the depths of the minima at $\pm \alpha_0$ different.

The situation when at $F_1(\alpha) \neq 0$ this difference between equilibrium energies of crystals with right- and left-hand spin helices does not arise, is an exceptional one and demands some special relation between the functions $F_0(\alpha)$ and $F_1(\alpha)$. The assertion of Ref. [4] that the effect is absent, is grounded just on the fine-tuning between the functions, on the relation

$$F_1(\alpha) = \gamma \frac{dF_0(\alpha)}{d\alpha} \quad (2)$$

between them; here $\gamma \ll 1$ is a small dimensionless parameter. Then the total energy of a crystal equals

$$F(\alpha) = F_0(\alpha) + F_1(\alpha) \approx F_0(\alpha + \gamma) \quad (3)$$

so that the weak interaction only shifts the locations of the energy minima, but does not change their depth.

However, this fine-tuning is in fact no law of nature, but only a result of the approximation made in Ref. [4] for the calculation of $F_1(\alpha)$. The approximation consists essentially in

the weak interaction of an electron with nuclei

$$W(\vec{z}) = \frac{G}{\sqrt{2}} \frac{Q}{4m} \sum_i \{ (\vec{\sigma} \vec{p}) \delta(\vec{z} - \vec{R}_i) + \delta(\vec{z} - \vec{R}_i) (\vec{\sigma} \vec{p}) \} \quad (4)$$

being "smeared out" over the entire crystal:

$$W(\vec{z}) \rightarrow \frac{G}{\sqrt{2}} \frac{Q}{2m} \frac{1}{V_0} (\vec{\sigma} \vec{p}). \quad (5)$$

Here G is the Fermi weak interaction constant; Q is the "weak" charge of the nucleus connected with the parameter q from Ref. [2] by the relation $Q = 2Zq$; \vec{z} , \vec{p} , $\vec{\sigma}$ and m are, correspondingly, the coordinate, momentum, spin and mass of electron; \vec{R}_i is the coordinate of the lattice site; V_0 is the volume per ion in the crystal. To make the things simpler we do not take into account here an enhancement factor arising due to the difference between the conduction electron density at the nucleus and its average density over the crystal.

The discussed contribution to P-odd crystal energy arises in third order perturbation theory: in first order in W and in second order in the exchange interaction between conduction electrons and electrons of the unfilled ion shells

$$V(\vec{z}) = -\frac{1}{2} \mathcal{J} V_0 \sum_i (\vec{\sigma} \vec{S}_i) \delta(\vec{z} - \vec{R}_i). \quad (6)$$

Here \vec{S}_i is the spin of an ion located at the point \vec{R}_i ; \mathcal{J} is the exchange integral. The resulting expression for $F_1(\alpha)$ is reduced to a triple sum over lattice sites. In our paper [2] it was shown (see formulae (34)-(40) of Ref. [2]) that the contribution to the sum found in the approximation (5) does not exceed some per cent of the true value and is of the opposite sign.

Therefore, the approximation (5) used in Ref. [4] is completely inadequate for the calculation of the P-odd correction $F_1(\alpha)$ to the energy of a crystal with helicoidal spin structure.

The main contribution to the discussed triple sum is gi-

ven by the terms of another kind, those where a "weak" site coincides with one of "exchange" sites. This contribution is not only dominating numerically, it leads to quite different dependence of the P-odd energy F_1 on the angle α , so that no fine-tuning is left. The energies of right- and left-hand spin structures are indeed different. It is especially obvious for the terms of the most interesting type (see formulae (25), (30)-(33) of Ref. [2]) where the effective interaction (1) between ions depends on the distance as follows

$$U(\vec{R}_{ij}) \sim (\vec{J}_i \times \vec{J}_j) \vec{R}_{ij} / R_{ij}^4. \quad (7)$$

Such a long-range interaction leads to the contribution to the crystal energy with quite nontrivial dependence on the angle α :

$$F_1(\alpha) \sim \frac{\alpha}{|\alpha|} - \frac{\alpha}{\pi}, \quad -\pi < \alpha < \pi. \quad (8)$$

