

splittings of muonic atoms (for example, by methods of resonant transitions in the hyperfine structure [4]). A study of the hyperfine structure of the mesic helium atom $[(\mu^- \text{He})^+ e^-]$, which has properties close to those of muonium, provides another method of determining the fine-structure constant $\alpha = e^2/\hbar c$.

The authors thank Professor S.S. Gershtein, Corresponding Member of the USSR Academy of Sciences I.I. Gurevich, and L.I. Smilga for useful discussions and interest in the work, and also Corresponding Member of the USSR Academy of Sciences V.P. Dzheleпов and Professor L.I. Lapidus for help with the work.

- [1] V.G. Varlamov, Yu.P. Dobretsov, B.A. Dolgoshein, V.G. Kirillov-Ugryumov, and A.M. Rogozhin, ZhETF Pis. Red. 16, 318 (1972) [JETP Lett. 16, 224 (1972)].
- [2] D. Buckle, J. Kane, G. Siegel, and R. Wetmore, Phys. Rev. Lett. 20, 705 (1968).
- [3] V.G. Varlamov, Yu.P. Dobretsov, B.A. Dolgoshein, and A.M. Rogozhin, Proceedings of International Conference on Apparatus for High-energy Physics, Dubna, 1970 (p. 800).
- [4] K. Ziocck, V. Huges, R. Prepost, J. Bailey, and W. Cleland, Phys. Rev. Lett. 8, 103 (1962).

LOW-TEMPERATURE PHASE TRANSITION IN $\text{KDy}(\text{MoO}_4)_2$ PRODUCED BY THE COOPERATIVE JAHN-TELLER EFFECT

A.I. Zvyagin, T.S. Stetsenko, V.G. Yurko, and R.A. Vaishnoras¹⁾
Physico-technical Institute of Low Temperatures, Ukrainian Academy of Sciences

Submitted 2 January 1973

ZhETF Pis. Red. 17, No. 4, 190 - 193 (20 February 1973)

The investigation of the cooperative Jahn-Teller effect has been given greater attention of late, both as a result of the increased theoretical interest in the general problem of phase transition, and as a result of the recent observation of a number of new rare-earth compounds having a structural phase transition at low temperatures because of this effect (e.g., DyVO_4 [1]).

A characteristic feature of the cooperative Jahn-Teller effect in these compounds is that it appears in crystals with low structure symmetry. Unlike the previously investigated spinels, where the electron-level degeneracy due to symmetry is lifted, "randomly" degenerate electron levels can participate in the Jahn-Teller effect in this case. For example, for a dysprosium compound with low crystal-structure symmetry, the eightfold Kramers degeneracy of the ground term ${}^6\text{H}_{15/2}$ of the Dy^{3+} ion is completely lifted, but a situation is possible wherein the energies of different Kramers doublets, including the two lower ones, turn out to be equal or close at certain values of the crystal-field constant. Understandably, the "random" degeneracy of a lower level is in principle a rather rare situation, and therefore there is a small number of known low-symmetry crystals in which the cooperative Jahn-Teller effect is observed.

Judging from the calculations for the energy spectrum of the impurity ion Dy^{3+} in the $\text{KY}(\text{MoO}_4)_2$ crystal with rhombic structure symmetry, which were performed by us from results of measurements of optical, resonance, and magnetic properties [2], the energy distance between the two lower Kramers doublets in the spectrum of the ground term ${}^6\text{H}_{15/2}$ of the Dy^{3+} ion is small for this crystal. We can therefore expect an onset of the cooperative Jahn-Teller effect

¹⁾Institute of Semiconductor Physics, Lithuanian Academy of Sciences

when the concentration of the Dy^{3+} ion in such a crystal is increased. An investigation of the optical and magnetic properties of the isostructural crystals of the system $KY(MoO_4)_2 + KDy(MoO_4)_2$, the results of which are reported here, shows that the cooperative Jahn-Teller effect takes place in samples with a high Dy content (85 - 100%) and leads to a structural phase transition at $\sim 10^\circ K$. The measurement procedure is analogous to that described earlier [2].

