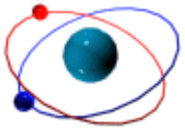

LASER SCANNING CONFOCAL LUMINESCENT POLARIZATION MICROSCOPY OF SINGLE RADIATION DEFECTS

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THE SUBJECT AND RESEARCH PROBLEMS

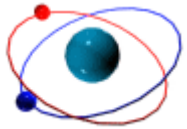
The subject of our research *is the single luminescent defects induced in the bulk of the crystalline medium by various types of radiation.*

Research objectives:

✓ *Study of the properties of single radiation defects, which can be created by irradiating dielectric crystals with various types of radiation.*

✓ *Development and testing of methods for spectroscopic differentiation of quantum systems created by ionizing radiation in such media, systematization of types and determination of the characteristics of their quantum transitions.*

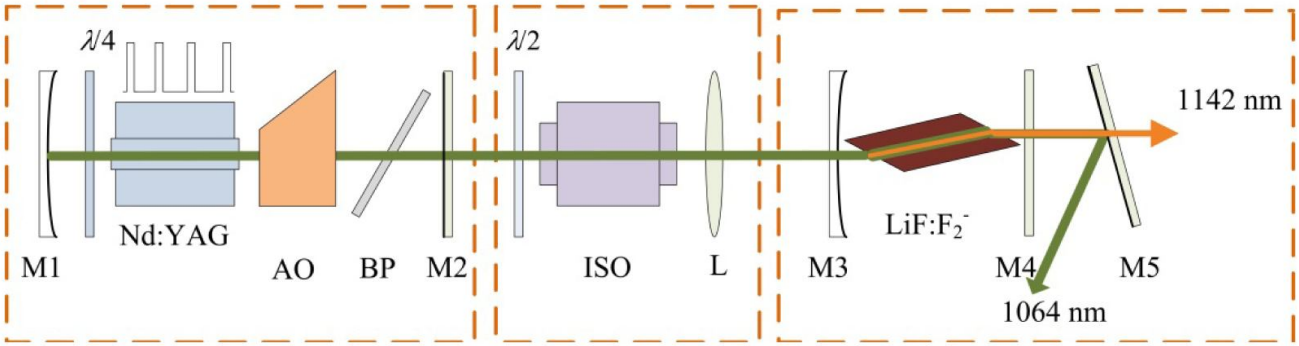
Content of the report



1. Motivation. Why is it necessary to investigate color centers induced by various types of ionizing radiation?
2. Methods for determining the type (multipolarity) and orientation of quantum systems in crystalline media.
3. Methods of traditional luminescence spectroscopy for ensembles of radiation defects.
4. Experimental equipment.
5. Quantum trajectories of photoluminescence intensity for single radiation defects.
6. Possibilities of spectroscopic individualization (or differentiation) of various types of fluorescent quantum systems in condensed matter
7. Dynamic models of F_2, F_3^+ color centers in a lithium fluoride crystals.
8. A universal method for determining the type (multipolarity) and orientation of quantum systems in crystalline media
9. Conclusions

Motivation

Color centers are working quantum systems in laser elements and passive laser switches



Han Rao, Zhenhua Cong, Yongfu Li at. al. High power broadband LiF:F_2^- color center laser//OPTICS EXPRESS. – 2015. - Vol. 23. - № 17.

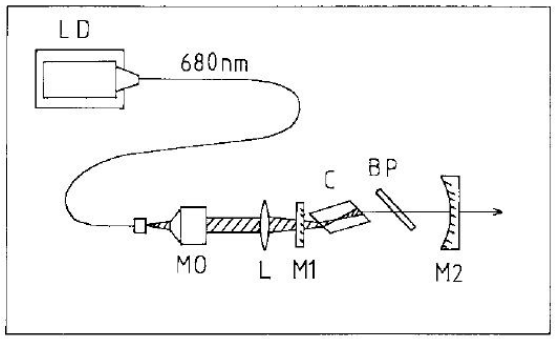


Fig. 2. Experimental setup of the diode-pumped LiF : F_2^{+*} laser. LD: Laser diode array. F: Fiber. MO: Microobjective. L: Lens. BP: Birefringent plate. M1 and M2: Cavity mirrors. C: LiF : F_2^{+*} color center laser active element.

Valerii V. Ter-Mikirtychev. Diode-Pumped LiF:F_2^{+} Color Center Laser Tunable in 880–995-nm Region at Room Temperature//IEEE PHOTONICS TECHNOLOGY LETTERS. – 1998. - Vol. 10. - № 10.*

Martynovich E.F., Grigorov V.A., Tokarev A.G. Laser medium for active elements and passive switches. Author's certificate SU 1018573 A1, 10.04.1995. Application No. 3327352/25 dated 08/05/1981.

Motivation

Color centers are working quantum systems in gamma and neutron detectors

Vinogradov Institute of Geochemistry SB RAS

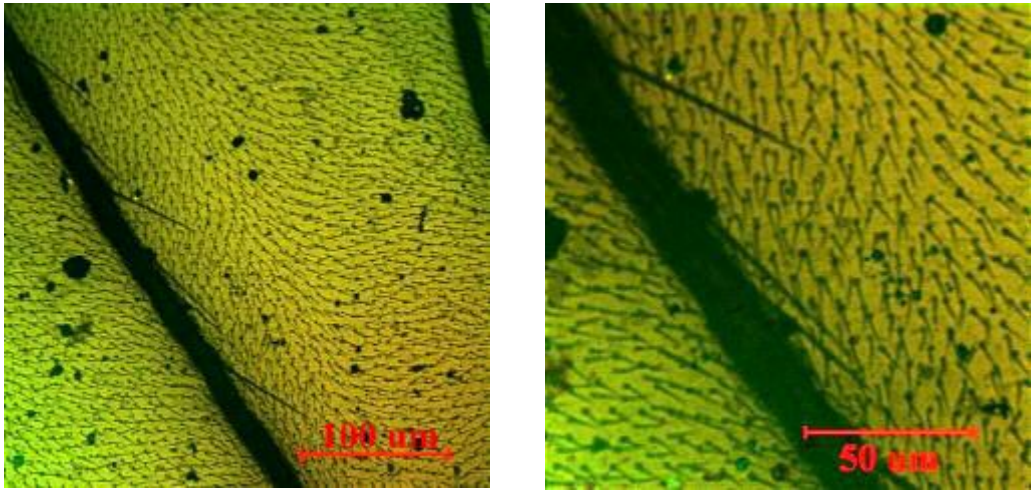
Детекторы	ДТГ-4
Тип кассеты	ДТУ или ДТЛ-02
Состав детектора	LiF:Mg,Ti
Измеряемая величина	Доза Hp(10) фотонного излучения
Диапазон измерений Hp(10)	50,0 мкЗв ÷ 10 Зв
Диапазон энергий	0,015 ÷ 3,0 МэВ
Число циклов использования детекторов	Не менее 500
Толщина детекторов	0,8 ÷ 1,0 мм
Диаметр детекторов	4,5 ± 0,2 мм
Воспроизводимость показаний детекторов при повторном использовании	При повторном использовании показания детекторов отличаются не более 5 %
Потеря информации при хранении	Не более 5% в год

Nepomnyashchih A.I., Mironenko S.N., Afonin G.P., Selyavko A.I. Monocrystalline detectors based on lithium fluoride // Atomic Energy - 1985. - Volume 58. - P. 257–259.

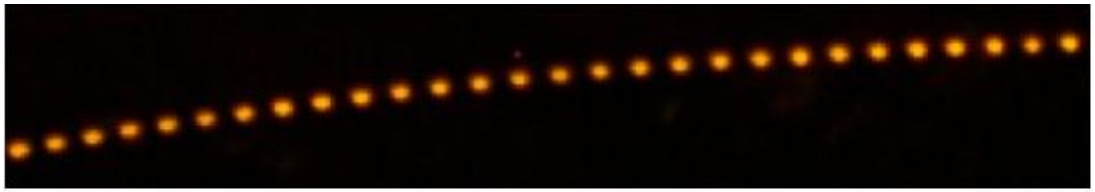
Nepomnyashchih A.I., Mironenko S.N. A method of producing monocrystalline detectors based on lithium fluoride. Author's certificate SU 1707088 A1, 23.01.1992. Application No. 3394517 dated 02/12/1982.

Motivation

Color centers are working quantum systems in volumetric and multilayer fluorescent media for recording information in the form of images or digital codes



G. Baldacchini, F. Bonfigli, A. Faenov, F. Flora, R.M. Montereali, A. Pace, T. Pikuz, L.Reale.//Nanoscience and Nanotechnology. – 2003. – Vol. 3. № 6. – p. 483.



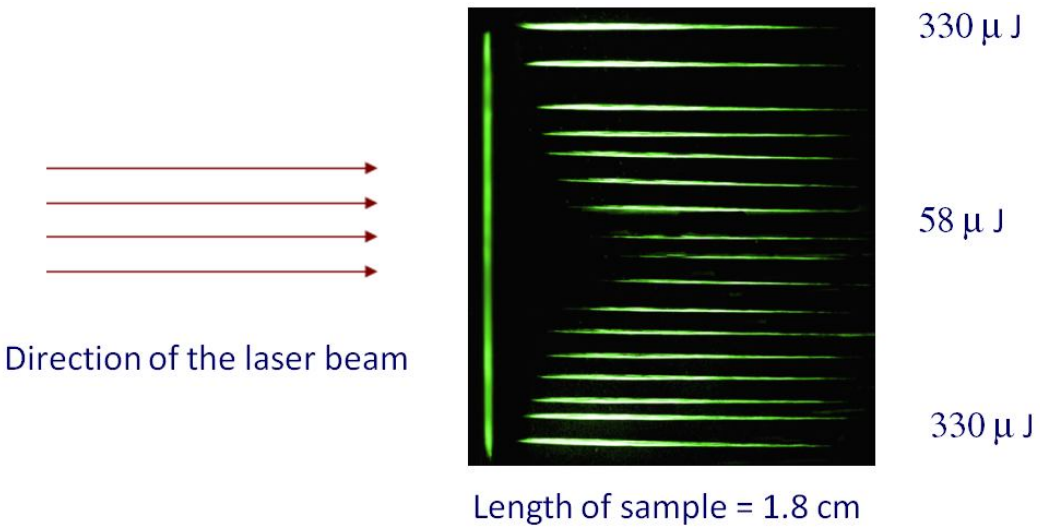
E.F. Martynovich, V.P. Dresvyanskii, A.P. Voitovich, S.N. Bagayev. Highly sensitive nonlinear luminescent ceramics for bulk and multilayer data carriers. Quantum Electronics, 2015, 45 (10), p. 953 – 958

E.F. Martynovich, V.P. Dresvianskiy, A.V. Kuznetsov, S.V. Alekseev, V.F. Losev, A.N. Ratakhin, S.N. Bagayev. 3D fluorescent carriers of visual and digital information //OSA Advanced Photonics 2015, (Optical Society of America, 2015), paper NS2A.6.

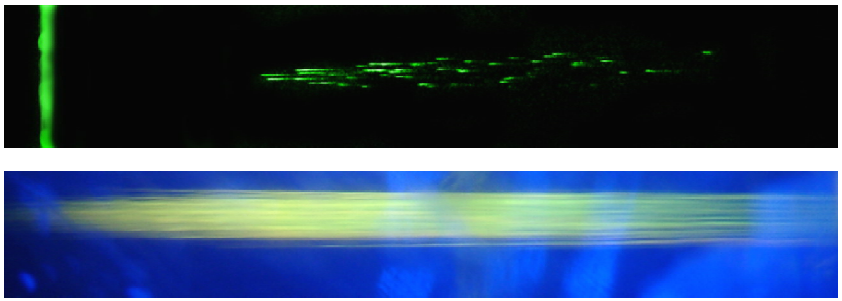
Motivation

Crystals with color centers make it possible to study the spatial characteristics and dynamics of the interaction of intense laser radiation with matter during self-focusing and filamentation

Spatial distribution of the concentration of color centers in a lithium fluoride crystal after femtosecond laser irradiation with different pulse energies



Distribution of the luminescence intensity of color centers in LiF crystals induced by femtosecond laser irradiation:
from above - as a result of the action of a single impulse;
from below - as a result of exposure to a series of 10000 femtosecond pulses.

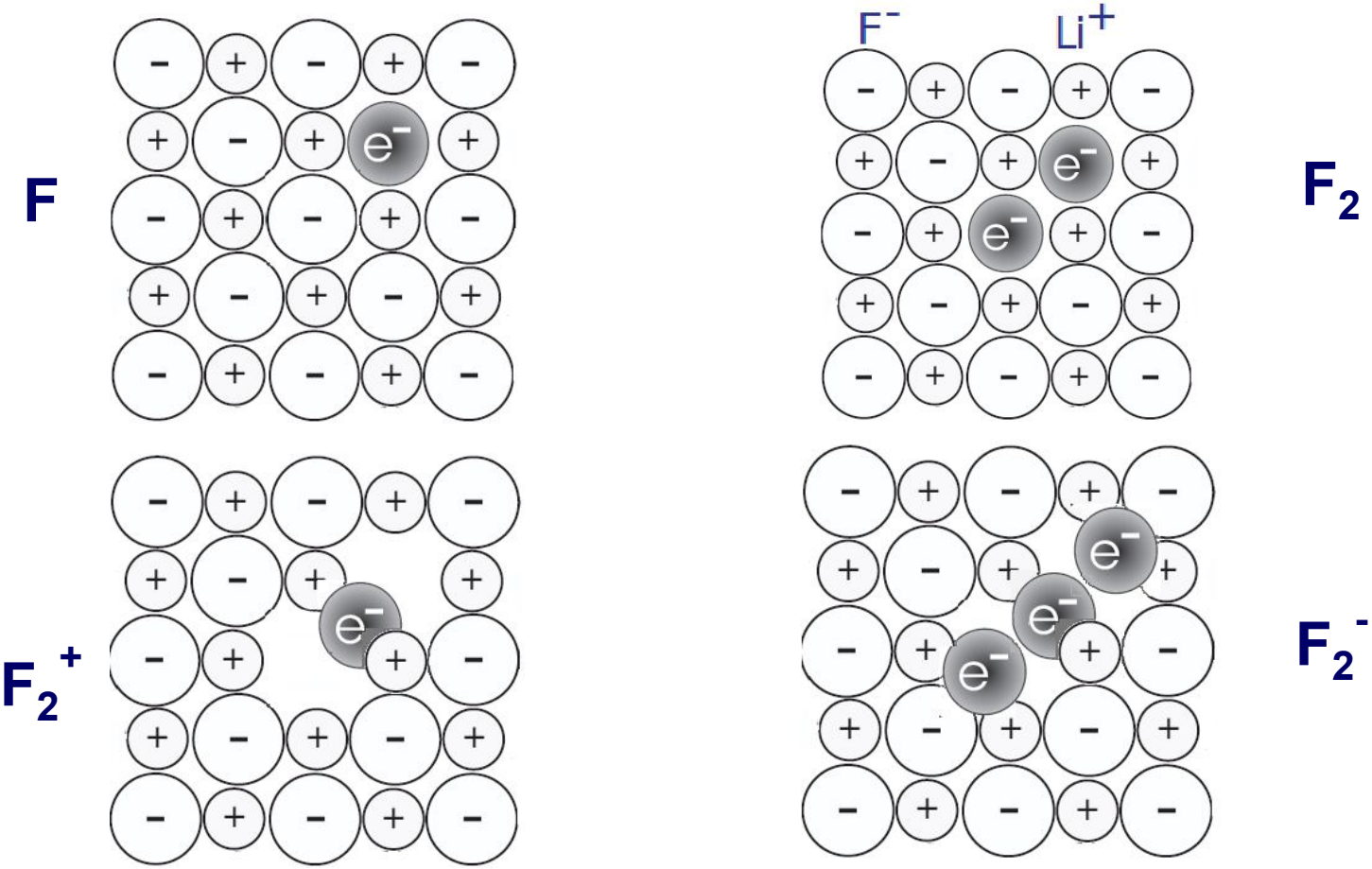


Kuznetsov A.V., Martynovich E. F. The mechanism of filamentation of femtosecond laser radiation in wide-gap dielectrics during the formation of color centers // Izvestiya vuzov. Physics. - 2009. - Vol. 52. - No. 12/3. - S. 180-182.

