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Noncollinear spin and orbital magnetism in actinide compounds: effects of symmetry and relativity

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The density functional theory is applied to study the nature of complex magnetic structures in various Uranium compounds: U_2Pd_2Sn, U_3X_4, UPdSn, UX_3, UPdSn and UPtGe. A general approach is developed which allows to treat principally different magnetic states of these compounds on the basis of one physical concept. This concept relates the strong spin-orbit coupling in the U systems and the symmetry of the crystal and magnetic structures to the stability of the magnetic configurations.

KEYWORDS: noncollinear magnetic structure, Uranium compounds, density functional theory

I. Introduction

Recent density-functional-theory (DFT) studies[1–9] revealed a crucial role played by noncollinear magnetism in understanding the ground state magnetic properties, excitations, spin-dynamics in various magnetic systems. In the present paper we discuss the noncollinear magnetism in U compounds and focus on one aspect of the physics of noncollinear magnetism: the interplay between the symmetry of a magnetic system, relativistic interactions and magnetic structure.

II. Density functional theory of a noncollinear magnet

The calculational scheme used in the calculations discussed in this paper is described in earlier publications.[6,10,11] An important feature of this scheme is an allowed variation of the directions of the atomic moments from iteration to iteration: The eigenstates of the Kohn-Sham Hamiltonian (KSH), ψ, are used to calculate the density matrix

$$\vec{\rho}(\vec{r}) = \sum_{i,occ} \psi_i(\vec{r})\psi_i^{\dagger}(\vec{r}) \qquad (1)$$

After integration of (1) over atomic spheres one gets the atomic matrices.[10] Diagonalization of the atomic matrices gives the directions of the atomic magnetic moments corresponding to these matrices. In general, calculated directions of the atomic moments are different from the directions used in the formulation of the KSH at the beginning of the iteration. In the self-consistent state, the initial and calculated directions of atomic moments coincide.

III. Relation between symmetry and stability of magnetic structures

The relation between the symmetry of a system and its magnetic structure attracted much attention in the history of solid state magnetism. Much consideration was given to the prediction of the magnetic structures which can appear in the system as the result of a continuous phase transition. We will focus on another aspect of the relation between the symmetry and magnetic structure: the stability of a given magnetic configuration, independent of the kind of the phase transition into magnetic state. Applications of the DFT to the studies of complex noncollinear magnetic configurations have shown that the magnetic structure chosen at the beginning of the DFT calculation is, in general, unstable: the magnetic moments deviate in the course of iterations from the initial directions tending to form another magnetic state. On the other hand, in some cases the magnetic moments, although allowed to move, keep their initial directions. The ability to predict to which of the two types of structures a given magnetic configuration belongs is an important help in the study of the magnetism of the system.

In an earlier publication[2] it was shown that there exists an intimate connection between the stability of the magnetic structure in the DFT calculations and the symmetry of the system. Here we discuss application of the symmetry principles and the DFT calculations to the studies of the properties of various U compounds. We begin with the formulation of the symmetry principle.

It can be shown[12] that the symmetry of the initial Kohn-Sham Hamiltonian is preserved in the iterational DFT calculations. For nonrelativistic problems the operations are of the $\{\alpha_S|\alpha_R|\vec{t}\}$ type where α_S is a spin rotation, α_R is a space rotation, $\vec{t}$ is a space translation.[6] In the case of relativistic problems α_S is always equal to α_R and the operators are of the $\{\alpha_R|\alpha_R|\vec{t}\} \equiv \{\alpha_R|\vec{t}\}$ type.[6] In both cases these transformations can be accompanied by the time reversal.

We will distinguish two types of magnetic configurations. In the first case, the symmetry determines the magnetic structure uniquely. This means that any deviation of the magnetic moments from the initial directions disturbs, at least, one of the symmetry operations. Since all symmetry operations must be preserved the structure cannot change in the course of calculations. We will refer to this type of structures as type-I structures. **(Fig. 1)**.

In the second case (type-II structures) there is an infinite set of magnetic configurations which, first, possess the same symmetry operations and, second, can be continuously transformed into one another. Let θ be a continuous parameter which describes this set of magnetic configurations. (The number of parameters can be larger than one, but this does not change the essence of arguments.) As all magnetic configurations are described by the same symmetry none of the θ values is distinguished. The purpose of the DFT calculations

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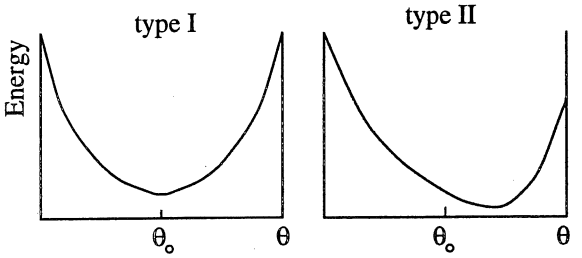

Fig. 1 Type-I and type-II structures (schematic picture). Continuous parameter θ describes different magnetic configurations. (a) The state with $\theta = \theta_0$ corresponds to the type-I structures. (b) Type-II structures. The states with different θ possess the same symmetry. Probability that θ_0 accidentally coincides with θ_{min} is negligible.

in this case is to find the value of θ which corresponds to the state with the lowest energy. Since all θ values are equivalent, this minimum cannot be predicted without calculations (Fig. 1).

