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Laser Modification of Mossbauer Spectra in Eu2+:CaS

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The major goal of this project is to make a proof of principle experiment demonstrating the influence of laser radiation on the Mossbauer spectrum of ^{151}Eu^{2+}:CaS.

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FINAL REPORT

Laser Modification of Mossbauer Spectra in Eu^{2+}:CaS

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Air Force Office of Scientific Research
FINAL REPORT

Contract/Grant Title: Laser Modification of Mossbauer Spectra in Eu^{2+}:CaS
Amount: $30,000
Duration of project: 3 months
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Number of Papers submitted to refereed journals, but not published: 9

[1] R. Coussement, Y. Rostovtsev, J. Odeurs, P. Mandel, R. Shakhmuratov, and O. Kocharovskaya, EIT for gamma radiation via nuclear level-crossing, Phys. Rev. Lett., submitted.

[2] Y. Rostovtsev, O. Kocharovskaya, Laser-Mossbauer spectroscopy as a new tool for nuclear transitions, Hyperfine Interaction, submitted.

[3] O.Kocharovskaya, R.Kolesov and Yu.Rostovtsev, Mossbauer gamma-ray laser with coherent optical driving, Hyperfine interactions, submitted.

[4] O. Kocharovskaya, A. Belyanin, and Y. Rostovtsev, Atomic and Nuclear Interference Effects for Quantum Information Processing, Quantum Computers and Computing, accepted for publication (2002).

[5] R.Kolesov and O. Kocharovskaya, Ultrashort pulses generation in solid media with a long lived spin coherence, Phys. Rev.A., submitted.

[6] A. Javan, O. Kocharovskaya, H. Lee, M. O. Scully, Narrowing of electromagnetically induced transparency resonance in a Doppler broadened medium, Phys. Rev. A, submitted.

[7] E. Kuznetsova, P. Hemmer, O. Kocharovskaya, M.O. Scully, "Effects of inhomogeneous line broadening on Electromagnetically Induced Transparency (EIT) and slow group velocity," Phys. Rev. A, submitted.

[8] Y. Rostovtsev, O. Kocharovskaya, G. Welch, M.O. Scully, Optics Photonics News, submitted.

[9] H. Zameer, F. Vagizov, Journal of Modern Optics, submitted.

Number of Papers published in refereed journals 4

[1] Y. Rostovtsev, and O. Kocharovskaya, Modification of Mossbauer spectra under the action of electromagnetic fields, Hyperfine Interaction 135, 233-255 (2001).

[2] R. Kolesov, Optical continua generation in a coherently prepared Raman medium, Phys. Rev. A 64, 063819 (2001)

[3] A.B. Matsko, Yu. Rostovtsev, O. Kocharovskaya, A. Zibrov, M.O. Scully, Nonadiabatic Approach to Quantum Optical Information Storage, Phys. Rev. A 64, 043809 (2001).

[4] A. S. Zibrov, A. B. Matsko, O. Kocharovskaya, Y. V. Rostovtsev, G. R. Welch, and M. O. Scully, Transporting and Time Reversing Light via Atomic Coherence, Phys. Rev. Lett. 88, 103601 (2002).

Number of books or chapters submitted, but not yet published: 1

[1] R.Kolesov and O. Kocharovskaya, Chapter 6.7.1.4 Mossbauer Spectroscopy, Enciclopedia of Life Support System, UNESCO, EOLSS Publishers Co. Ltd., submitted.

Number of books or chapters published (for each, provide a complete citation): 1

[1] A.B. Matsko, O. Kocharovskaya, Y. Rostovtsev, G.R. Welch, A.S. Zibrov, M.O. Scully, Slow, ultra-slow, stored and frozen light, The advances in Atomic, Molecular, and Optical Physics 46, 191 (2001), edited by B. Bederson and H. Walther.

Number of invited presentations (for each, provide a complete citation): 14

- Symposium on coherent sources: semiconductor lasers and gamma-rays, April 4-6, 2001, Brussels, Belgium.

  1 O. Kocharovskaya, Laser control of nuclear transitions as a way to laser-Mossbauer spectroscopy and gamma-ray laser

  2 Y. Rostovtsev, Electromagnetically Induced Transparency for gamma-ray transition

- 17-th International Conference on Coherent and Nonlinear Optics ICONO, Belarus, Minsk (June, 2001),

  3 Kocharovskaya O. and Kolesov R., Atomic interference phenomena: from optics to gamma-rays

- International Conference on Progress in Nonlinear Science, dedicated to the 100th Anniversary of A.A. Andronov, Nizhny Novgorod, Russia, July 2-6, 2001.

  4 Kocharovskaya O, Nonlinear optics with coherently prepared medium

- International Workshop on Laser Physics and Quantum Optics, Jackson Hole, Wyoming, July 29-August 4, 2001.