Martynovich E.F., Kuznetsov A.V., Kirpichnikov A.V., Pestryakov E.V., Bagaev S.N. Creation of luminescent emitters by intense laser radiation in transparent media // Quantum Electronics. - 2013. - Volume 43. - No. 5. - P. 463–466.

Motivation

Color centers are a model of quantum systems for various fundamental research



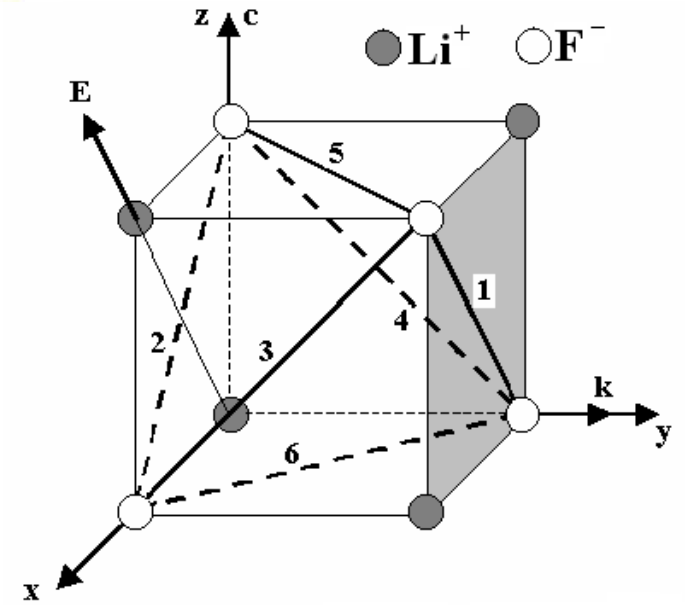
The structure of mono- and bivacant color centers

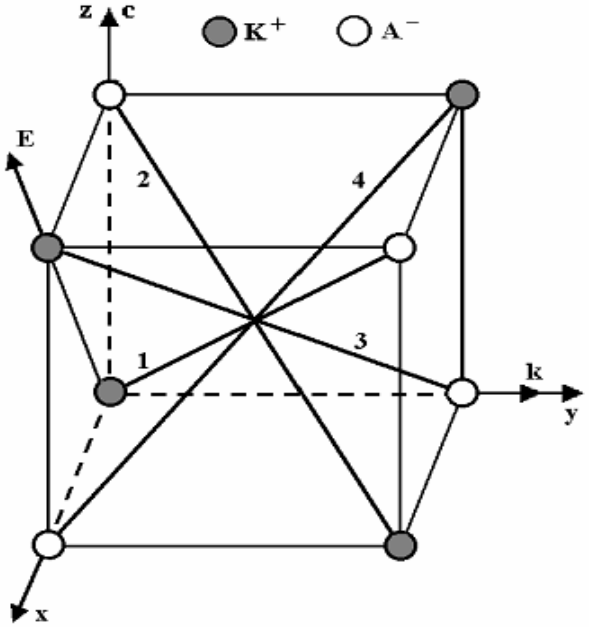
HISTORY

- S.I. Vavilov (1932) - wide-angle interference method.
- S.I. Vavilov (1940) - method of polarization diagrams.
- P.P. Feofilov (1954) - the method of polarized luminescence for studying the orientation and multipolarity of quantum systems for their ensembles in cubic crystals.
- K. Lee and I. Crawford, M.E. Springis (1977-1980) - polarized luminescence method for studying the orientation and multipolarity of quantum systems for their ensembles in anisotropic crystals.
- E.F. Martynovich, V.P. Dresvyanskiy (2003) - piezomodulation method for studying orientation and multipolarity of quantum systems.
- E.F. Martynovich, N.L. Lazareva, Al. V. Kuznetsov (2017) - method of polarization ratios for ensembles of particles in anisotropic crystals.

SB RAS
IB ILP

Methods for determining the type (multipolarity) and orientation of quantum systems in crystalline media





F_2^+ F_2 F_2^-

F_3^+ F_3 F_3^-

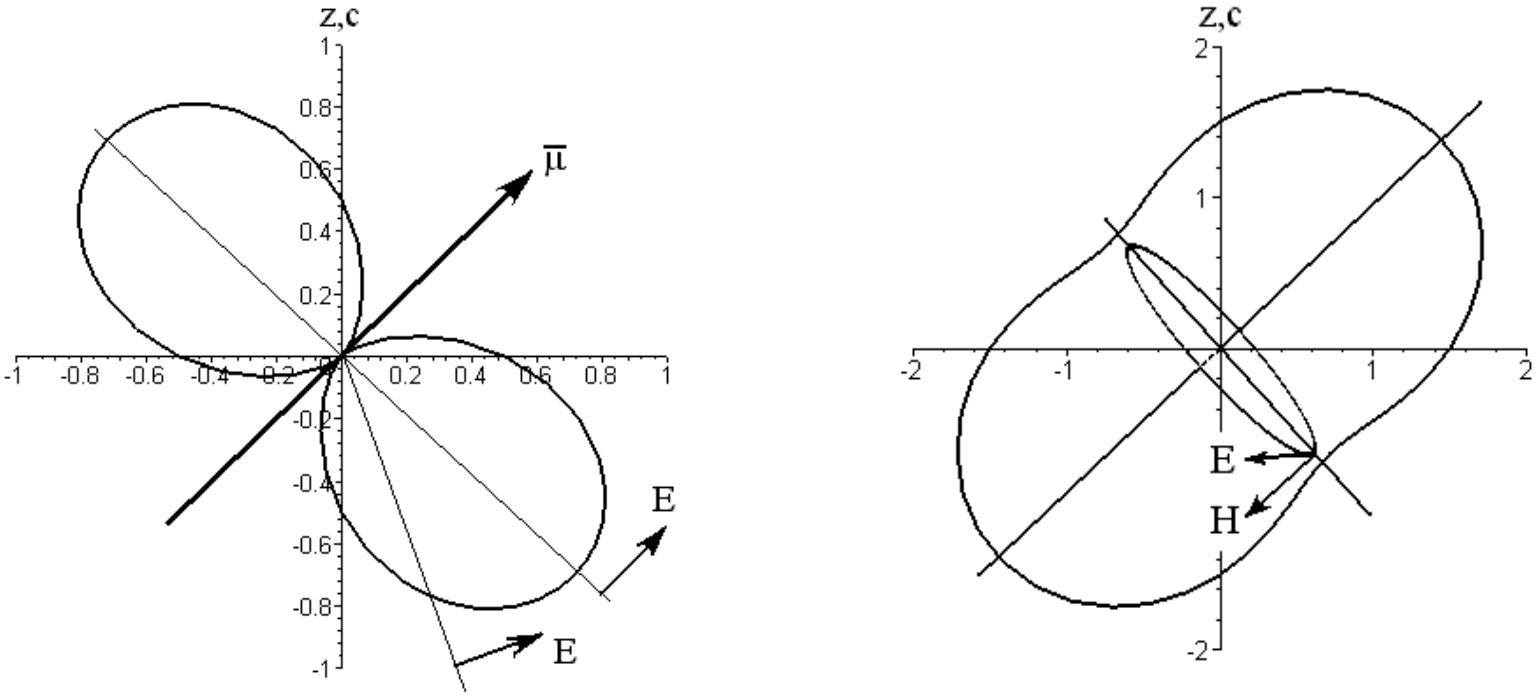
- **F**, F_2^+ - Systems with one optical electrons;
- F_2 , F_3^+ , F^- - Systems with two optical electrons;
- F_2^- , F_3 , F_4^- - Systems with three optical electrons.

Centers with two three or more optical electrons have a systems of singlet, triplet, quartet, and more challenging levels

SB RAS

IB ILP

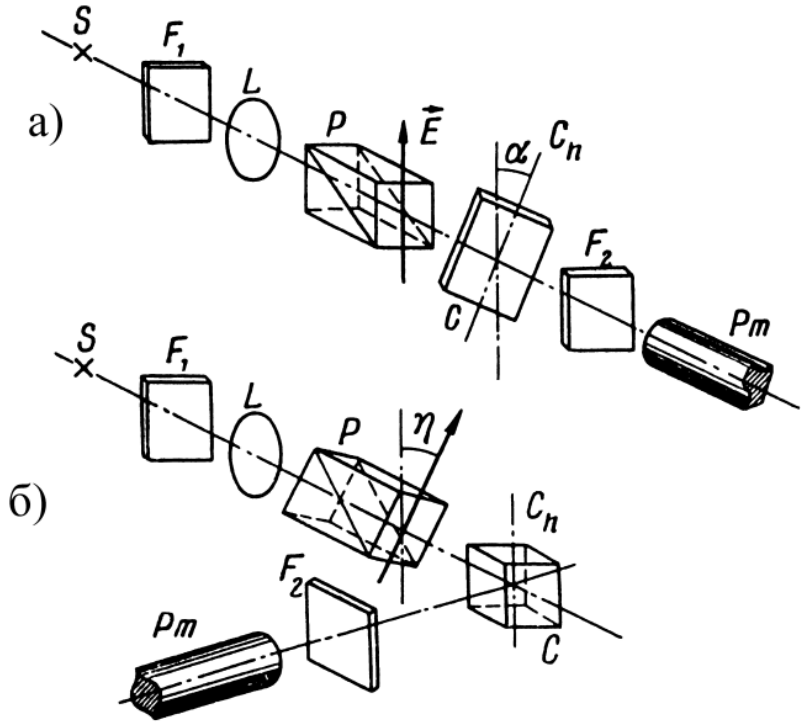
Methods for determining the type (multipolarity) and orientation of quantum systems in crystalline media



Directional patterns of radiation of elementary emitters:
on the left - a linear electric dipole;
on the right - a linear electric rotator.

Methods for determining the type (multipolarity) and orientation of quantum systems in crystalline media

Feofilov experiment scheme



Installation schemes for research:
a) - azimuthal dependences of luminescence polarization P(α);
b) - polarization diagrams of luminescence P(η).

S - excitation source, F_1 and F_2 - light filters, L - lens, P - polarizer, C - crystal under study, P_m - polarimeter

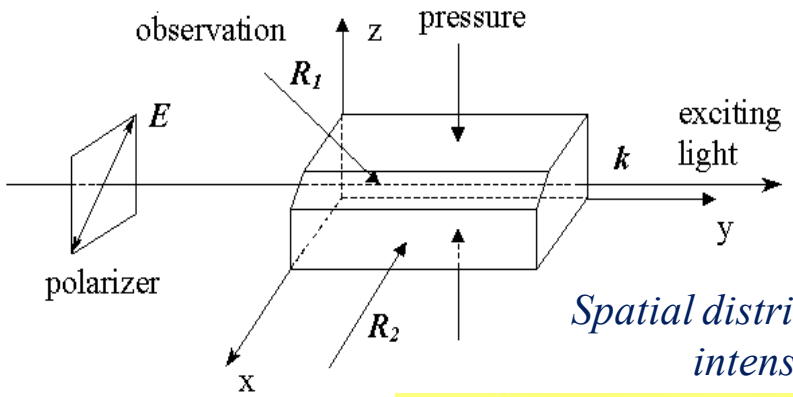
$$P = (I_{II} - I_{\perp})/(I_{II} + I_{\perp})$$

The setups make it possible to study the so-called azimuthal dependences of the luminescence polarization, i.e., the curves expressing the change in the degree of polarization with a change in the angle of rotation α of the crystal plate under study, and the so-called polarization diagrams, which characterize the change in P when the angle of rotation of the polarizer η is changed.