To begin the DFT calculation a value θ_0 of parameter θ is selected. Since it is improbable that θ_0 accidentally equals θ_{min} providing the minimum of the total energy the initial state in the case of type-II structure is unstable. In the iterational process, the magnetic structure deviates from the state described by θ_0 tending to assume the state with the lowest energy.

The type-II structures are related to many interesting physical phenomena. In a typical case the neglect of a part of interactions leads to the magnetic ground state of the system which belongs to type I and, therefore, is uniquely determined by symmetry. With account for the full Hamiltonian this state corresponds, however, to type II. Therefore in the full-Hamiltonian study it becomes unstable and a variation of the state must take place. Examples of such systems are, e.g., Fe_2O_3 and Mn_3Sn where the SOC leads to the phenomenon of weak ferromagnetism.[6]

It is important to distinguish between the stability in the DFT calculations and the stability in the nature. Magnetic configurations stable in the calculations may not necessarily be the physical ground state, since random fluctuations characteristic for real systems are absent in the DFT calculations. On the other hand, the instability of a magnetic state in the DFT calculations can be directly related to the instability in nature, because this instability is a consequence of the interactions in the system. The latter property is of primary importance for the discussion of concrete physical systems in the next sections.

IV. Stable magnetic structures in U_2Pd_2Sn and USb

First, we consider examples of magnetic structures distinguished by symmetry relative to the structures obtained by infinitesimal variation of the directions of atomic moments.

The crystallographic unit cell of the U_2Pd_2Sn compound is shown in **Fig. 2**. The magnetic state of U_2Pd_2Sn was established by Purwanto *et al.*[13] who considered six magnetic structures shown schematically in Fig. 2 in the analysis of the neutron diffraction data. These six structures were selected on the basis of the symmetry arguments of the Landau theory of the second order phase transitions. The noncollinear magnetic configuration NC1 was found to be the magnetic ground state of the system.

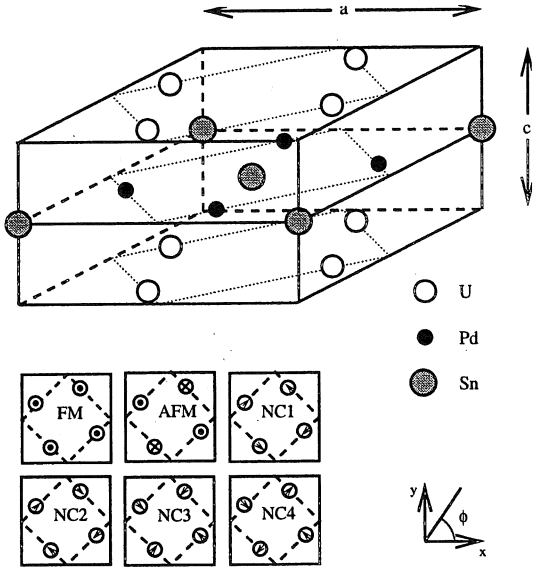

Fig. 2 Unit cell of the U_2Pd_2Sn crystal structure. The six magnetic structures studied are indicated.

We performed the DFT calculations for all six magnetic configurations.[2] All of them correspond to type I and are stable in the calculations. For example, the magnetic structure NC1 possesses the following symmetry operations: (a) the 180° rotation about the z axis, (b) the 180° rotation about the $x = y$ axis, (c) the 90° rotation about the z axis accompanied by inversion, (d) the 90° rotation about the z axis accompanied by time reversal. (Only the generators of the symmetry group are given.) If the coordinate center is chosen at the position of the central Sn atom (Fig. 2) operation (b) is accompanied by non-primitive translation $a(0.5, 0.5, 0)$. Other operations are pure point transformations. Any infinitesimal deviation of the magnetic moments destroy the invariance of the system with respect to at least one of the symmetry operations. This additional symmetry of the NC1 structure is illustrated in **Fig. 3** where we show the total energy of the magnetic structures obtained by the rotation the NC1 structure by different angles about the z axis. The structure NC1 can be transformed into NC4 by a rotation by 90° about the z axis.