Figure 1 shows the temperature dependence of the energy distance ΔE_{1-2} between the two lower doublets of the ${}^6H_{15/2}$ term of the Dy^{3+} ion in $KDy(MoO_4)_2$. The value of ΔE_{1-2} was determined as the distance between the absorption bands of the transitions from the aforementioned doublets to the lower level of the term ${}^6H_{13/2}$. The form of the fundamental absorption band of the transition ${}^6H_{15/2} \rightarrow {}^6H_{13/1}$ (3518 cm^{-1}) and of its satellite at temperatures 10 and $5^\circ K$ is illustrated by the insert of Fig. 1. Lowering the temperature leads to a noticeable shift of the satellite frequency at temperatures near $10^\circ K$. An increase of the energy interval ΔE_{1-2} below $10^\circ K$ is evidence of a change in the parameters of the potential of the crystal field of $KDy(MoO_4)_2$ in the region of this temperature. The effect of the anomalous temperature behavior of the quantity ΔE_{1-2} in the spectrum of the crystal $KY_{0.15}Dy_{0.85}(MoO_4)_2$ is less clearly pronounced, and is practically nonexistent in the spectra of crystals with dysprosium concentration 60% and lower.

The temperature dependences of the ratios of magnetic-susceptibility (χ_n) of the crystals of the system $KY(MoO_4)_2 + KDy(MoO_4)_2$ with different dysprosium concentrations n to the susceptibility ($\chi_{5\%}$) of the $KY(MoO_4)_2$ crystal with small content ($\sim 5\%$) of Dy^{3+} ions, shown in Fig. 2, demonstrate that the susceptibilities of all the samples at temperatures above $10^\circ K$ have a similar behavior and

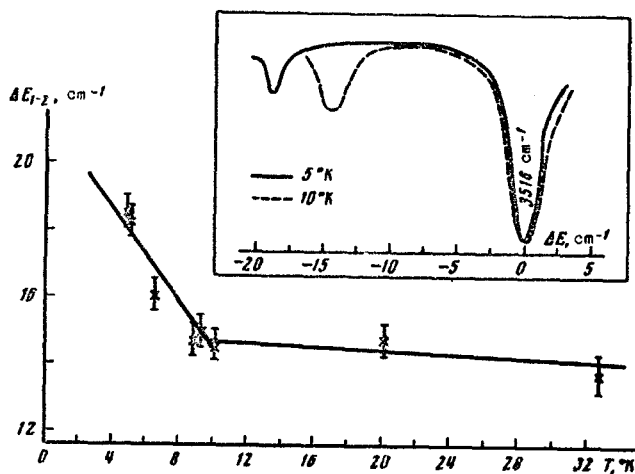


Fig. 1

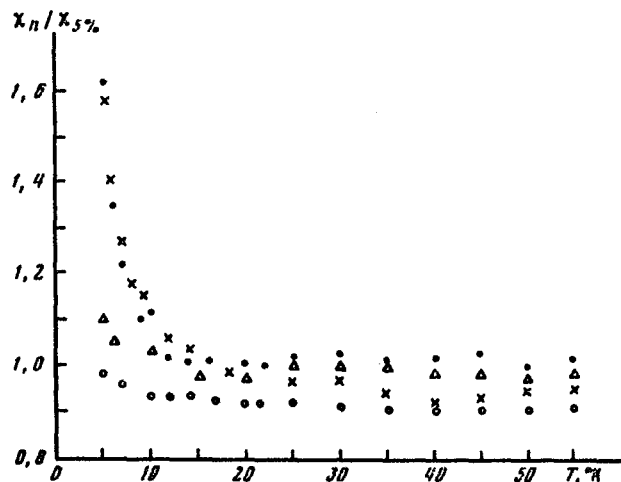


Fig. 2

Fig. 1. Temperature dependence of the energy distance ΔE_{1-2} between the lower and first-excited doublets of the ground term ${}^6H_{15/2}$ of the Dy^{3+} ion in the $KDy(MoO_4)_2$ crystal field. The insert illustrates the form of the absorption bands of transitions from the two lower doublets of the term ${}^6H_{15/2}$ to the term ${}^6H_{13/2}$ for the temperatures 10 and $5^\circ K$.