Methods for determining the type (multipolarity) and orientation of quantum systems in crystalline media

Piezomodulation method for studying the orientation and multipolarity of quantum systems

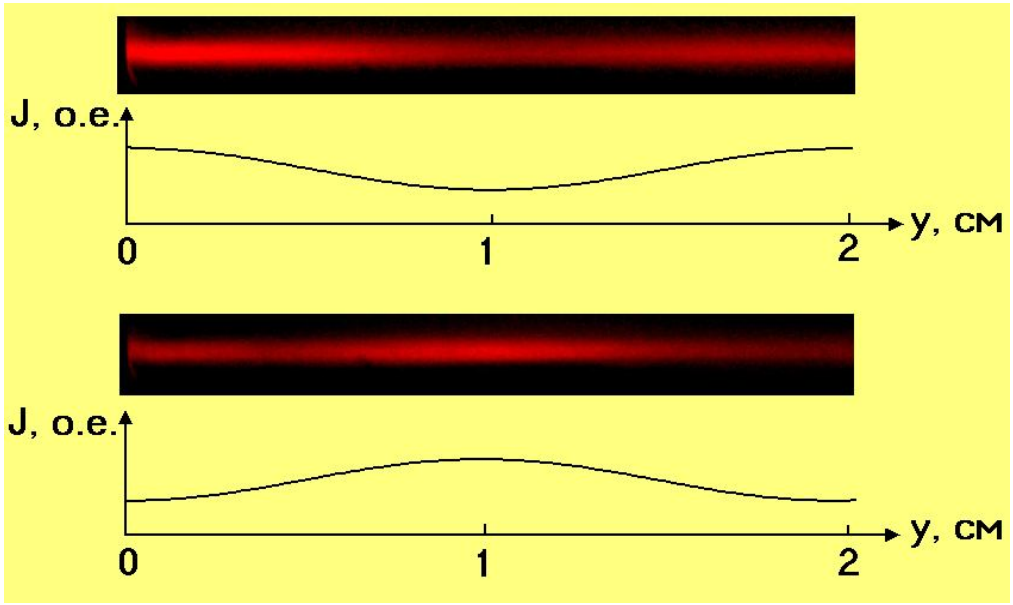
Dresvyanskiy V.P., Martynovich E.F. The piezomodulation method for investigating the multipolarity of elementary oscillators in cubic crystals. Optics Communications. 2003, vol. 65, No. 6, p. 154-157.



$$\Delta n = \frac{\sigma n^3}{2}(\pi_{11} - \pi_{12})$$

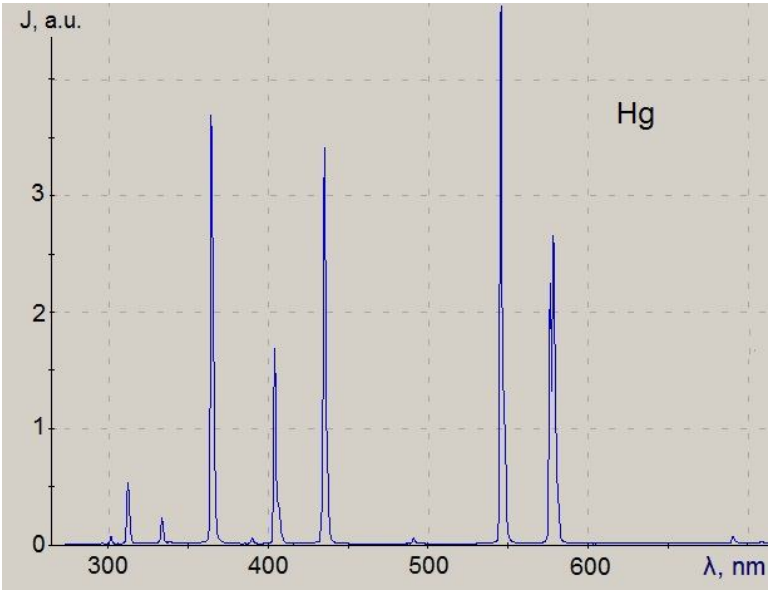
$$\Delta n = \frac{\sigma n^3}{2}\pi_{44}$$

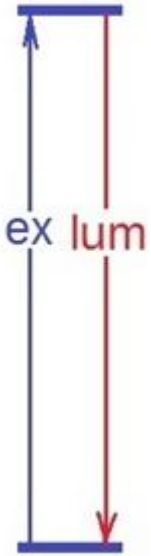
Spatial distribution of the luminescence intensity of the F_2 centers



Methods of traditional luminescence spectroscopy for ensembles of radiation defects

The luminescence spectra of atoms in gases and quantum systems in condensed media are fundamentally different

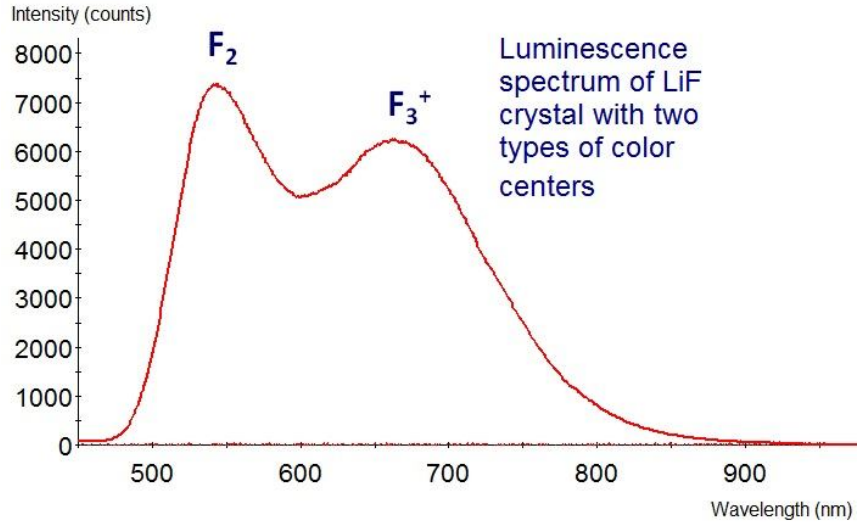


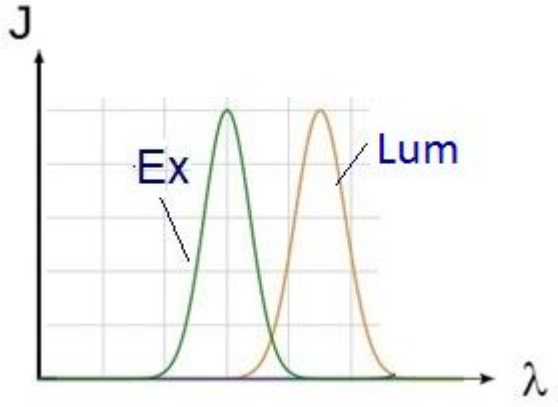


The absorption and luminescence spectral lines in atomic gases are resonant. The lines are very narrow and distinctive. By their position in the spectrum, it is easy to distinguish atoms or ions in a gas.

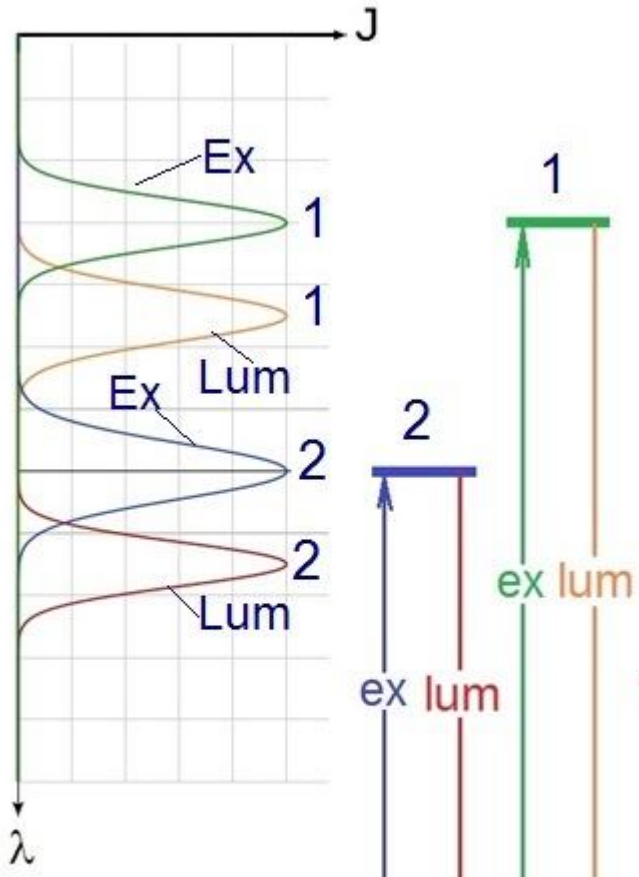
There is a significant Stokes shift between the absorption and luminescence spectral bands in condensed media.

In condensed media, the situation is more complicated. A very large electron-phonon broadening of spectral lines is observed, which complicates spectroscopy.



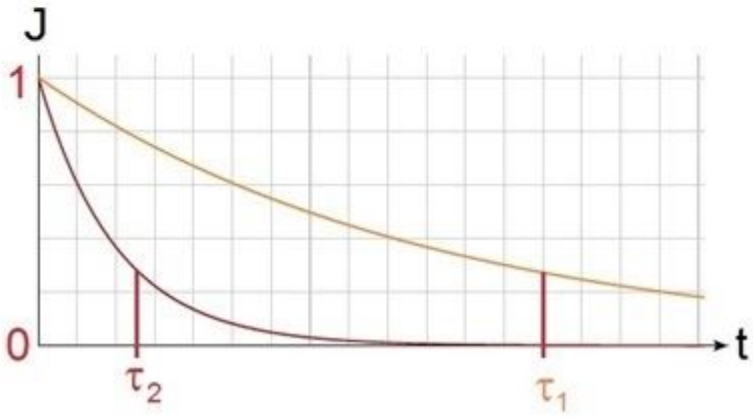


Methods of traditional luminescence spectroscopy for ensembles of radiation defects

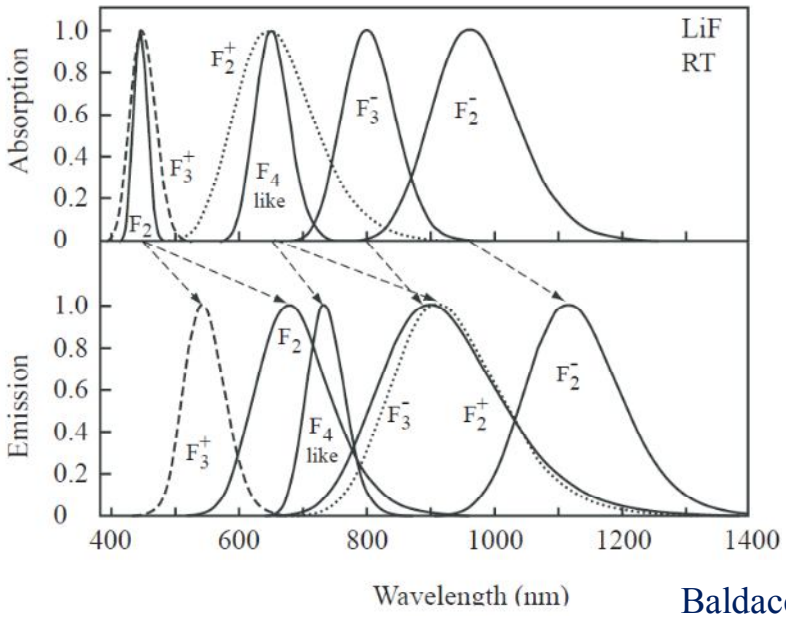


There are two types of luminescence centers in the crystal. Their spectral bands of excitation and luminescence separated. The lifetimes of these centers in the excited states are also different.

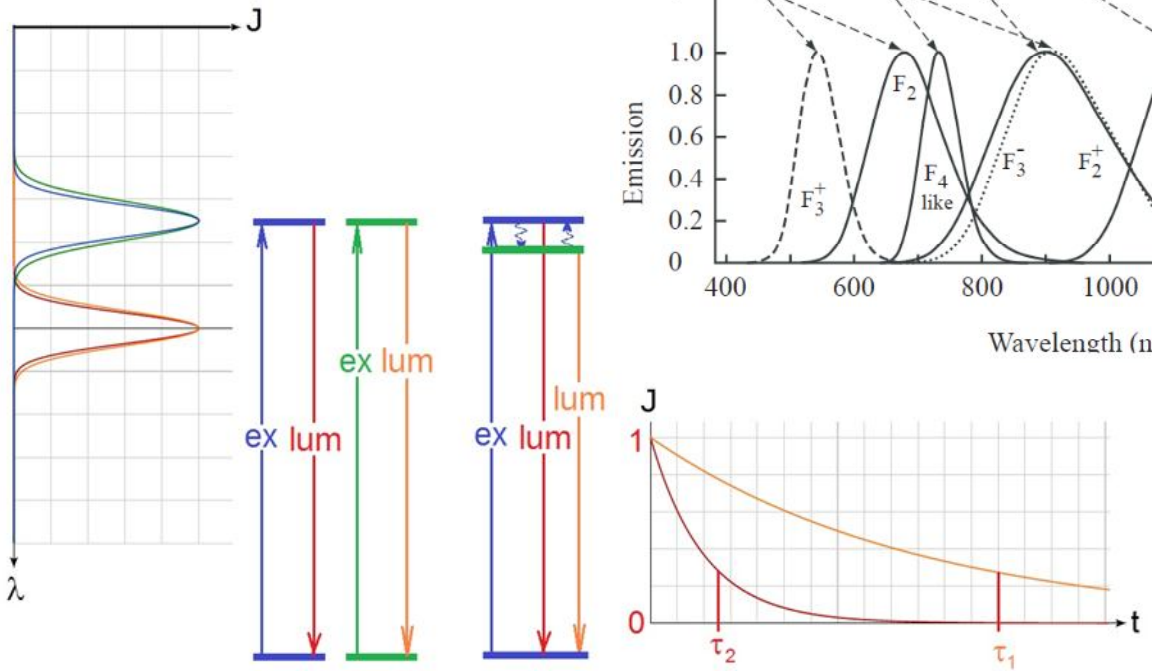
Спектроскопические параметры: ω_{max}, $\Delta\omega$, τ



Methods for determining the type (multipolarity) and orientation of quantum systems in crystalline media

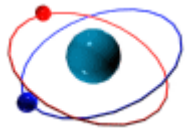


The absorption and emission bands of color centers at room temperature in an irradiated LiF crystal approximated in the form of Gaussian curves.



Baldacchini G., Montereali R.M., Tsuboi T. Energy transfer among color centers in LiF crystals//Eur. Phys. J. D. – 2001. – Vol.17. – P. 261–264.

The two types of centers can have the same absorption and luminescence bands. In addition, luminescence decay times can be poorly discernible. This complicates the spectroscopic distinction of centers.