Another example of a stable magnetic state is a so-called triple-$\vec{k}$ magnetic structure in USb. The picture and the list of the symmetry operations of this structure can be found in the paper by Knöpfle and Sandratskii.[14]

In the next sections we consider relativistic instabilities of the magnetic structures.

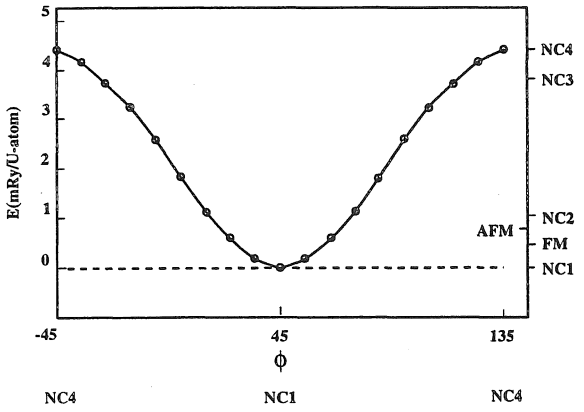

Fig. 3 Total energy of U_2Pd_2Sn as a function of ϕ calculated with SOC (solid line) and without SOC (dashed line). On the right hand side the energies of the six magnetic structures (see Fig. 2) are indicated.

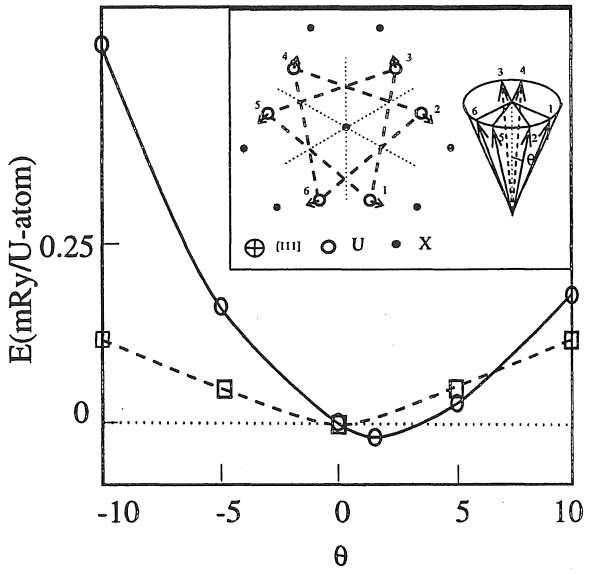

Fig. 4 The total energy of U_3P_4 as a function of the deviation of the magnetic moments from the (111) axis. Solid/dashed line shows the result of the calculation with/without the spin-orbit coupling. The inset shows the projection of the crystal and magnetic structure to the (111) plane. The magnetic moments form a cone structure.

V. Relativistic instability of collinear ferromagnetism. The case of U_3P_4

In nonrelativistic systems, collinear magnetic configurations are always stable in the calculations. The symmetry operations responsible for the stability of this regularity are the pure spin rotations about the magnetization axis.[6] In the relativistic case, such operations cannot be symmetry operations of the system. The pure spin rotations are not the only symmetry operations that can be responsible for the stability of a collinear magnetic state. If, however, the system possesses none of the symmetry operations responsible for the stability of a collinear magnetic configuration, this structure must be unstable. For example, any relativistic magnetic structure with atomic disorder is noncollinear.[12]

The inset in **Fig. 4** shows the experimentally determined magnetic structure of U_3P_4. The atomic moments form a cone with the axis parallel to the (111) axis. The system possesses a strong ferromagnetic component. The DFT calculation started with all U moments parallel to the (111) axis results immediately in the noncollinear magnetic structure similar to the structure found in the experiment.[2] Analysis of the symmetry of the system shows that the deviation of the magnetic moments does not influence the symmetry of the magnetic structure. Therefore we deal here with a type-II structure and the initial collinear structure must be unstable. The minimum of the total energy is at an accidental point. With the SOC being neglected the curve of the total energy as a function of the deviation angle θ is symmetrical with respect to the change of the sign of θ (Fig. 4).

VI. Relativistic instability of collinear antiferromagnetic structures. The case of UPdSn

Next we discuss an example of the relativistic instability of a collinear antiferromagnetic structure.

Much attention was attracted by two magnetic phase transitions[15,16] in UPdSn. The paramagnetic state has the hexagonal GaGeLi crystal lattice. Below 45 K UPdSn becomes magnetic with a noncollinear antiferromagnetic structure. In this phase all magnetic moments of the Uranium atoms lie parallel to a plane and compensate one another completely. Simultaneously orthorhombic lattice distortions are detected. At 20 K a second phase transition is observed. Here the magnetic structure is still noncollinear and compensated, however, the magnetic moments deviate from the plane developing components perpendicular to it.