(In our paper [2] the explicit form of this function is presented for the case $|\alpha| \ll 1$ only: $F_1(\alpha) \sim \alpha/|\alpha|$. But in the numerical result given in Ref. [2] the dependence on α is completely taken into account). With such a function $F_1(\alpha)$ one cannot have any doubt that the energies of right- and left-hand spin helices are different. One can check easily that other terms arising from the coincidence of "weak" and "exchange" sites in the aforementioned triple sum (see formulae (4), (26)-(29) of Ref. [2]) also give nonvanishing contribution to the discussed energy difference. Therefore, although we indeed have overlooked that one of the contributions to $F_1(\alpha)$ does not split the values of energy minima, our conclusion about the existence of the P-odd energy difference between right- and left-hand spin structures remains valid. Moreover, due to the smallness of the overlooked contribution our result does not change in practice quantitatively.

Since the fact of the existence of the energy difference between crystals with right- and left-hand spin helices is established, it is easy to give a quite simple estimate of its

magnitude. Note for it that the Néel temperature T_N (i.e., the temperature of the phase transition paramagnetic-antiferromagnetic) is equal by an order of magnitude to the energy of the indirect exchange arising in second order in the interaction (6). In comparison with T_N the discussed energy difference contains evidently an additional small factor - the magnitude of the weak interaction on atomic scale

$$\zeta \sim \frac{G}{\sqrt{2}} \frac{m^2 \alpha^2 Q Z^2 R}{\pi}. \quad (9)$$

Here $\alpha = e^2 = 1/137$; Z is the charge of a nucleus; R is the relativistic correction factor which reaches the value 4.5 at $Z \approx 70$. The product $Z^2 R$ in the expression (9) just describes the difference between the wave function of a conduction electron at a nucleus and its average value over the crystal. Taking $T_N \sim 100$ K, we find that the energy difference we are interested in, constitutes by an order of magnitude

$$\zeta T_N \sim 100 \text{ Hz} \quad (10)$$

in agreement with more detailed estimates made in [2].

And at last, on the sign of the effect. In Ref. [2] there is a remark that in the free-electron approximation the left-hand spin structure is favored in energy over the right-hand one. Having formulated clearly in Ref. [2] the assumption under which this remark is valid, we readily agree with the assertion made in Ref. [4] the meaning of which may be reduced to the following: in reality the sign of the effect may be opposite.

In conclusion of this note we wish to say that its purpose is not only to clear up a theoretical question, but also to attract once more the attention of experimentalists to the interesting and important problem of the search for effects of parity nonconservation in magnetically ordered crystals.

References

1. O.L.Zhizhimov, I.B.Khriplovich. Zh. Eksp. Teor. Fiz. 82, 1026, 1982 (Sov. Phys. JETP 55, 601, 1982); Novosibirsk Institute of Nuclear Physics preprint 81-133.
2. O.L.Zhizhimov, I.B.Khriplovich. Zh. Eksp. Teor. Fiz. 84, 342, 1983 (Sov. Phys. JETP 57, 197, 1983); Novosibirsk Institute of Nuclear Physics preprint 82-119.
3. A.G.Gukasov, I.A.Zobkalo, V.I.Kozlov, V.P.Plakhtiy. Leningrad Institute of Nuclear Physics preprint N 896, September 1983.
4. C.Bouchiat, M.Mézard. J. de Phys. 45, 1583, 1984.

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СУЩЕСТВУЕТ ЛИ Р-НЕЧЕТНАЯ РАЗНОСТЬ ЭНЕРГИЙ
ГЕЛИКОИДАЛЬНЫХ СПИНОВЫХ СТРУКТУР?

Препринт
№ 85-15

Работа поступила - 28 января 1985 г.

Ответственный за выпуск - С.Г.Попов
Подписано к печати 4.02-1985 г. МН 06520
Формат бумаги 60x90 1/16 Усл.0,7 печ л., 0,6 учетно-изд.л.
Тираж 290 экз. Бесплатно. Заказ № 15.

Ротапринт ИЯФ СО АН СССР, г.Новосибирск, 90