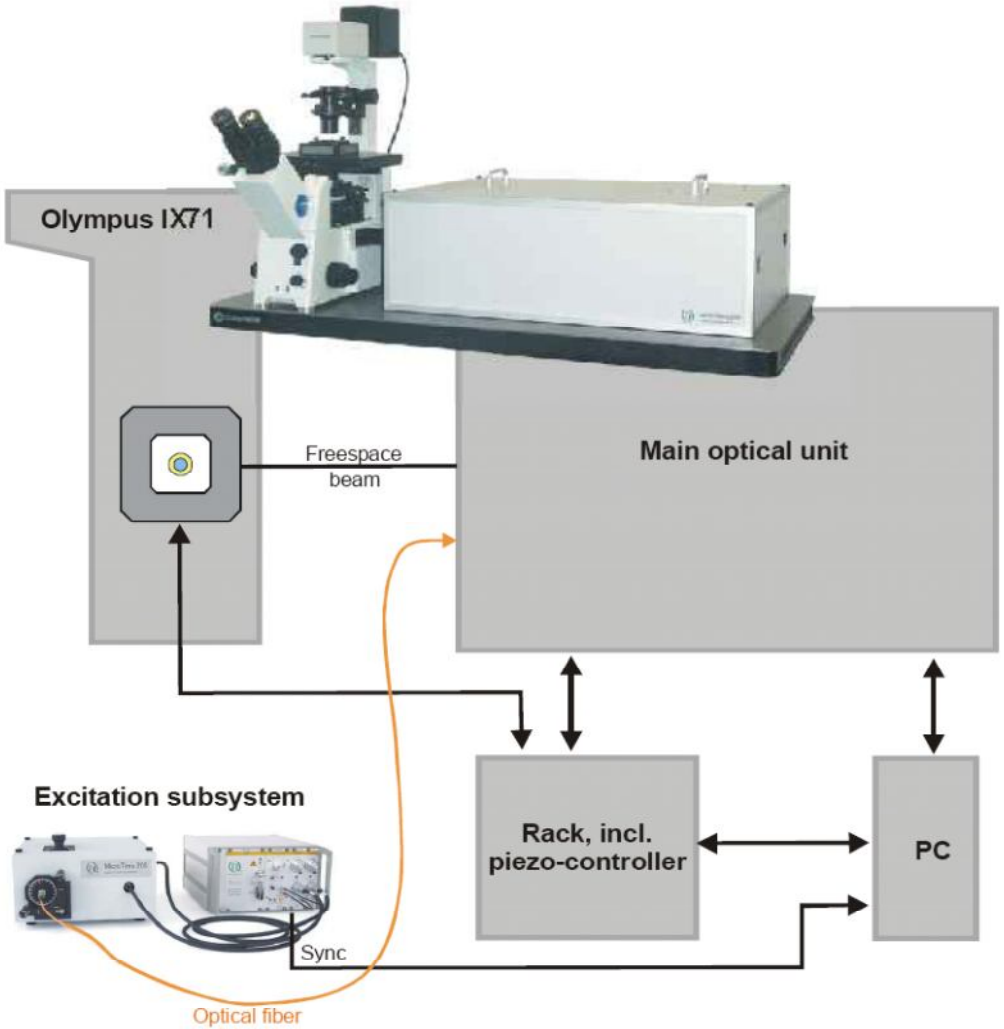


IT IS USEFUL TO HAVE ALTERNATIVE METHODS OF FLUORESCENCE SPECTROSCOPY.

SUCH POSSIBILITIES APPEAR WHEN STUDYING THE PROPERTIES OF LUMINESCENCE OF SINGLE QUANTUM SYSTEMS.

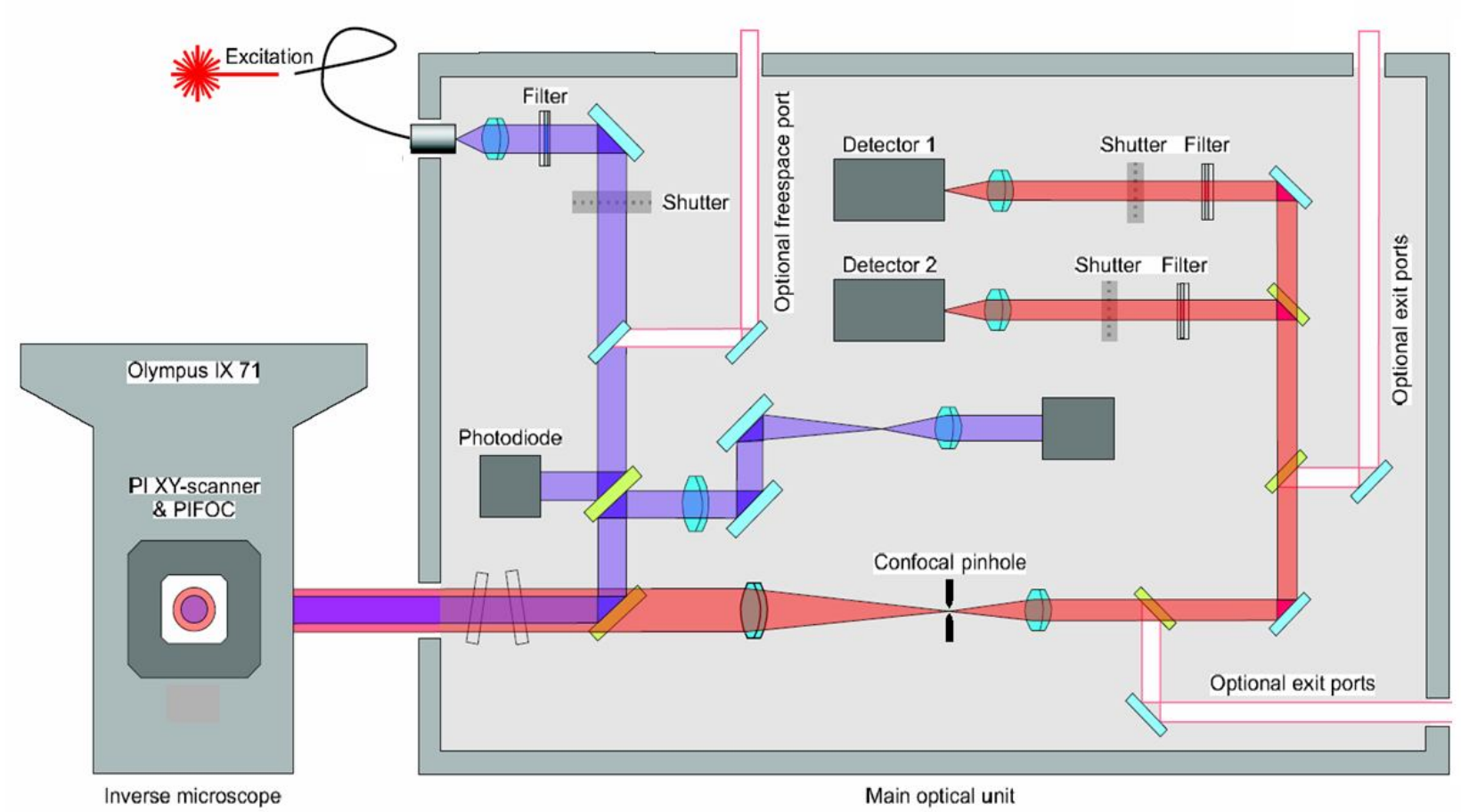
Experimental equipment

MicroTime 200: scanning fluorescence time-resolved confocal laser microscope (PicoQuant Gmbh)



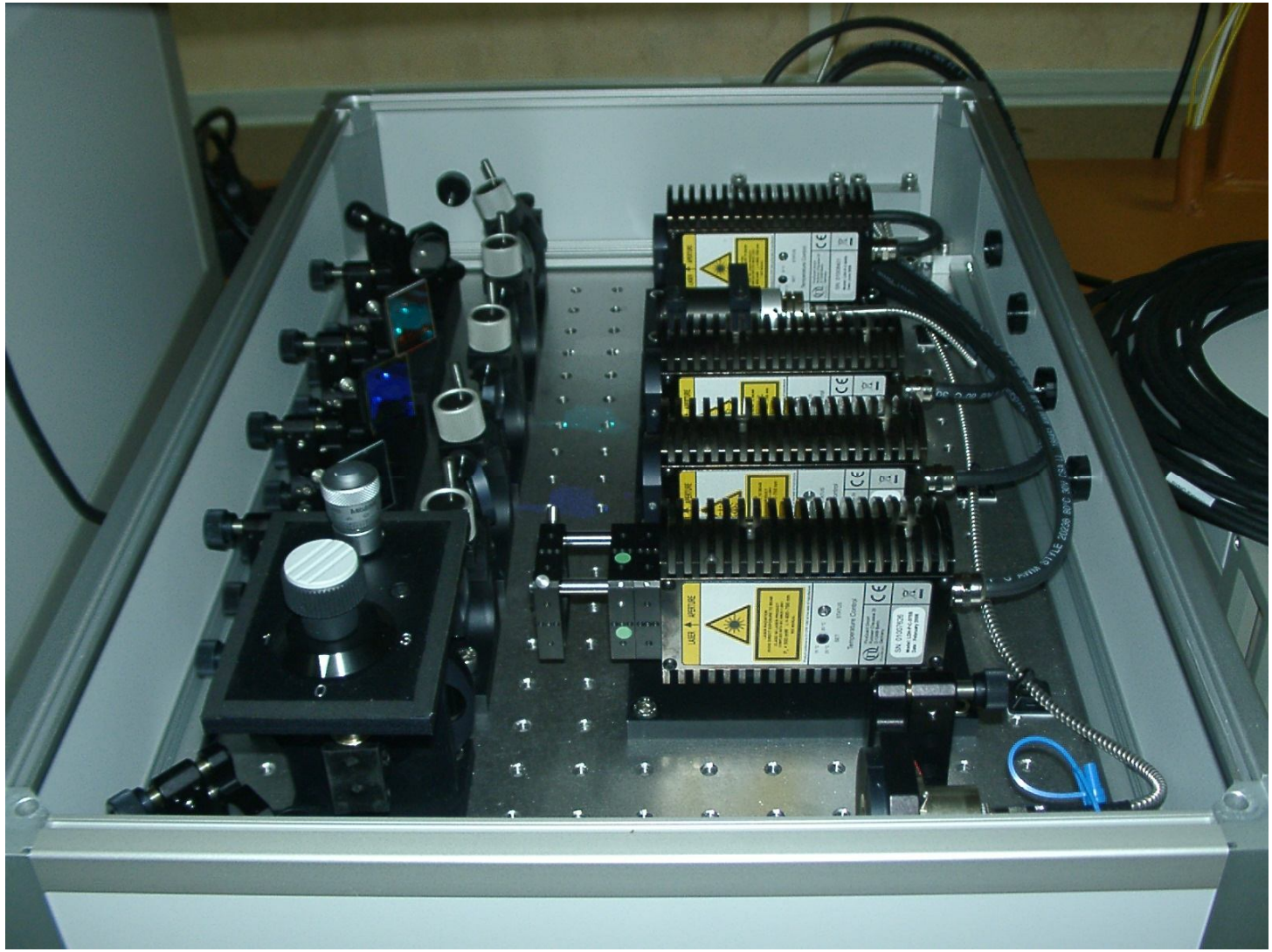
Experimental equipment

Optical scheme of MicroTime 200



Experimental equipment

Emitter unit of microscope



Experimental equipment

Receiving unit of microscope

Experimental equipment

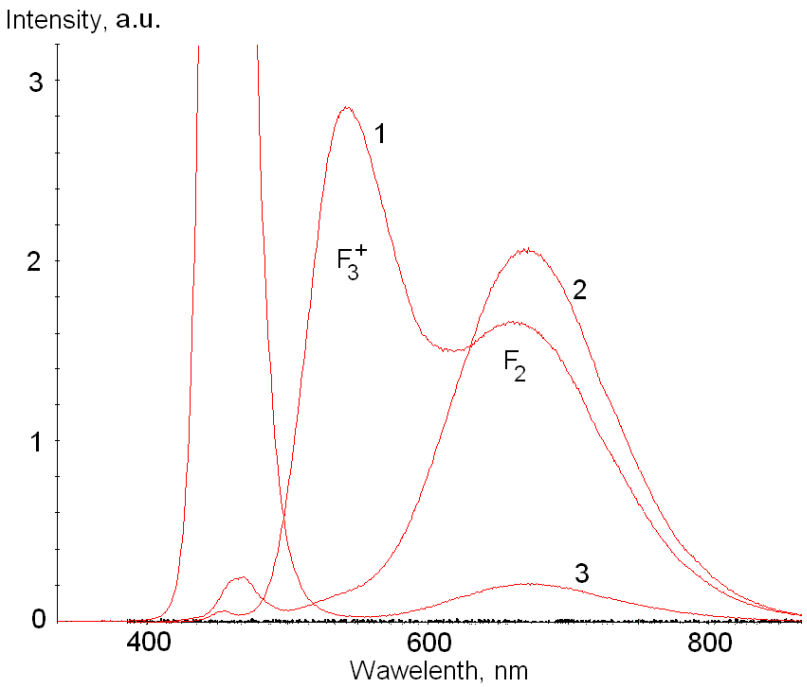
PicoQuant MicroTime 200: scanning fluorescence time-resolved confocal microscope

- **Excitation**: 50 picosecond diode lasers with wavelengths 375 to 640 nm. Repetition rate up to 40 MHz.
- **Systems of time-correlation single photon counting.**
- **Scanning**: piezo-positioner, 80 µm x 80 µm range, 10 nm resolution.
- **Detectors**: 2 single-photon avalanche diodes, spectral range 400-1000 nm, dark counts 20-100 cps.
- Overall **time resolution** is 0.05-0.3 ns.
- XY and Z - **spatial resolution** is ~0.2 and ~1 mm respectively.

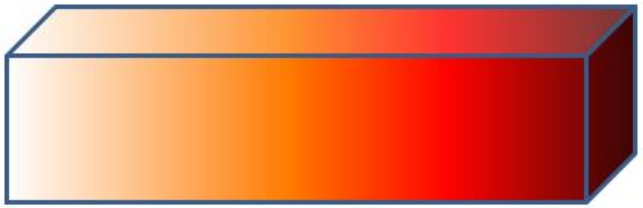
Main applications:

- Time-resolved microscopy.
- Fluorescence Lifetime Imaging (FLIM).
- Single Molecule Spectroscopy (SMS).
- Förster Resonance Transfer (FRET).
- Fluorescence Correlation Spectroscopy (FCS).