The calculations[17] were started with the undistorted hexagonal lattice and uranium magnetic moments directed along the z axis and forming a collinear antiferromagnetic structure (**Fig. 5**). Allowed to rotate, the moments deviated immediately from the z axis keeping however their equivalence and the compensated character of the magnetic structure. The resulting self-consistent directions of the magnetic moments are shown in Fig. 5a; they form a magnetic structure which is very similar to the experimental structure. The symmetry principle, formulated above helps us to expose the physical reasons for the instability of the initial collinear structure.

The analysis of the restrictions imposed by the symmetry operations[17] on the directions of the magnetic moments shows that m_x^i=0 for each atom i. For other two components the following conditions must be satisfied: $m_y^1 = m_y^2 = -m_y^3 = -m_y^4$ and $m_z^1 = -m_z^2 = m_z^3 = -m_z^4$. This means that the initial collinear structure has the same symmetry as a noncollinear structures satisfying these relations. The noncollinear magnetic structure detected experimentally belongs to this type of structures. Thus we again deal with the case of type-II structure.

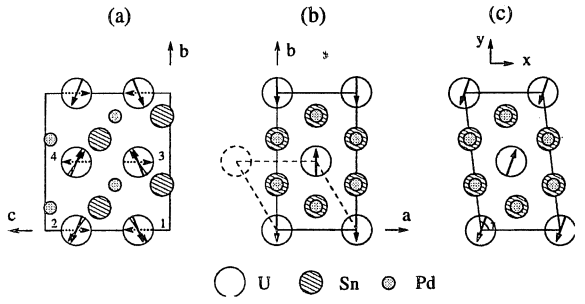

Fig. 5 Projections of the crystal and magnetic structure onto the xy and yz planes. (a) Projection of the orthorhombic unit cell onto the yz plane. Dotted arrows show the initial magnetic structure used to start the calculation, thick arrows show the resulting self-consistent directions of the magnetic moments. Thin arrows show the experimental magnetic structure. (b) Projection of the orthorhombic unit cell onto the xy plane. Both experimental and theoretical projections of the magnetic moments are parallel to the y axis. (c) Projection of the monoclinic unit cell onto the xy plane. Arrows show schematically the deviations of the magnetic moments from the yz plane.

Next the influence of lattice distortions on the magnetic structurewas was studied.[17] First, following the experiment[16] we introduced a small variation of the lattice parameters a and b such that the relation $b = \sqrt{3}a$ valid for the ideal hexagonal lattice is no longer satisfied. This distortion does not affect the symmetry of the system because the magnetic structure has already lowered the symmetry of the crystal from hexagonal to orthorhombic. As a result no qualitative changes of the magnetic structure were observed due to the orthorhombic lattice distortion and quantitative changes appeared to be very small,too.

A basically different response was obtained to the monoclinic distortions.[17] In agreement with experiment the b-side of the basal rectangle (Fig. 5) was rotated by 0.4° about the c axis. We started the calculations with the magnetic structure of the undistorted lattice. Already after the first iteration all Uranium magnetic moments deviated from the yz plane staying however mutually equivalent. The compensating character of the magnetic structure was also preserved.

Again, a symmetry analysis helps to understand this process. The monoclinic distortion decreases the symmetry of the system such that only a half of the of the symmetry operations of the orthorhombic structure are left over in this case.[17]

VII. Intersublattice interaction in UFe_4Al_8

For a number of years the magnetic structure of UFe_4Al_8 was the matter of much controversy.[18,19] Recent investigation of a single crystal of UFe_4Al_8 with the use of unpolarized and polarized neutron diffraction revealed an ordered magnetic structure with a number of unique features[19] **(Fig. 6)** . Two magnetic sublattices were detected. The magnetic moments of the U sublattice form a collinear ferromagnetic structure. A strong noncollinearity is, however, observed between the U and Fe magnetic moments which are almost orthogonal to one another. The magnetic structure of the Fe sublattice is close to a collinear antiferromagnetic Additionally, there is a canting of the Fe moments which leads to the second type of noncollinearity in UFe_4Al_8. The noncollinearity within the Fe sublattice results in a weak ferromagnetic moment parallel to the U moments.