  5 Belyanin A., Coherent radiation from neutral molecules moving above the grating

  6 Rostovtsev Y., EIT for nuclear transition via level crossing

- XXII Solvay Conference in Physics, November 2001, Delphi, Greece. Invited talk.

  7 Kocharovskaya O., Nuclear Interference Effects for Quantum Information Processing,

- International Conference on Lasers 2001, Tucson, Arizona (2001),

8 Kocharovskaya O., Rostovtsev Y., Kolesov R., Mossbauer Gamma-Ray Laser with Optical Driving

9 Rostovtsev Y., Kolesov R., Kocharovskaya O., Laser-Mossbauer Spectroscopy as a New Tool for Nuclear Transitions

10 Coussement R, EIT for gamma-radiation

- 32nd Winter Colloquium "Physics of Quantum Electronics", Snowbird, Utah, January 2002.

11 Kocharovskaya O., Electromagnetically induced transparency in gamma-rays

12 Rostovtsev Y., Kocharovskaya O., Scully, Stop and go control of light Pulse via quantum coherence

13 Kolesov R., Optical continua generation in a coherently prepared Raman medium, oral

14 E. Kuznetsova, O. Kocharovskaya, P. Hemmer, and M. O. Scully, Atomic interference phenomena in solids with a long-lived spin coherence

Number of submitted presentations (for each, provide a complete citation): 5

- International Conference on Progress in Nonlinear Science, dedicated to the 100th Anniversary of A.A. Andronov, Nizhny Novgorod, Russia, July 2-6, 2001.

1 E. Kuznetsova, R. Kolesov, and O. Kocharovskaya, Atomic interference phenomena in solids with a long-lived spin coherence,

- 17-th International Conference on Coherent and Nonlinear Optics ICONO, Belarus, Minsk (2001),

2 Kolesov R. and Kocharovskaya O., Short pulse generation due to coherent population trapping

3 E. Kuznetsova, O. Kocharovskaya, and M. O. Scully, Electromagnetically induced transparency in solids with long-lived spin coherence,

4 Kolesov R., Kuznetsova E., Modification of Mossbauer spectra by means of polarization-selective optical pumping

- International Workshop "Mid-Infrared Coherent Sources", S.-Petersburg, Russia, June 25-29, 2001 (1 paper).

5 Belyanin A., Inversionless lasing with self-generated driving field

Honors/Awards/Prizes for contract/grant employees: 4

1. Olga Kocharovskaya, the PI of the contract, has been given a tenure and has been promoted to the rank of Full Professor of Physics at Texas A&M University.
2. Zameer Hasan, the Co-PI has been promoted to the rank of Full Professor
3. Jeff Carroll, the Co-PI has been promoted to the rank of Full Professor
4. Roman Kolesov, PhD student, who is involved in this project, received an award of the International Conference on Mossbauer Spectroscopy for the best student's oral paper, and the TAMU Physics Graduate Student's Award for Excellence in Research.

Other funding

- DARPA, Mossbauer Gamma-ray laser with coherent optical driving, $282,576 (2001-2002).
- Texas Advanced Technology and Research Programs, Multiple Raman Scattering in solids for the new coherent sources of ultrashort pulses, $150,000 (2002-2003).

Part II

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(a2) Co-Investigator::
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(c) Program Objective:
The major goal of this project is to make a proof of principle experiment demonstrating the influence of laser radiation on the Mossbauer spectrum of $^{151}Eu^{2+}$:CaS.

(d) Significant Results:

Modifications of Mossbauer spectra

i) **EIT for gamma-rays** In the first time electromagnetically-induced transparency (EIT) for gamma-rays at the nuclear transitions has been demonstrated by studying Mössbauer spectra of ^{57}Fe in a $FeCO_3$ crystal in the presence of a magnetic field. The experimental results have been explained in terms of quantum interference involving nuclear level-crossing.

ii) **Mossbauer spectra of 0.01% Eu^{2+}, Eu^{3+} in MgS** Eu^{2+} and Eu^{3+} Mössbauer spectra in MgS powder with the record small density of Eu ions of 0.01 atomic % were observed. These spectra provide a unique information about the ratio of Eu^{2+}/Eu^{3+} in MgS which is an important characteristics of this permanent hole-burning material. The density was chosen to be the same as in Eu:MgS films which are produced at Temple University by Zameer Hasan's group. So this experiment presents an important step forward a realization of laser control of nuclear transition because it shows that recording of Mossbauer spectra with such low density (which presently available in films) is possible.

iii) **Nuclear interference effects for quantum information processing**

Collective excitations of nuclear spins in solids manipulated by coherent optical pulses are proposed as a system of choice for implementation of quantum information processing. It is shown that a high speed of the optical excitation of nuclear polarization (of the order of submicrosecond) can be nicely combined with a long storage time (of the order of second) and with a nearly 100% efficiency.