Preparation of the samples for the study of individual centers

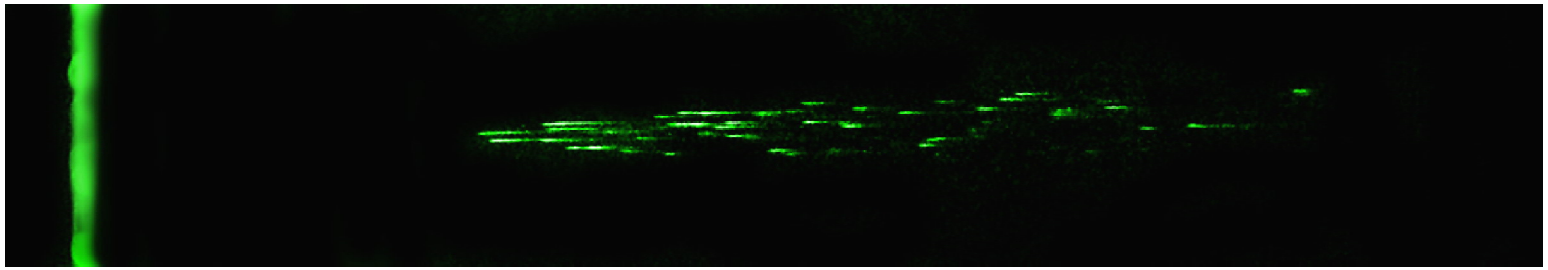


$$n < L^{-3}$$



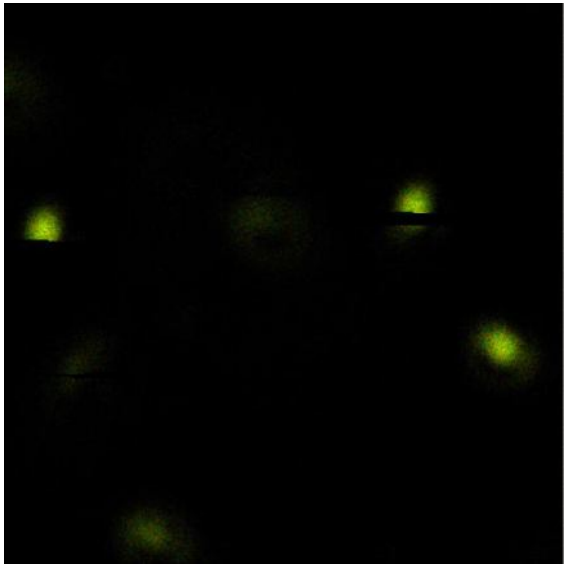
1. *Crystal LiF, gradient colored by gamma radiation.*
2. *2. Crystals, irradiated by small dose of X-ray.*

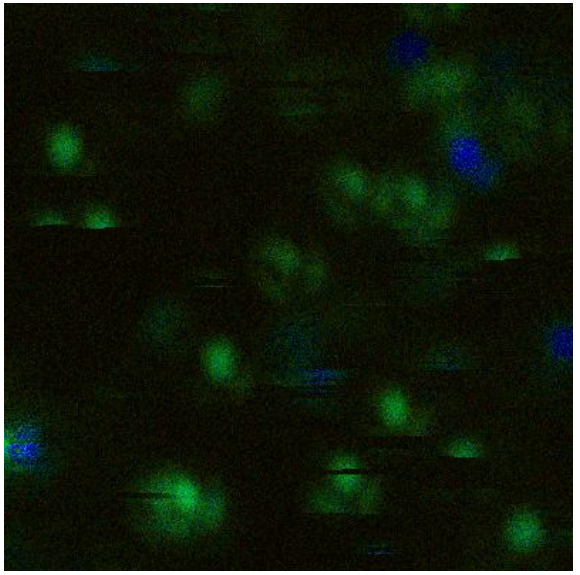
Traces of filamentation of Ti-Sapphire laser single pulse: 30 fs, 850 nm, 0.5 mJ, in LiF

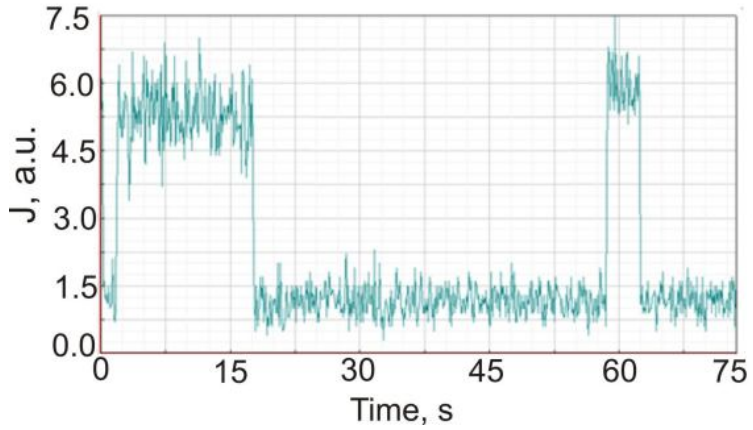


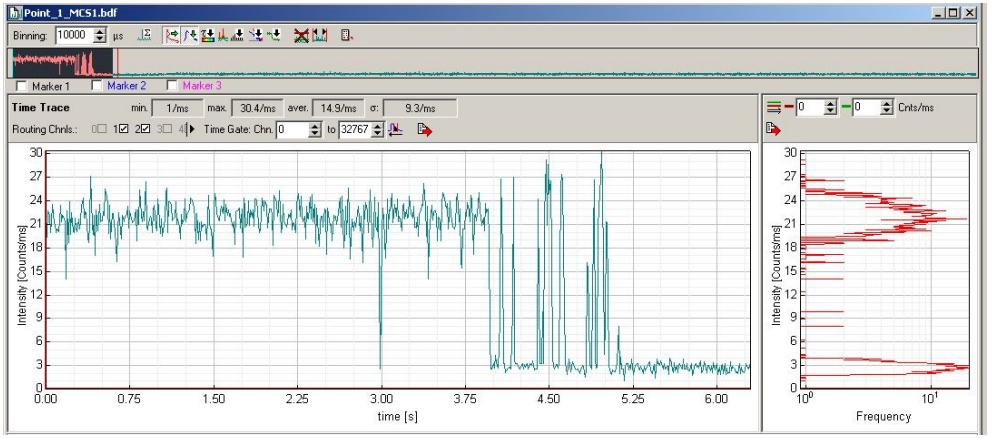
Quantum trajectories of photoluminescence intensity for single radiation defects.

Confocal luminescent images and quantum trajectories of single F_2 (left) and F_3^+ (right) color centers in a LiF crystal (scan area 6 × 6 μm, excitation 470 nm)









Possibilities of spectroscopic individualization (or differentiation) of various types of fluorescent quantum systems in condensed matter

Fluorescent images of two types of single crystal centers created by irradiation

Images of individual color centers. Various false color image of luminescence centers 1, 2 (blue) and 3, 4 (green) represent a slight difference of the luminescence decay times, which suggests a different nature centers 1, 2 and 3, 4.

The size of the display area of 6 × 6 microns.

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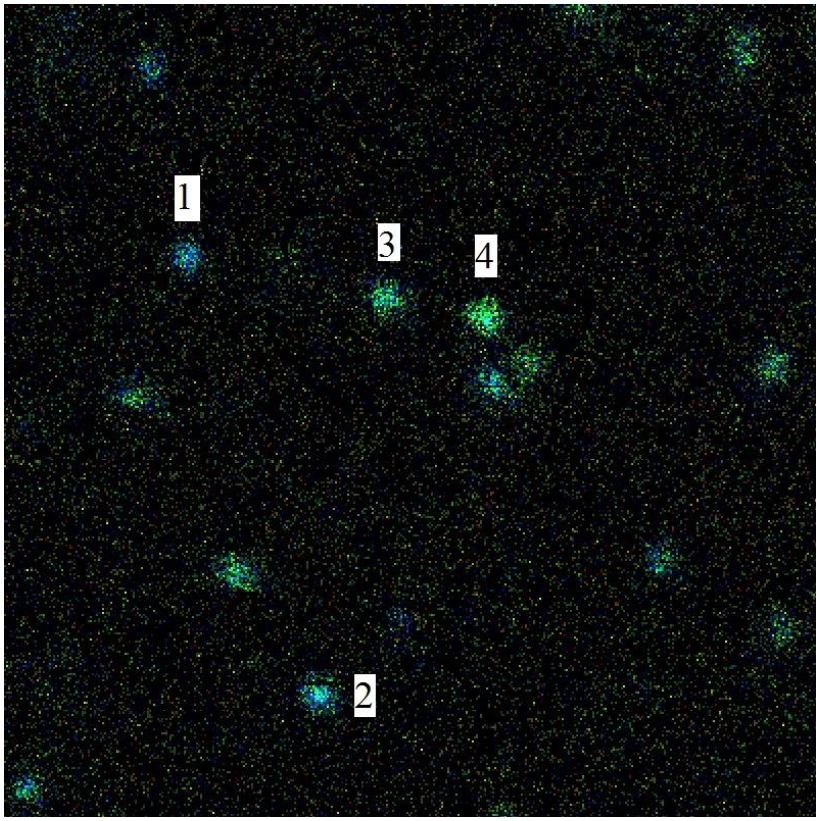

Confocal scanning fluorescence microscope with a time resolution of MicroTime 200

The excitation 532 nm emission in the area of registration of 690 ± 30 nm

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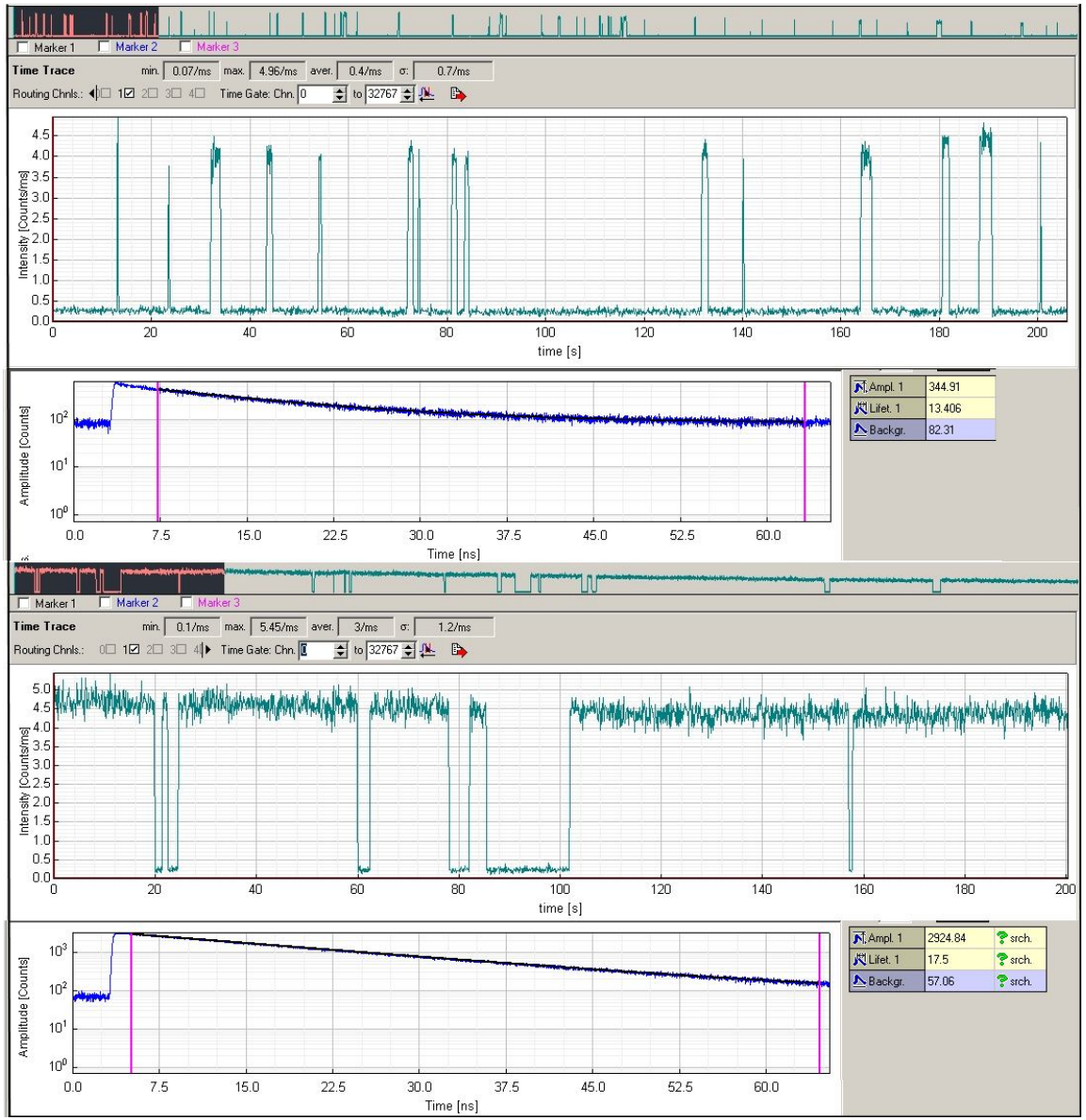
Photoluminescence quantum trajectories (green lines) for two different types of single luminescent centers with similar emission spectra and similar kinetics (blue lines)

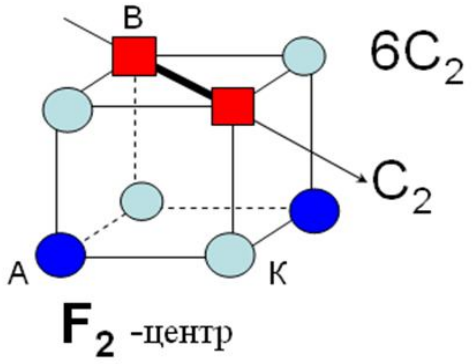
F_3 Mg^{++} V_c^-

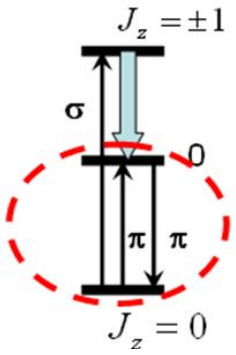
F_2 Center

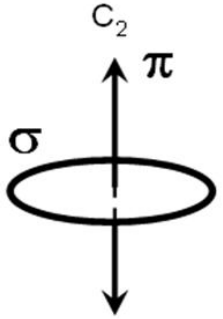


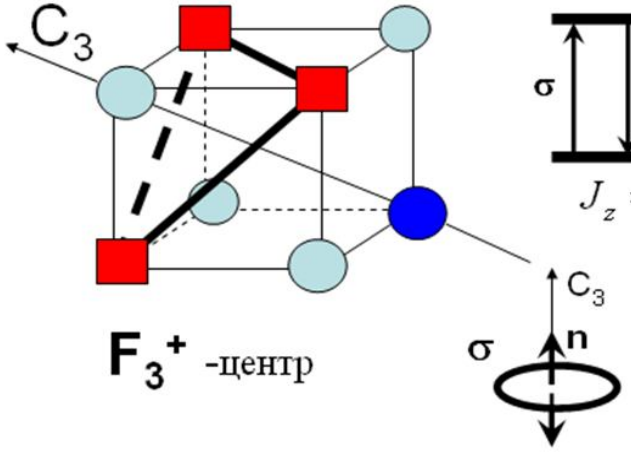
Dynamic models of F_2, F_3^+ color centers in a lithium fluoride crystals

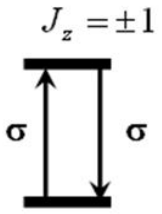
Generally accepted models of aggregate F_2 (top) and F_3^+ (bottom) centers