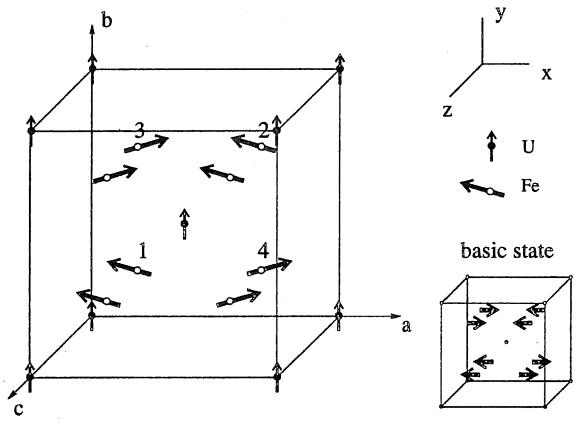

Fig. 6 Experimental magnetic structure and basic magnetic state of UFe_4Al_8

We have shown[20] that the complex noncollinear magnetic structure of UFe_4Al_8 is a necessary consequence of the properties of a much simpler magnetic state with collinear antiferromagnetism of the Fe sublattice and nonmagnetic U sublattice (Fig. 6). To stress the importance of this state for understanding of the magnetism of UFe_4Al_8 we refered to it as the basic state (BS).

The BS possesses a number of regular features: the Fe atoms have equal magnetic moments, these magnetic moments are collinear, the magnetic moment of the U atoms has the value of zero. We emphasize that the property that the U moment is equal to zero must be considered as a regular feature of the system which can be stable only in the case that there exists a symmetry operation which is responsible for the stability of this feature in the sense of our symmetry criterion.

The DFT calculation started with the BS[20] shows immediately that two of these three regular features are not preserved by the system: An induced moment appear at the U site. It is orthogonal to the initial directions of the Fe moments. Simultaneously the Fe moments deviate from their collinear directions and form a canted noncollinear configuration. Thus the BS is transformed into the complex magnetic state observed experimentally. Symmetry analysis helps to understand the origin of this transformation. All symmetry transformations[20] of the BS of UFe_4Al_8 leave m_y invariant. As a direct consequence of this property the appearance of a magnetic moment parallel to the y axis at the U sites does not disturb any of the symmetry operations. Therefore we deal here with type-II structure where the value of the U magnetic moment plays the role of the variable parameter. The symmetry predetermined instability of the nonmagnetic state of the U atoms is illus-

trated by the properties of the total energy as a function of m_y (**Fig. VII.**). The most important feature of the $E(m)$ curve is its asymmetry which leads to an accidental position of the minimum at a non-zero value of m_y.

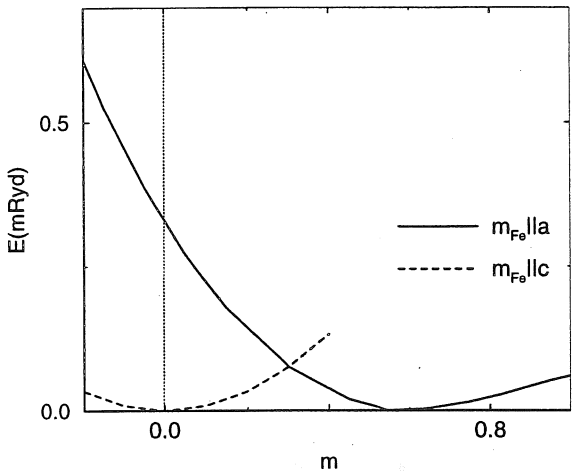

Fig. 7 Total energy as a function of the U spin moment for the Fe moments collinear to the a (basic state) and c axes. For the Fe moments parallel to the c axis no induced U moment appears

The orthogonality of the inducing and induced moments is also closely connected with the symmetry properties of the system since appearance of a nonzero m_x or m_z component of the U moment would disturb at least one of the symmetry operations of the BS. We emphasize that the symmetry analysis and DFT calculations reported in this section were performed with account for the SOC. With the SOC neglected none of the effects discussed here appear and the BS is stable.

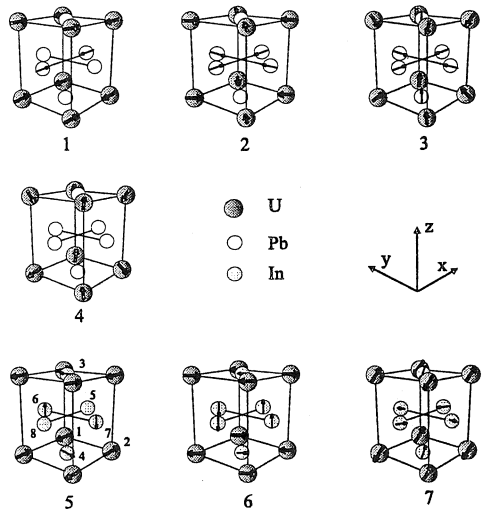

Fig. 8 Models for the magnetic structure of UX_3 compounds.[21] The induced magnetic moments on sites which follow from the symmetry analysis are shown.