iv) **Laser-Mossbauer Spectroscopy**

A new type of spectroscopic technique, Laser-Mossbauer spectroscopy, which is based on comparison of the original Mossbauer spectra with those modified under the action of laser radiation was suggested. This technique, providing a unique information about nuclear structure and crystal environments which is unavailable by any other methods, is illustrated by calculation of possible laser modifications of Mossbauer spectra for a number of different nucleads.

v) **Mossbauer Gamma-ray laser with coherent optical drive**

The novel concept of Mossbauer gamma-ray laser with coherent optical drive is suggested. The essence of this concept is in usage of the resonant optical driving of bounded electrons in atoms in order to

provide a suppression of resonant absorption by 3-5 orders of magnitude reducing it up to the level of the off-resonant losses in the host matrix. It leads to two profound consequences: (i) release in requirement for incoherent pump threshold and accordingly in the heating of the active sample, providing the possibility for pumping of active nuclei in the host lattice without destroying the conditions of both Mossbauer and Borrmann effects (ii) possibility to pump directly at the operating nuclear transition, increasing additionally the efficiency of the incoherent pump by 1-2 orders of magnitude.

Electromagnetically induced transparency(EIT) and its applications

i) **Atomic interference phenomena in solids with a long-lived spin coherence** We generalize a theory of EIT and slow group velocity for the case of inhomogeneouse line broadening on both one and two-photon- transitions which unavoidably takes place in solid materials with a long-lived spin coherence. We identify the new regimes of EIT where EIT linewidth is proportional to the amplitude of the driving field and where it can be essentially reduced due to inhomogeneous broadening of an optical transition. We suggest also a new class of solid materials, namely, rare-earth ions doped semiconductors or dielectrics with electro-dipole allowed transitions, which is very promising for realization and applications of EIT.

ii) **Ultra-short pulse generation in solid medium with long-lived spin coherence** We show that utmost possible Raman coherence between equally populated levels can be excited by two-photon resonant bichromatic field far from one-photon resonance with an optical line via relaxation process. On this basis we suggest a novel mechanism for generation of extremely short pulses with high pulse duty factor and large energy in the pulse. It can be realized in solid materials, such as rare-earth doped dielectrics with long-lived spin coherence or NV-centers in diamond and provide a simple , reliable and convenient technique for many practical applications

Ultraslow and stopped light and its applications

i) **Stopping light via hot atoms**

We prove that it is possible to freeze a light pulse (i.e., to bring it to a full stop) or even to make its group velocity negative in a coherently driven Doppler broadened atomic medium via electromagnetically induced transparency (EIT). This remarkable phenomenon of the ultraslow EIT polariton is based on the spatial dispersion of the refraction index n(w,k), i.e., its wave number dependence, which is due to atomic motion and provides a negative contribution to the group velocity. This is related to, but qualitatively different from, the recently observed light slowing caused by large temporal (frequency) dispersion.

ii) **Nonadiabatic approach to quantum optical information storage** We show that there is no need for adiabatic passage in the storage and retrieval of information in the optically thick vapor of lambda-atoms. We show that even in the case of instantaneous switching of the writing and reading fields compared with adiabatic switching, an almost perfect information storage is possible if the group velocity of the signal pulse is much less than the speed of light in the vacuum and the bandwidth of the signal pulse is much less then the width of the two photon resonance.

iii) **Multiplexing, time-reversing and transporting of the light via atomic coherence** We show that manipulating with the characteristics of the control pulses allows to transfer the information about the quantum state of the signal pulse (stored in the medium) to the light pulse with different frequency, the state of polarization, or the direction of propagation than original signal pulse. It can be called multiplexing stored light. Even the time-reversing of the pulse becomes possible: so that its tail can precede to the head and vice versa. Moreover, the coherently driven atoms moving in the gas can transport the quantum information from one spatial point to another (transporting stored light). The experiments in support of our theoretical consideration have been performed in Rb vapor.

Impact:

i) First experimental demonstration of EIT in gamma-rays at the nuclear transitions

ii) New method for generation of gamma-ray radiation

iii) New type of spectroscopy, Laser-Mossbauer spectroscopy.

iv) New regimes of EIT (EIT line-narrowing, mixed EIT-SIT) and new EIT media (E1 electronic and nuclear transitions in rare-earth doped crystals)

v) New regimes for quantum information storage (nonadiabatic storage, multipleaxing, time-reversing and transporting stored light)

vi) New method of ultra-short pulse generation in a solid medium with a long-lived coherence

vii) Proposal for usage of nuclear spins in rare-earth doped solids as a system of choice for implementation of quantum information processing

Summary of Plans

Further theoretical investigation and experimental demonstration of

i) Nuclear spectra manipulations by means of laser radiation: observation of HF structure from the optically excited electronic transitions and suppression of the resonant gamma-ray absorption

ii) EIT and ultra-slow group velocity for gamma-rays at the nuclear transitions

iii) Ultra-short pulse generation in solids with a long-lived spin coherence