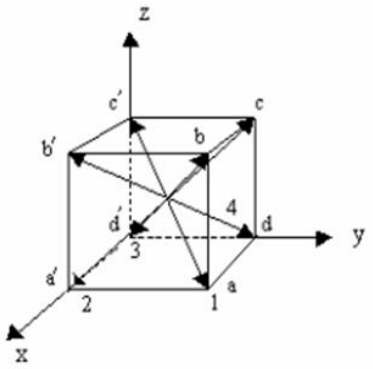












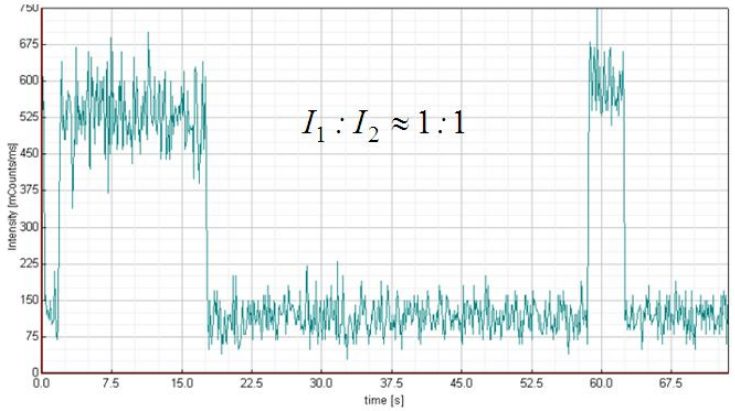
ориентации нормалей $\mathbf{n}_i$ к ротаторам, направленных по четырем осям C_3

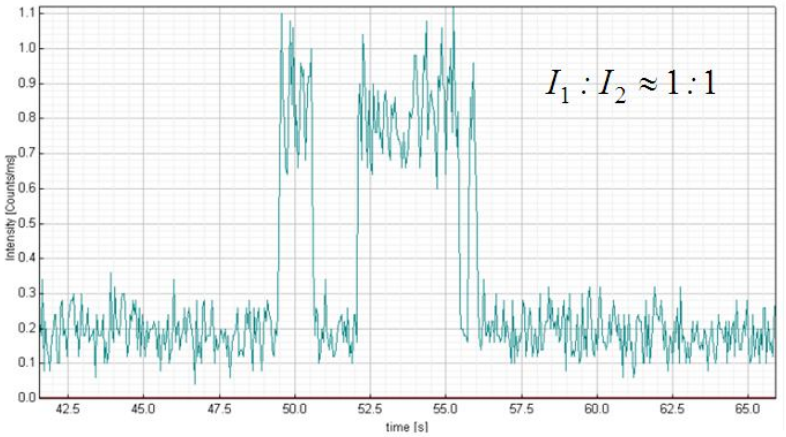
Dynamic models of F_2, F_3^+ color centers in a lithium fluoride crystals

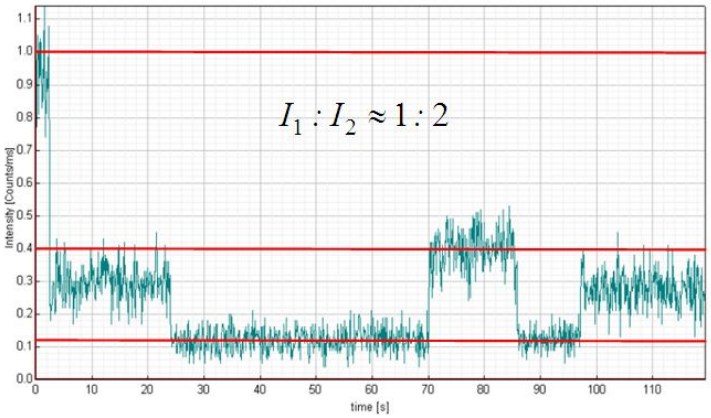
Time dependence of the luminescence of a single F_2 center for the polarization of the exciting light along the edge of the cube (left) and along the side diagonal of the cube (right)

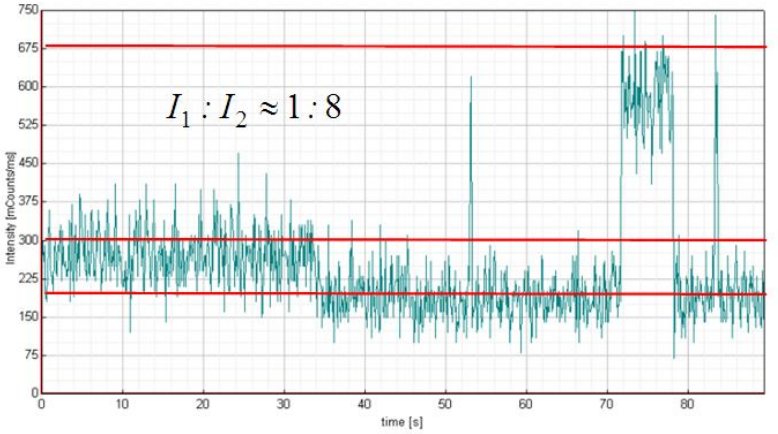
Ориентация образца "0º"

Ориентация образца "45º"







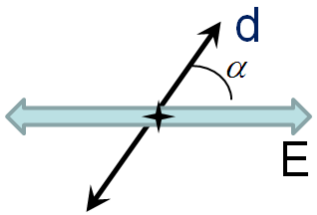


Dynamic models of F_2, F_3^+ color centers in a lithium fluoride crystals

$$\langle \psi_2 | \left(\vec{d} \cdot \vec{E} \right) | \psi_1 \rangle = \left(\langle \psi_2 | \vec{d} | \psi_1 \rangle \cdot \vec{e} \right) E_0$$

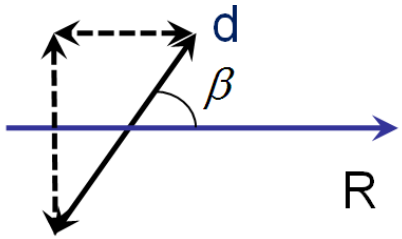
probability of absorption of a photon by a linear oscillator

$$P_{погл} = C \cos^2 \alpha$$



probability of photon emission by an excited linear oscillator

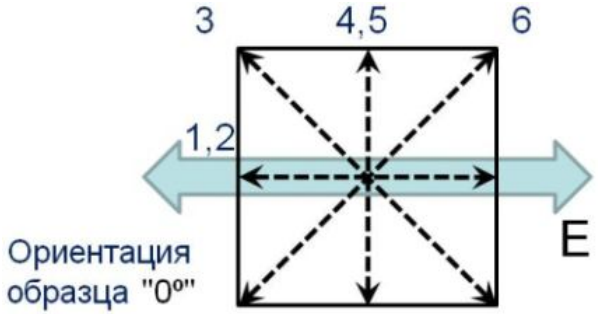
$$P_{изл} = C \sin^2 \beta$$

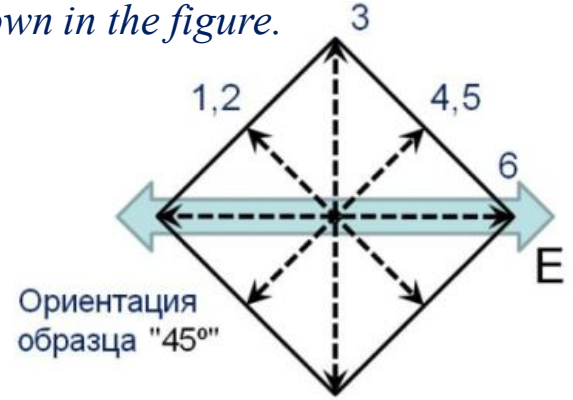


total probability of photon emission by linear oscillator

$$I = P_{погл} \cdot P_{изл}$$

The projections of linear oscillators on the (100) plane corresponding to one of the six possible orientations of the F_2 center. The exciting light was incident normal to the plane of the figure and the vector E was polarized as shown in the figure.





Dynamic models of F_2, F_3^+ color centers in a lithium fluoride crystals

Transition probabilities and intensity ratios for two orientations

	$P^{погл}$	$P^{изл}$	I
ориентация *"0°"*	$P_{1,2}^{погл} = C\cos^2\alpha = C\left(\frac{1}{2}\right)$ $P_{3,6}^{погл} = C\left(\frac{1}{2}\right)$ $P_{4,5}^{погл} = 0$	$P_{1,2}^{изл} = C\left(\frac{1}{2}\right);$ $P_{3,6}^{изл} = C(1);$ $P_{4,5}^{изл} = 0$	$I_{1,2} = C\left(\frac{1}{4}\right);$ $I_{3,6} = C\left(\frac{1}{2}\right);$ $I_{4,5} = 0;$
ориентации *"45°"*	$P_{1,2,4,5}^{погл} = C\left(\frac{1}{4}\right)$ $P_3^{погл} = 0$ $P_6^{погл} = C(1)$	$P_{1,2,4,5}^{изл} = C\left(\frac{1}{2}\right)$ $P_3^{изл} = 0$ $P_6^{изл} = C(1)$	$I_{1,2,4,5} = C\left(\frac{1}{8}\right)$ $I_6 = C(1)$ $I_3 = 0$

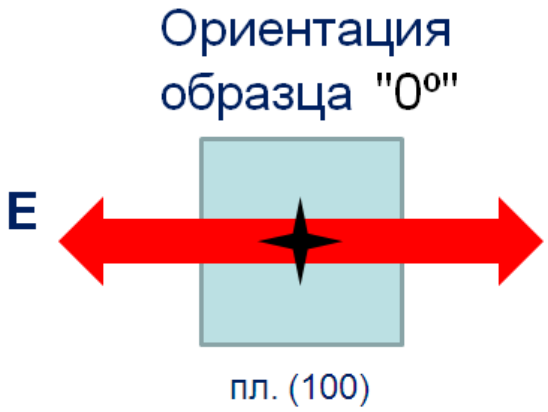
The obtained ratios of luminescence intensities for possible orientations of a single F_2 center correspond to those obtained in experiments

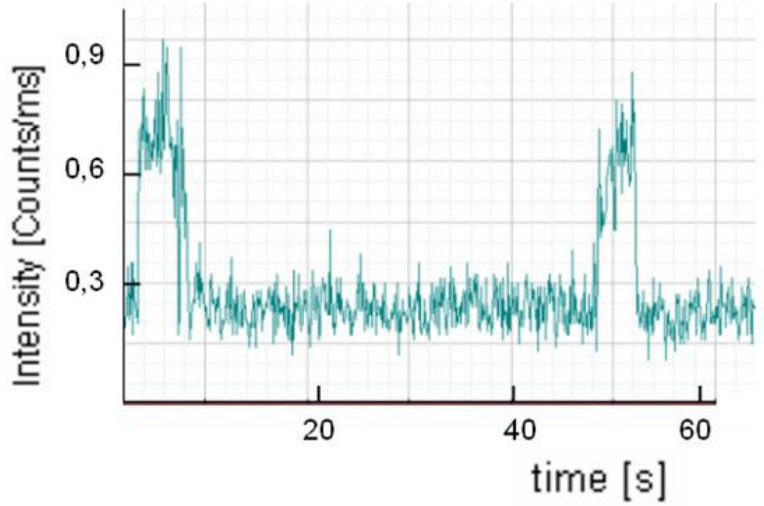
$$I_{1,2} : I_{3,6} : I_{4,5} = 1 : 2 : 0$$

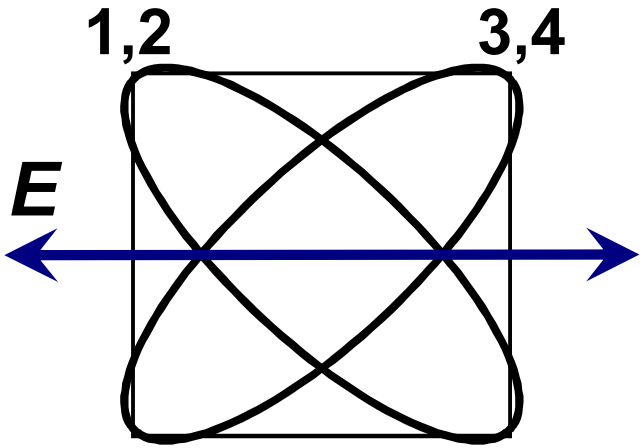
$$I_6 : I_{1,2,4,5} : I_3 = 8 : 1 : 0$$

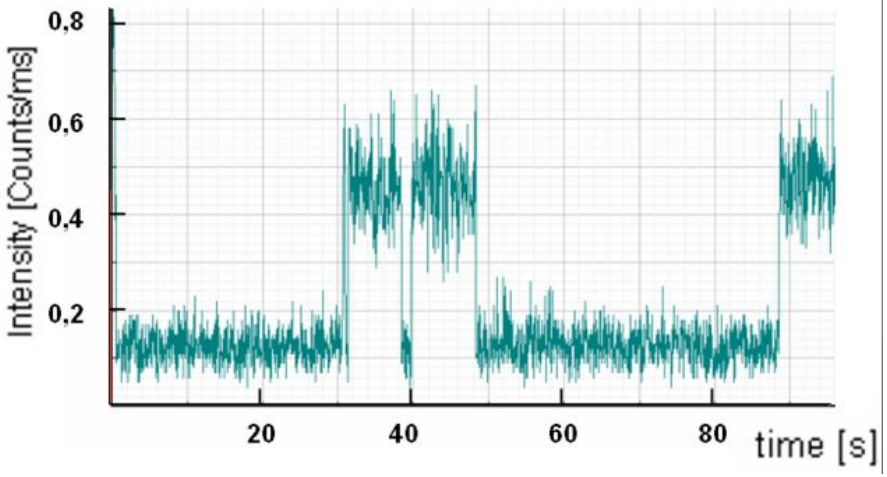
Dynamic models of F_2, F_3^+ color centers in a lithium fluoride crystals

Trajectories of luminescence intensity of single F_3^+ centers for sample orientations "0°"