VIII. Magnetic structure of UX_3 compounds

We have shown[21] that the relation between the inducing and induced moments which follows from the symmetry analysis discussed in the previous sections can be helpful in the determination of the magnetic structure of the inducing subsystem. In UX_3 the neutron diffraction did not provide complete information about the magnetic structure of the U sublattice. Since, according to our symmetry principles, different directions of the U magnetic moments result in different properties of the induced moments of the X atoms, the study of the induced moments provides information about the magnetic structure of the U sublattice. Measuring the hyperfine field on the positions of X atoms with, for example, perturbed-angular-correlation technique allows to draw the conclusions about the induced moments. **Figure 8** illustrates the properties of induced moments of the X atoms for different orientations of the U moments. (See the paper by Demuynck *et al.*[21] for all details of the study of the magnetic structure of UX_3 compounds.)

IX. Helical structures in systems with relativistic interactions

Here we discuss an example of an actinide system where a helical magnetic structure was reported to be observed.

In accordance with the experimental situation we consider plane helical magnetic structures of the form

$$\vec{e}_\nu^{\,\vec{q}} = (\cos(\vec{q}\vec{a}_\nu + \phi_o), 0, \sin(\vec{q}\vec{a}_\nu + \phi_o)) \qquad (2)$$

where $\vec{a}_\nu$ the positions of the U atoms and $\vec{q}$ is the helix vector. Although not periodic with the underlying lattice periodicity, the helical structure is very regular. This regularity can be described by the generalized translations[6] which combine lattice translations $\vec{R}_n$ with spin rotations by $\vec{q}\vec{R}_n$ about the y axis. The scalar-relativistic Hamiltonian of the helix commutes with the generalized translations.[6] This symmetry is crucial for the stability of the regularities characteristic for a helix.

The spin-orbit coupling term of the Hamiltonian does not commute with the generalized translations. Therefore the relativistic Hamiltonian cannot be invariant with respect to the generalized translations. This leads to the instability of the incommensurate helical structures for the systems where the SOC plays important role in the formation of the magnetic structure.

In actinide systems the SOC is very strong. The considerable spatial extent of the 5f electron states enhances the influence of the SOC on the directions of the atomic moments. This property is confirmed by the observation of a large magnetic anisotropy[22] in almost all actinide compounds. Taking into account the influence of the SOC on helical structures, the formation of a helix in U compounds can be considered as highly improbable.[6,23] This conclusion seems to be in good agreement with the experimental observations. There is, however, one exception: UPtGe was reported to possess a helical ground-state structure.[24,25] An understanding of the nature of the unique magnetism of UPtGe is essential for the physics of incommensurate magnetic structures. The explanation of

the properties of UPtGe is suggested by Sandratskii and Lander.[26]

Two different types of helices are known. The first type is formed, e.g., in fcc-Fe and REM and results from the properties of the exchange interactions. As stated above such a helix can be formed only in the case the MA is much weaker than the interatomic exchange interactions.

In apparent contradiction to the arguments above the second type of helices is formed because of the influence of SOC, e.g. the helix in MnSi.[27,28] The exchange interaction in MnSi favors a collinear ferromagnetic ordering. To explain the formation of the helix in MnSi a model Hamiltonian was used[27] which in addition to the exchange interaction contains the Dzialoshinski-Moriya interaction (DMI) $\vec{D}(\vec{S}_1 \times \vec{S}_2)$. Although the DMI is a consequence of the SOC, the simultaneous rotation of all atomic moments about the direction of the $\vec{D}$ vector does not change the energy of the system. This property of the DMI allows the symmetry of the system with respect to the generalized translations, which is a necessary condition for the stability of helical structures. To allow the formation of the helical structure of the MnSi type the SOC must be present, but the magnetic anisotropy must be smaller than the DMI.

Table 1 Magnetic anisotropy in UPtGe

	mRyd/U atom
$E_{FM}(010)$-$E_{FM}(100)$	1.5
$E_{FM}(010)$-$E_{FM}(001)$	1.4
$E_{FM}(001)$-$E_{FM}(100)$	0.1
$E_{AFM}(010)$-$E_{AFM}(100)$	1.3
$E_{AFM}(010)$-$E_{AFM}(001)$	1.2
$E_{AFM}(001)$-$E_{AFM}(100)$	0.1

Since for both types of helices the smallness of the magnetic anisotropy is important, we studied this quantity (**Table 1**). Calculations show that the MA in the xz plane is very small. Since the SOC is strong and there is no symmetry reason for the smallness of the in-plane anisotropy this property results from an accidental compensation of the contributions of different electron states.