Fig. 2. Temperature dependences of the ratio of the magnetic susceptibility (χ_n) of a crystal with varying dysprosium concentration n to the susceptibility ($\chi_{5\%}$) of a crystal with a small ($\sim 5\%$) content of Dy^{3+} ions in the $KY(MoO_4)_2$ crystal, calculated per ion: o - $n = 100\%$, x - $n = 85\%$, Δ - $n = 60\%$, \square - $n = 30\%$.

do not depend on the dysprosium concentration in the system. Below 10°K, the temperature dependences of the susceptibilities of samples with $n \geq 85\%$ and of samples with low dysprosium concentrations differ strongly. (Figure 2 pertains to an external field parallel to the C axis of the crystal, an orientation for which the effect is particularly noticeable.) Above $\sim 1.5^\circ\text{K}$, judging from our measurements of the magnetic susceptibility, $\text{KDy}(\text{MoO}_4)_2$ is a paramagnet, so that the change of the slopes of the $\chi(T)$ curves of samples with large dysprosium concentrations near $T \sim 10^\circ\text{K}$ indicates that the phase transition observed at this temperature is structural and not magnetic.

It is shown in [3] that the change of the distance between the doublets, due to the cooperative Jahn-Teller effect, should be described by the expression $\Delta E_{1-2}(0)/\Delta E_{1-2}(\infty) = \tanh \Delta E_{1-2}(\infty)/2kT_D$, where the indices 0 and ∞ correspond to temperatures much lower and much higher than the phase-transition point T_D . For our data, this relation is well satisfied, and we are therefore inclined to assume that the observed structural phase transition in $\text{KDy}(\text{MoO}_4)_2$ is due to the cooperative Jahn-Teller effect.

The investigated rare-earth Jahn-Teller compounds have one large and two small principal values of the g-factor. The Ising model was therefore used in the formalism of the molecular-field theory to describe the interaction in the Jahn-Teller effect. In $\text{KDy}(\text{MoO}_4)_2$, two values of the g-factor are large and almost equal (~ 10), and the third is small (~ 1), so that the x-y model is apparently more suitable here.

The authors are indebted to V.V. Eremenko for a discussion of the results, and to L.N. Pelikh and M.I. Kobets for help in growing the single crystals.

- [1] A.H. Cooke, C.J. Ellis, K.A. Gehring, M.J.M. Leask, D.M. Martin, B.M. Wanklym, M.R. Wells, and R.L. White, *Solid State Comm.* **8**, 689 (1970).
- [2] T.S. Stetsenko, V.G. Yurko, S.D. El'chaninova, and A.I. Zvyagin, in: *Fizika nizkikh temperature (Low-temperature Physics)*, Physico-tech. Inst. of Low Temp., Ukr. Acad. Sci., Khar'kov, No. 20, 74 (1972).
- [3] G.A. Gehring, A.P. Malozemoff, W. Staude, and R.N. Tyte, *J. Phys. Chem. Solids* **33**, 1487 (1972).

ABSORPTION LINE SPECTRA OF ZnP_2 CRYSTALS

I.S. Gorban', V.V. Lugovskii, I.I. Tychina, and A.V. Fedotovskii
Kiev State University, Kiev State Pedagogical Institute
Submitted 9 January 1973
ZhETF Pis. Red. **17**, No. 3, 193 - 197 (20 February 1973)

We obtained the edge absorption spectrum of ZnP_2 crystals with monoclinic syngony at 4.2°K . Its distinguishing feature is that it consists of a large number of narrow lines forming sequences that converge to the boundary lines at 1.5471 eV ($E \perp C$), 1.5471 eV and 1.4972 eV ($E \parallel C$).

ZnP_2 is a semiconducting compound of the $A^{II}B_2^V$ type and is formed in two different modifications, tetragonal and monoclinic [1].

We have investigated samples of monoclinic ZnP_2 obtained by sublimation in a two-temperature oven in quartz ampules evacuated to 10^{-4} mm Hg. The initial materials were red phosphorus and metallic zinc (grade V-5), in the stoichiometric ratio. Unlike the procedures used in [1], we obtained crystals of monoclinic syngony only by adjusting the temperature conditions in the ampules. The single crystals had regular faceting with perfect face surfaces.