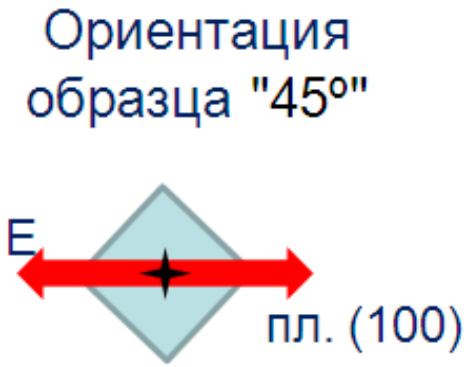


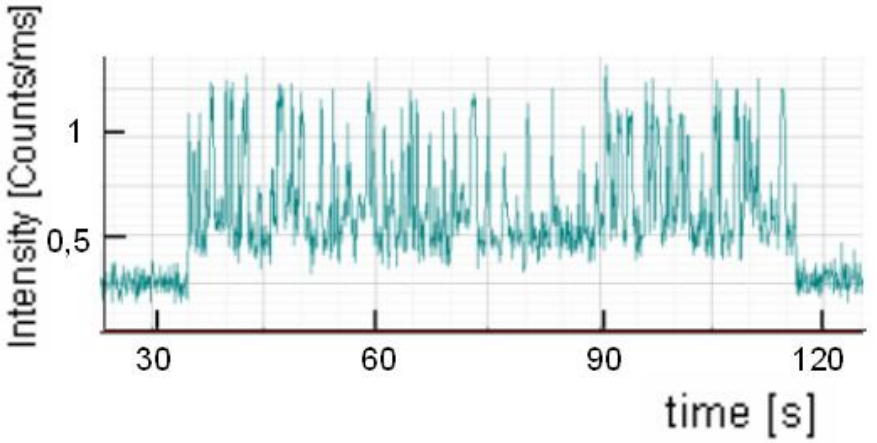


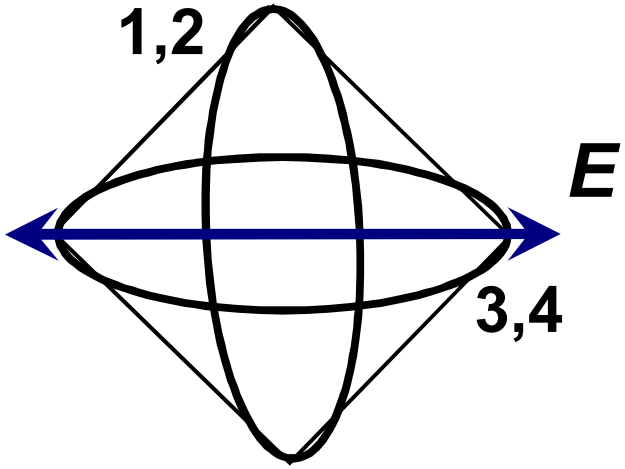


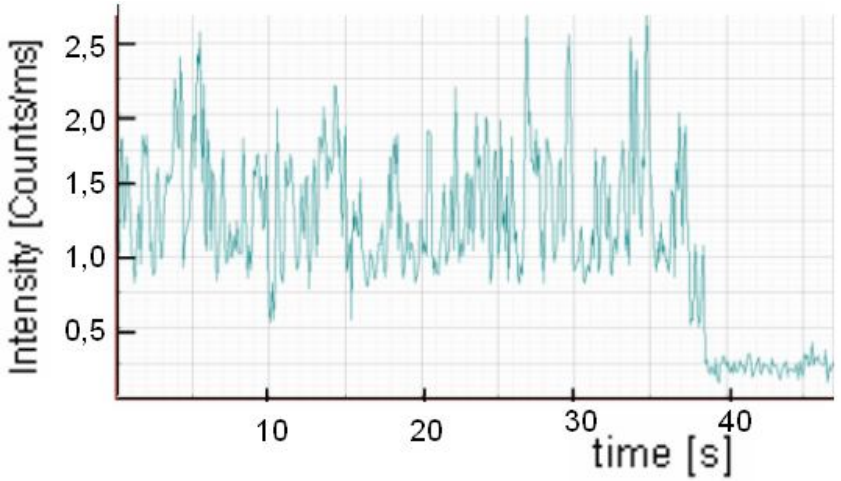
Dynamic models of F_2, F_3^+ color centers in a lithium fluoride crystals

Trajectories of luminescence intensity of single F_3^+ centers for sample orientations «45°"



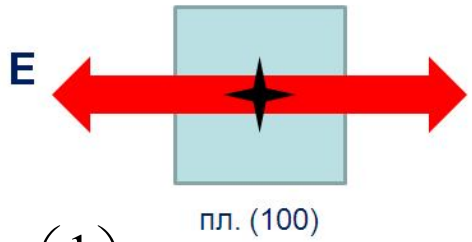






Dynamic models of F_2, F_3^+ color centers in a lithium fluoride crystals

Trajectories of luminescence intensity of single F_3^+ centers for sample orientations «45°"



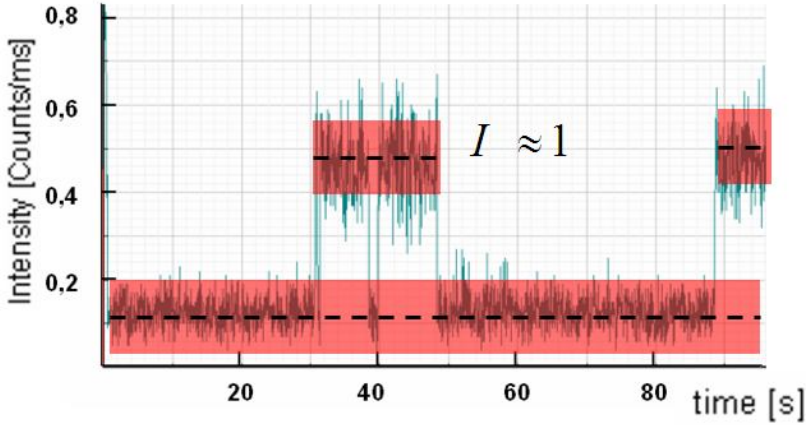
$$P_{1,2}^{погл} = C_1 \cos^2\alpha = C_1\left(\frac{1}{3}\right),$$

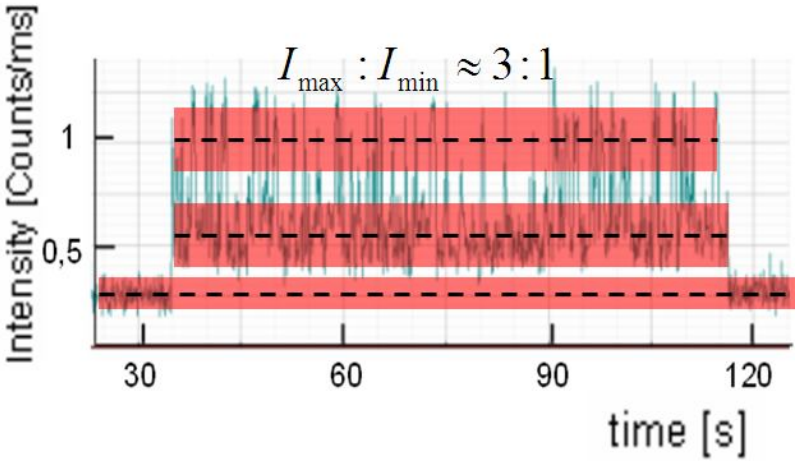
$$P_{1,2,3,4}^{изл} = C_2\left(1+\frac{1}{3}\right), \quad I_{1,2} = C_1C_2\left(\frac{4}{9}\right);$$

$$P_{3,4}^{погл} = C_1(1),$$

$$I_{3,4} = C_1C_2\left(\frac{4}{3}\right);$$

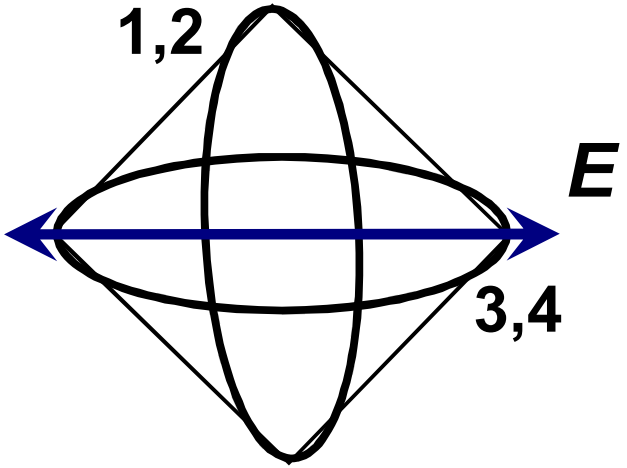
$$\frac{I_{1,2}^{min}}{I_{3,4}^{max}} = \frac{1}{3}$$





Dynamic models of F_2, F_3^+ color centers in a lithium fluoride crystals

Polarized components of the luminescence intensity of a single F_3^+ center for sample orientations «45°"



$$P_{1,2}^{погл} = C_1\left(\frac{1}{3}\right), \quad P_{1,2}^{изл,\,II} = C_2\left(\frac{1}{3}\right), \quad P_{1,2}^{изл,\,\perp} = C_2(1),$$

$$I_{1,2}^{II} = C_1C_2\left(\frac{1}{9}\right), \quad I_{1,2}^{\perp} = C_1C_2\left(\frac{1}{3}\right);$$

$$P_{3,4}^{погл} = C_1(1), \quad P_{3,4}^{изл,\,II} = C_2(1), \quad P_{3,4}^{изл,\,\perp} = C_2\left(\frac{1}{3}\right),$$

$$I_{3,4}^{II} = C_1C_2(1), \quad I_{3,4}^{\perp} = C_1C_2\left(\frac{1}{3}\right);$$

$$\frac{I_{1,2}^{II}}{I_{3,4}^{II}} = \frac{1}{9}, \quad \frac{I_{1,2}^{\perp}}{I_{3,4}^{\perp}} = 1; \quad I_{max} : I_{max}^{II} : I^{\perp} = 4 : 3 : 1.$$

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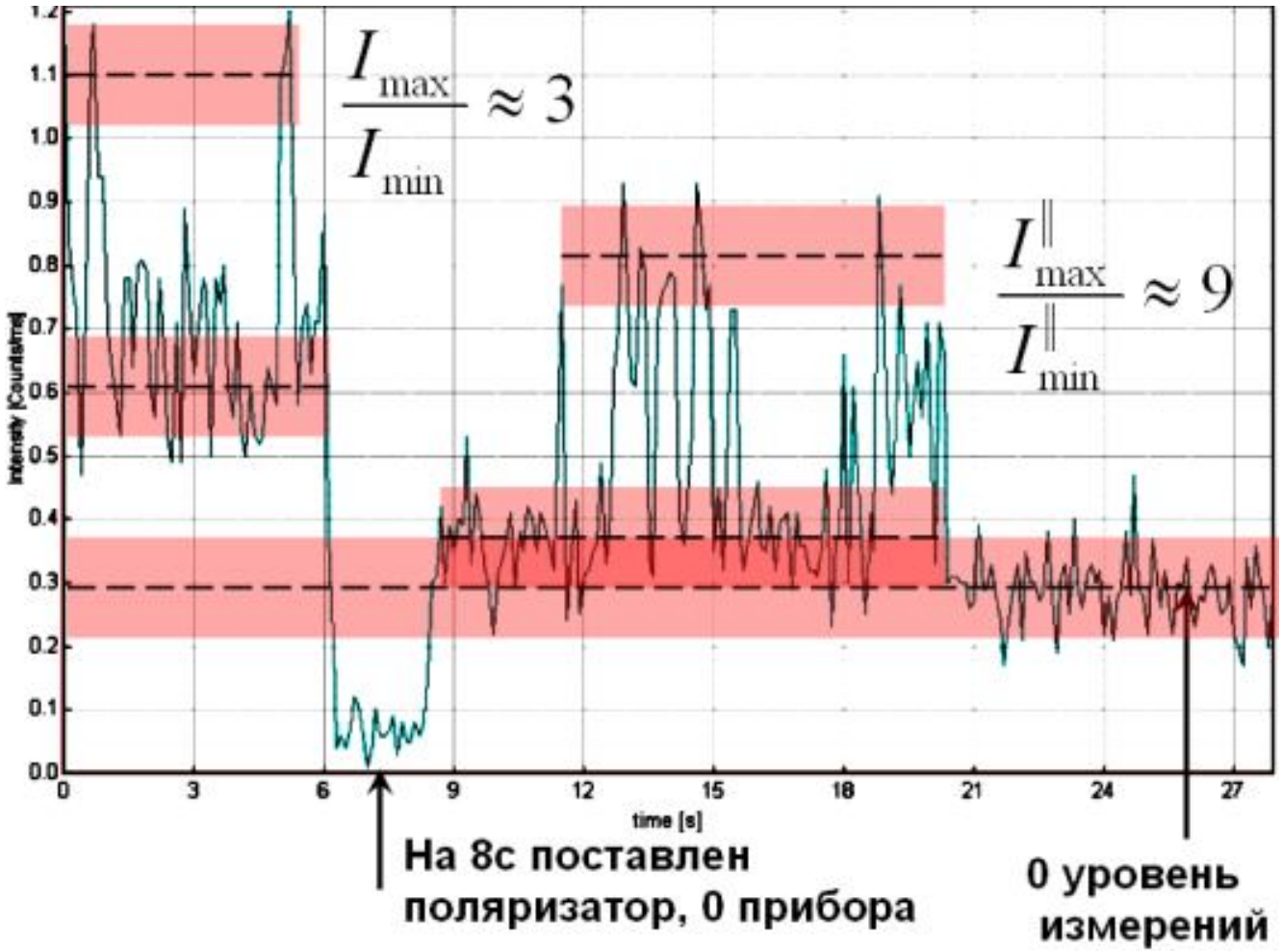
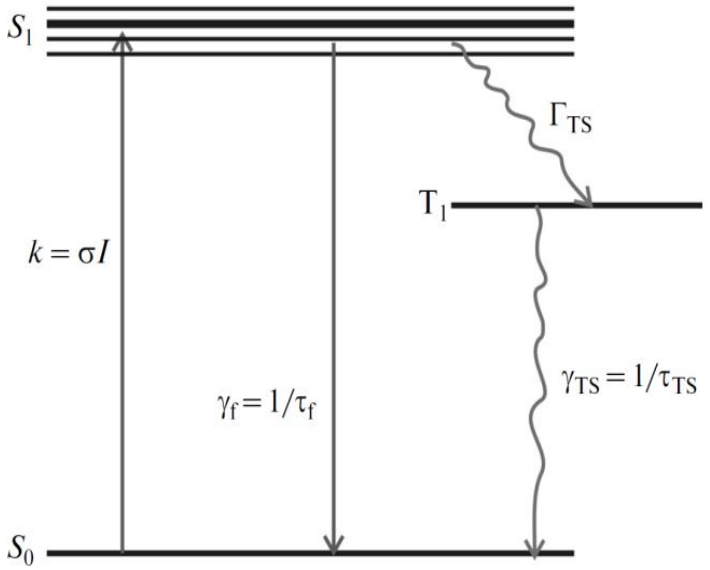
Dynamic models of F_2, F_3^+ color centers in a lithium fluoride crystals

Polarized components of the luminescence intensity of a single F_3^+ center for sample orientations «45°"



Dynamic models of F_2, F_3^+ color centers in a lithium fluoride crystals



$$\dot{\rho}_0 = -k\rho_0 + \gamma_f\rho_1 + \gamma_{ST}\rho_2;$$

$$\dot{\rho}_1 = k\rho_0 - (\gamma_f + \Gamma_{TS})\rho_1;$$

$$\rho_2 = \Gamma_{TS}\dot{\rho}_1 - \gamma_{ST}\rho_2.$$

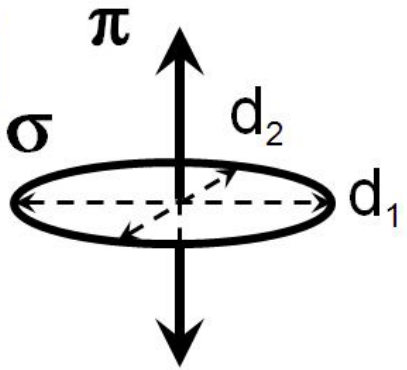
$$w_{on} = \frac{1}{\tau_{on}}\exp\left(-\frac{t}{\tau_{on}}\right), \quad w_{off} = \frac{1}{\tau_{off}}\exp\left(-\frac{t}{\tau_{off}}\right),$$

$$w_{reo} = \frac{1}{\tau_{reo}}\exp\left(-\frac{t}{\tau_{reo}}\right),$$

For F_2 center, reorientation is "enabled" only for off intervals, for F_3^+ center always.