The weakness of the in-plane magnetic anisotropy is a necessary condition for the formation of the helical structure. It does not, however, provide the physical mechanism leading to the formation of the helix. In **Fig. 9** we show the q dependence of the total energy which was calculated neglecting the SOC. A clear trend to the formation of the helix with an incommensurate q value close to 0.5 is obtained.

On the basis of the Fourier transformation of the $E(q)$ curve the following qualitative picture of the magnetism of UPtGe was suggested. The U positions in UPtGe form a structure rather close to a simple hexagonal (**Fig. 10**). The effective exchange interaction between the magnetic moments of atoms 0 and 2 is strong and antiferromagnetic. The exchange interaction of the magnetic moments of atoms 1 and 3 with the moments of atoms 0 and 2 is much weaker. Evidently the antiparallel directions of the moments 0 and 2 lead to the frustration of the direction of the moments 1 and 3. The frustrated magnetic interactions are the reason for the minimum of the total energy at an incommensurate q value (Fig. 9). This result suggests to consider the helical magnetic structure in UPtGe as an exchange helix.

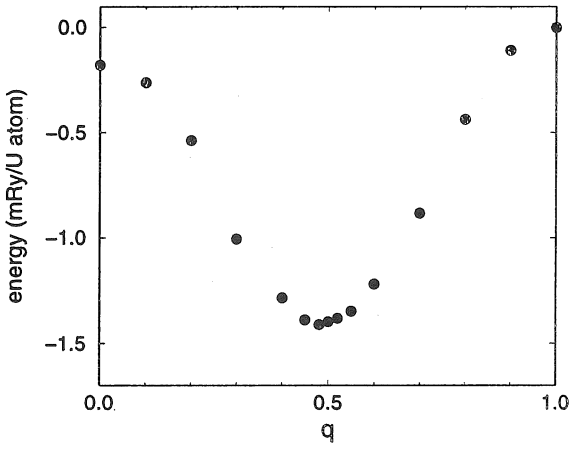

Fig. 9 Energy as a function of $\vec{q} = (q, 0, 0)$

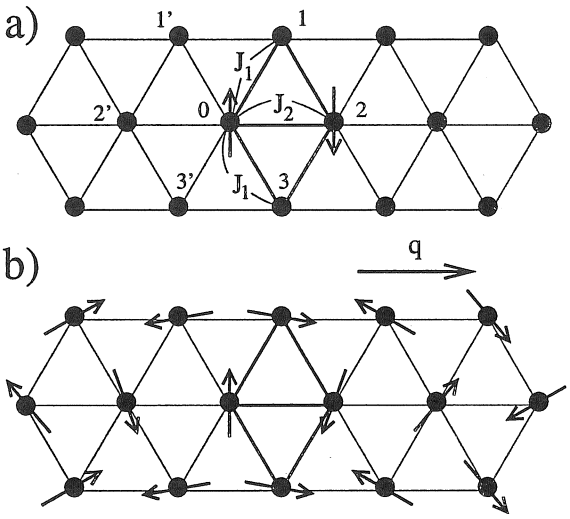

Fig. 10 Frustrated magnetic interactions. a) $|J_2| << |J_1|$. b) Helical magnetic structure as a consequence of the frustration.

One further remarkable experimental feature of UPtGe is, however, the observation of the domains of only one chirality.[25] This property is characteristic of the relativistic helices of the MnSi type.[28] We have shown[26] that the inequivalence of the domains of opposite chirality in UPtGe is a result of the SOC which leads to a substantial DMI in the system. Summarizing, an accidentally small in-plane magnetic anisotropy provides a necessary condition for the formation of the incommensurate helix. The formation and properties of the helix are determined by the frustrated exchange interactions and relativistic DMI. The magnetic structure of UPtGe cannot be classified either as a pure exchange or pure relativistic helix

but possesses the features of both.

X. Intraatomic magnetic noncollinearity

Another type of the magnetic noncollinearity is the noncollinearity of the spin and orbital magnetic moments of the same atom.[4,23,29] The collinearity of both atomic moments must be considered as a regularity in the system which, according to our symmetry principle, is possible only in the case that there is a symmetry operation which is responsible for this regularity. In all cases where *interatomic* magnetic noncollinearity is predetermined by symmetry (type II structure) the atomic spin and orbital moments are also noncollinear.

XI. Conclusion

Summarizing, we have shown that the spin-orbit coupling plays an important role in the formation of the magnetic structure and properties of Uranium compounds. The modern methods of the density functional theory allow to study these effects within a parameter-free calculational scheme. We have shown that the analysis of the symmetry aspects of the problem is very helpful in the predicting and understanding complex magnetic structures in systems with strong relativistic interactions.

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References

1) V. P. Antropov, M. I. Katsnelson, M. van Schilfgaarde, *et al.*, Phys. Rev. Lett., **75**, 729 (1995).
2) L. M. Sandratskii, J. Kübler, Phys. Rev. Lett. **75**, 946 (1995).
3) L. Nordström, D. J. Singh, Phys. Rev. Let. **76**, 4420 (1996).
4) I. Solovyev, N. Hamada, K. Terakura, Phys. Rev. Lett. **76**, 4825 (1996).
5) L. M. Sandratskii, J. Kübler, Phys. Rev. Lett. **76**, 4963 (1996).
6) L.M. Sandratskii, Advances Phys., **47**, 91 (1998).
7) M. van Schilfgaarde, I. A. Abrikosov, B. Johansson, Nature **400**, 46 (1999) .
8) M. Pajda, J. Kudrnovsky, I. Turek, *et al.*, Phys. Rev. Lett. **85**, 5424 (2000).
9) Ph. Kurz, G. Bihlmayer, K. Hirai, *et al.*, Phys. Rev. Lett. **86**, 1106 (2001).
10) J. Sticht, K. H. Höck, J. Kübler, J. Phys.: Condens. Matter **1**, 8155 (1989).
11) L. M. Sandratskii, J. Kübler, Phys. Rev. B **55**, 11395 (1997).
12) L. M. Sandratskii, Phys. Rev. **64**, 134402 (2001).
13) A. Purwanto, R. A. Robintson, L. Havela, *et al.*, Phys. Rev. **50**, 6792 (1994)
14) K. Knöpfle, L. M. Sandratskii, Phys. Rev. B **63**, 14411 (2001).
15) F. R. de Boer, E. Brück, H. Nakotte, *et al.*, Physica B **176**, 275 (1992). R. A. Robinson, A. C. Lawson, J. W. Lynn, *et al.*, Phys. Rev. B **45**, 2939 (1992). R. A. Robinson, J. W. Lynn, A. C. Lawson, *et al.*, J. Appl. Phys. **75**, 6589 (1994). R. Troc, V.H. Tran, M. Kolenda, *et al.*, J. Magn. Magn. Mater. **151**, 102 (1995).
16) R. A. Robinson, A. C. Lawson, J. A. Goldstone, *et al.*, J. Magn. Magn. Mater. **128**, 143 (1993).
17) L. M. Sandratskii, J. Kübler, J. Phys.: Cond. Matter **9**, 4897 (1997).
18) B. Ptaciewicz-Bak, A. Baran, W. Suski, *et al.*, J. Magn. Magn. Mater. **76-77**, 439 (1988); J. Gal, I. Yaar, E. Arbaboff, *et al.*, Phys. Rev. B **42**, 237 (1989); A. V. Andreev, H. Nakotte, F. R. de Boer, J. Alloys and Compounds **182**, 55 (1992).
19) J. A. Paixão, B. Lebech, A. P. Gonçalves, *et al.*, Phys. Rev. B **55**, 14370 (1997).
20) L. M. Sandratskii, J. Kübler, Phys. Rev. B **60**, R6961 (1999).
21) S. Demuynck, L. M. Sandratskii, S. Cottenier, *et al.*, J. Phys.: Condens. Matter**12**, 4629 (2000).
22) V. Sechovsky, L. Havela, "Magnetism of ternary intermetallic compounds of uranium". In: *Handbook of Magnetic Materials*, ed. by K. H. J. Buschow, Elsevier, Amsterdam, (1998), pp. 1-289.
23) L.M. Sandratskii, J. Kübler, Mod. Phys. Lett. B **10**, 189 (1996).
24) A. Szytula, M. Kolenda, R. Troc, *et al.*, Solid State Commun. **81**, 481 (1992); R. A. Robinson, A. C. Lawson, J. W. Lynn, *et al.*, Phys. Rev. B **47**, 6138 (1993); S. Kawamata, K. Ishimoto, Y. Yamaguchi, *et al.*, J. Magn. Magn. Mater. **104-107**, 51 (1992).
25) D. Mannix, S. Coad, G. H. Lander, *et al.*, Phys. Rev. B **62**, 3801 (2000).
26) L. M. Sandratskii, G. Lander, Phys. Rev. B **63**, 134436 (2001).
27) O. Nakanishi, A. Yanase, A. Hasegawa, *et al.*, Solid State Commun. **35**, 995 (1980).
28) M. Ishida, Y. Endoh, S. Mitsuda, *et al.*, J. Phys. Soc. Japan **54**, 2975 (1985).
29) L. M. Sandratskii, J. Kübler, Europhys. Lett. **33**, 447 (1996).