A universal method for determining the type (multipolarity) and orientation of quantum systems in crystalline media

1.



Поглощение-излучение

$\pi - \pi$

$\pi - \sigma$

$\sigma - \pi$

$\sigma - \sigma$

3. БМ

$i \Rightarrow i$

2.

$3C_4$

$4C_3$

$6C_2$

В кубическом кристалле

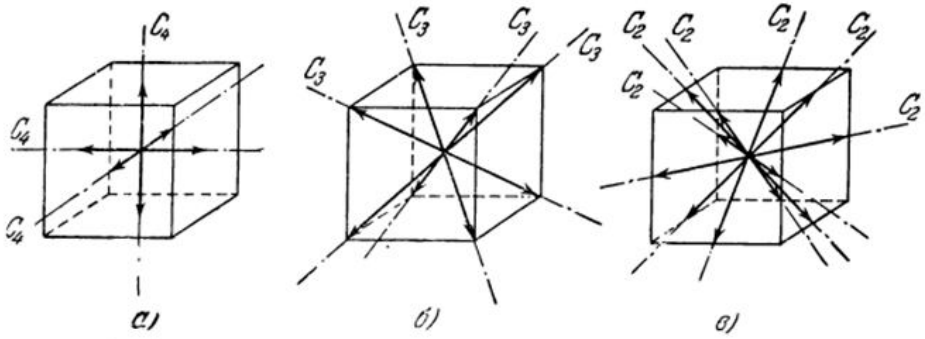


Рис. 75. Ориентация анизотропных центров по осям симметрии кубических кристаллов:
а—четвертого, *б*—третьего, *в*—второго порядков.

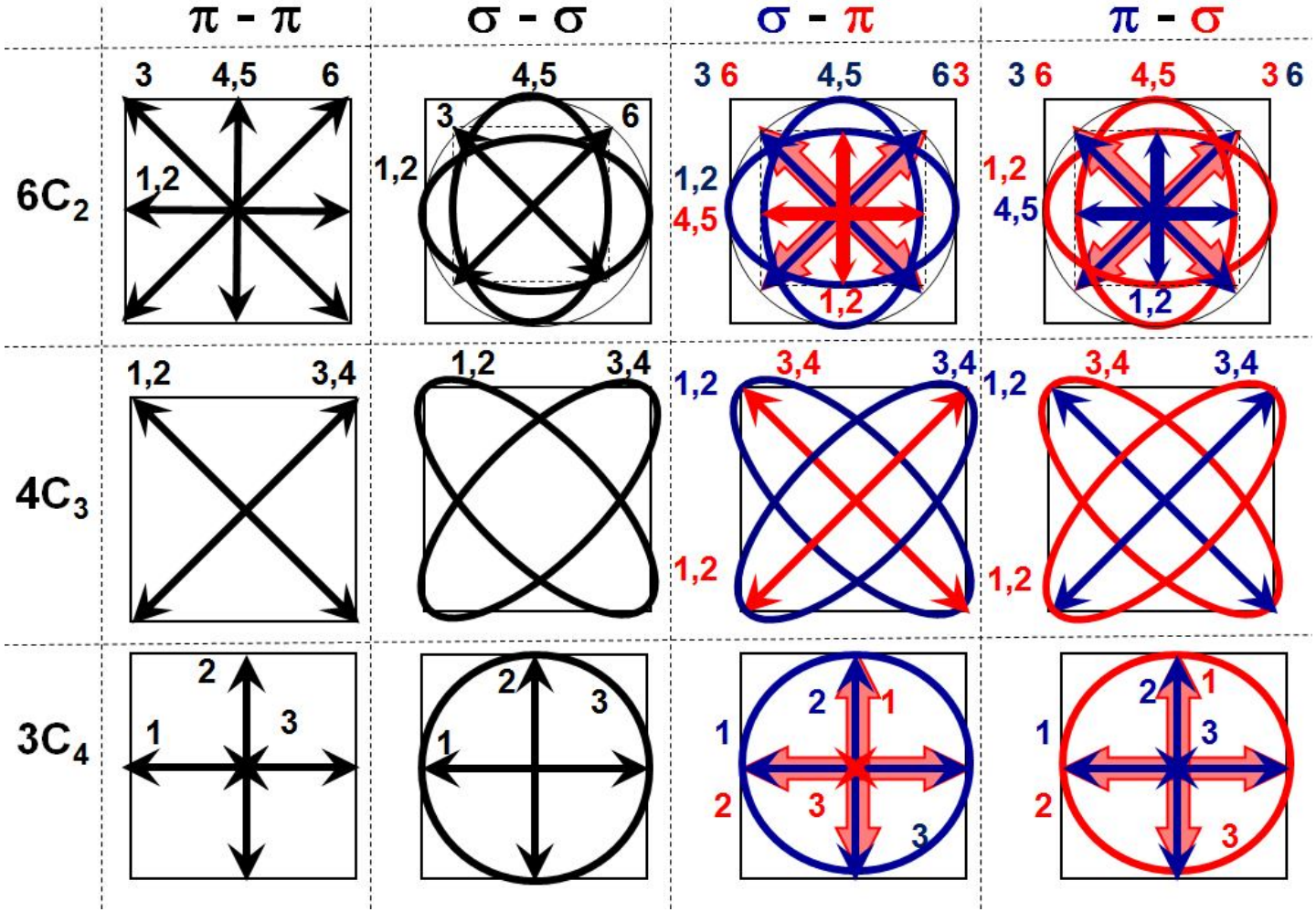
1) The absorbing and emitting transitions at the center of the luminescence are described by linear oscillators and "rotators".

2) These linear oscillators and "rotators" in a cubic crystal are directed along the axes of symmetry either $3C_4$, or $4C_3$, or $6C_2$.

3) There is no migration of energy between centers, i.e. the center absorbed the photon, and it also emitted it.

A universal method for determining the type (multipolarity) and orientation of quantum systems in crystalline media

Projections onto the (100) plane of linear oscillators and "rotators" for all centers possible in a cubic crystal



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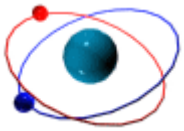
A universal method for determining the type (multipolarity) and orientation of quantum systems in crystalline media

The characters of quantum trajectories of single color centers (quantum systems) possible in a cubic crystal

	π - π	σ - σ	σ - π	π - σ
6C$_2$ a	$I_{1,2}:I_{3,6}:I_{4,5}=1:2:0$ $I^{\parallel}_{1,2}:I^{\parallel}_{3,6}:I^{\parallel}_{4,5}=1:1:0$ $I^{\perp}_{1,2}:I^{\perp}_{3,6}:I^{\perp}_{4,5}=0:1:0$	$I_{1,2}:I_{3,6}:I_{4,5}=6:2:3$ $I^{\parallel}_{1,2}:I^{\parallel}_{3,6}:I^{\parallel}_{4,5}=4:1:1$ $I^{\perp}_{1,2}:I^{\perp}_{3,6}:I^{\perp}_{4,5}=2:1:2$	$I_{1,2}:I_{3,6}:I_{4,5}=2:2:1$ $I^{\parallel}_{1,2}:I^{\parallel}_{3,6}:I^{\parallel}_{4,5}=0:1:1$ $I^{\perp}_{1,2}:I^{\perp}_{3,6}:I^{\perp}_{4,5}=2:1:0$	$I_{1,2}:I_{3,6}:I_{4,5}=0:2:3$ $I^{\parallel}_{1,2}:I^{\parallel}_{3,6}:I^{\parallel}_{4,5}=0:1:1$ $I^{\perp}_{1,2}:I^{\perp}_{3,6}:I^{\perp}_{4,5}=0:1:2$
6C$_2$ b	$I_6:I_{1,2,4,5}:I_3=16:2:0$ $I^{\parallel}_6:I^{\parallel}_{1,2,4,5}:I^{\parallel}_3=16:1:0$ $I^{\perp}_6:I^{\perp}_{1,2,4,5}:I^{\perp}_3=0:1:0$	$I_6:I_{1,2,4,5}:I_3=16:18:0$ $I^{\parallel}_6:I^{\parallel}_{1,2,4,5}:I^{\parallel}_3=16:9:0$ $I^{\perp}_6:I^{\perp}_{1,2,4,5}:I^{\perp}_3=0:9:0$	$I_6:I_{1,2,4,5}:I_3=16:6:0$ $I^{\parallel}_6:I^{\parallel}_{1,2,4,5}:I^{\parallel}_3=0:3:0$ $I^{\perp}_6:I^{\perp}_{1,2,4,5}:I^{\perp}_3=16:3:0$	$I_6:I_{1,2,4,5}:I_3=16:6:0$ $I^{\parallel}_6:I^{\parallel}_{1,2,4,5}:I^{\parallel}_3=16:3:0$ $I^{\perp}_6:I^{\perp}_{1,2,4,5}:I^{\perp}_3=0:3:0$
4C$_3$ a	$I_{1,2,3,4}=2$ $I^{\parallel}_{1,2,3,4}=1$ $I^{\perp}_{1,2,3,4}=1$	$I_{1,2}:I_{3,4}=2:2$ $I^{\parallel}_{1,2}:I^{\parallel}_{3,4}=1:1$ $I^{\perp}_{1,2}:I^{\perp}_{3,4}=1:1$	$I_{1,2}:I_{3,4}=2:2$ $I^{\parallel}_{1,2}:I^{\parallel}_{3,4}=1:1$ $I^{\perp}_{1,2}:I^{\perp}_{3,4}=1:1$	$I_{1,2}:I_{3,4}=2:2$ $I^{\parallel}_{1,2}:I^{\parallel}_{3,4}=1:1$ $I^{\perp}_{1,2}:I^{\perp}_{3,4}=1:1$
4C$_3$ b	$I_{1,2}:I_{3,4}=0:1$ $I^{\parallel}_{1,2}:I^{\parallel}_{3,4}=0:1$ $I^{\perp}_{1,2}:I^{\perp}_{3,4}=0:0$	$I_{1,2}:I_{3,4}=4:12$ $I^{\parallel}_{1,2}:I^{\parallel}_{3,4}=1:9$ $I^{\perp}_{1,2}:I^{\perp}_{3,4}=3:3$	$I_{1,2}:I_{3,4}=1:3$ $I^{\parallel}_{1,2}:I^{\parallel}_{3,4}=1:0$ $I^{\perp}_{1,2}:I^{\perp}_{3,4}=0:3$	$I_{1,2}:I_{3,4}=0:4$ $I^{\parallel}_{1,2}:I^{\parallel}_{3,4}=0:1$ $I^{\perp}_{1,2}:I^{\perp}_{3,4}=0:3$
3C$_4$ a	$I_1:I_2:I_3=1:0:0$ $I^{\parallel}_1:I^{\parallel}_2:I^{\parallel}_3=1:0:0$ $I^{\perp}_1:I^{\perp}_2:I^{\perp}_3=0:0:0$	$I_1:I_2:I_3=1:0:2$ $I^{\parallel}_1:I^{\parallel}_2:I^{\parallel}_3=1:0:1$ $I^{\perp}_1:I^{\perp}_2:I^{\perp}_3=0:0:1$	$I_1:I_2:I_3=1:0:0$ $I^{\parallel}_1:I^{\parallel}_2:I^{\parallel}_3=0:0:0$ $I^{\perp}_1:I^{\perp}_2:I^{\perp}_3=1:0:0$	$I_1:I_2:I_3=1:0:0$ $I^{\parallel}_1:I^{\parallel}_2:I^{\parallel}_3=0:0:0$ $I^{\perp}_1:I^{\perp}_2:I^{\perp}_3=1:0:0$
3C$_4$ b	$I_1:I_2:I_3=2:2:0$ $I^{\parallel}_1:I^{\parallel}_2:I^{\parallel}_3=1:1:0$ $I^{\perp}_1:I^{\perp}_2:I^{\perp}_3=1:1:0$	$I_1:I_2:I_3=2:2:8$ $I^{\parallel}_1:I^{\parallel}_2:I^{\parallel}_3=1:1:4$ $I^{\perp}_1:I^{\perp}_2:I^{\perp}_3=1:1:4$	$I_1:I_2:I_3=2:2:0$ $I^{\parallel}_1:I^{\parallel}_2:I^{\parallel}_3=1:1:0$ $I^{\perp}_1:I^{\perp}_2:I^{\perp}_3=1:1:0$	$I_1:I_2:I_3=2:2:0$ $I^{\parallel}_1:I^{\parallel}_2:I^{\parallel}_3=1:1:0$ $I^{\perp}_1:I^{\perp}_2:I^{\perp}_3=1:1:0$

Conclusions



1. *The methods of spectroscopy of quantum systems based on the measurement of parameters of photoluminescent quantum trajectories was proposed and experimentally proved .*
2. *The reorientation of single F_2 centers in the triplet state was experimentally observed; the theoretically obtained intensity ratios for different center orientations are in agreement with experiment.*
3. *The reorientation of single F_3^+ centers was experimentally observed, the theoretically obtained relations intensities for different orientations of the center, correspond to the experiment.*
4. *Unlike the F_2 center, which reorients only in the triplet ("dark") state, F_3^+ center is reoriented in the ground state, and such reorientation orientational diffusion does not lead to translational diffusion of the center.*
5. *A method is proposed for determining the orientation and type of absorbing and emitting oscillators of a single fluorescence center in cubic crystals, based on its polarized quantum trajectories.*

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Thank you for attention!

Спасибо за внимание