AD-A273 632

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE: Nov. 10, 1993

3. REPORT TYPE AND DATES COVERED: Final technical report 1/88 - 12/91

4. TITLE AND SUBTITLE: Quantum optical aspects of topological phases, such as Berry's phase

5. FUNDING NUMBERS: N00014-88-K-0126

6. AUTHOR(S): Raymond Y. Chiao

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES): University of California at Berkeley, Dept. of physics, Berkeley, CA 94720

8. PERFORMING ORGANIZATION REPORT NUMBER: 4124113

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES): Office of Naval Research, Detachment Arlington, 800 Quincy St., BCT #1, Code 1112LO, Arlington, VA 22217-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER: R&T 4124113

11. SUPPLEMENTARY NOTES: —

DTIC ELECTE DEC 13 1993 S A

12a. DISTRIBUTION/AVAILABILITY STATEMENT: This document has been approved for public release and sale; its distribution is unlimited

12b. DISTRIBUTION CODE: —

13. ABSTRACT (Maximum 200 words)

A newly discovered topological phase factor, commonly known as "Berry's phase," its generalizations, and closely related phases, are proposed to be observed at the quantal level using interference experiments with nonclassical light sources. Possible applications of these phases include inertial guidance devices.

93 12 7 006

93-29805

14. SUBJECT TERMS: quantum optics, Berry's phases

15. NUMBER OF PAGES: 5

16. PRICE CODE: —

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
None	None	None	—

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)

(12)

November 10, 1993

Linden Clausen, Administrative Contracting Officer
Department of the Navy
Office of Naval Research
University of California, Berkeley Office
Richmond Field Station
Richmond, CA 94804-0001

Dear Mr. Clausen:

RE: N00014-88-K-0126 Final technical report

This is in response to the letter of October 28, which requested a final technical report with transmittal document indicating distribution to required addresses, and the final report of inventions and subcontracts (DD882, enclosed). Attached to this letter is the final technical report.

Sincerely yours,

Raymond Chiao

Raymond Y. Chiao

cc. Nancy Caputo, SPO

Accesion For		
NTIS CRA&I	☑	
DTIC TAB	☐	
Unannounced	☐	
Justification		
By		
Distribution /		
Availability Codes		
Dist	Avail and / or Special	
A-1		

Final technical report for ONR contract N00014-88-K-0126, "Quantum optical aspects of topological phases, such as Berry's phase.

The contract was for performing experiments on a recently discovered topological phase factor known as "Berry's phase," We proposed to examine this phase at both the quantum and classical levels, in its various manifestations. The goals of this contract were successfully accomplished; in particular, we succeeded in demonstrating this phase at the single photon level, thereby demonstrating that this phase did not originate at the classical level. Possible applications of this phase were explored. A two-photon light source, in the form a parametric down-converter of uv laser photons into highly correlated red photons was successfully constructed, and coincidence counting techniques were successfully applied to the detection of the conjugate signal and idler red photons. This formed the experimental basis for the examination of not only Berry's phase, but of the energy-time uncertainty relations, the Franson experiment, the measurement of the tunneling time of the photon, the quantum eraser, and other optical phenomena closely related to the Einstein-Podolsky-Rosen "paradox."

Berry's topological phase, which is an Aharonov-Bohm-like phase which a system can acquire after a sequence of changes which returns the system back to its starting point, has be studied using quantum optical techniques in this contract. This phase was discovered in the quantum adiabatic theorem by Berry, and one of its early manifestations was discovered in optics by the principal investigator in collaboration with Wu and Tomita. The phase anholonomy which Berry discovered in the quantum adiabatic theorem can be expressed as an extra phase factor $\exp(i\gamma_n(C))$ which the wavefunction can acquire after a cycle C in the parameter space of the Hamiltonian H(R), where R denotes some slowly varying parameters which return to their starting values. This *topological* phase factor is accumulated by the wavefunction in addition to the usual *dynamical* phase factor, $\exp(-i\int E_n dt/\hbar)$. Explicitly, if $H(\mathbf{R})|n;\mathbf{R}\rangle = E_n(\mathbf{R})|n;\mathbf{R}\rangle$, then Berry's phase is

$$\gamma_n(C) = \oint_C \mathbf{A}_{eff} \cdot d\mathbf{R} , \qquad (1)$$

Although we predicted an early optical manifestation of this phase by means of quantum mechanics, we observed it by purely classical optical means. Also, this manifestation was only the first of four recent manifestations of this phase in optics.

Therefore the important scientific questions we would like to address include: Can we observe this phase in *quantum* optics? Are these four recently discovered Berry's phases all that there are in optics? Are there any purely quantum, i.e., ***nonclassical***, Berry's phases in optics? Are there any important applications of these phases?

As described more briefly in the introduction, to observe this phase at the quantum level, we have set up a correlated two-photon light source, in which a UV (pump) photon is broken up into two red photons (signal and idler photons) inside a KDP (potassium dihydrogen phosphate) crystal in the process of parametric down-conversion, following the method of Burnham and Weinberg, and of Mandel *et al.* These photons have been detected in coincidence. In this way, the detection of one photon in one beam can be used to insure that there is one and only one photon in the conjugate beam. Thus a one-photon Fock state can been prepared for our experiment. When this photon enters an interferometer inside which optical elements are placed in such a configuration as to generate a Berry's phase, then the resulting interference pattern can only be understood as resulting from a single photon interfering with itself inside the interferometer. We have also set up a two-photon interferometer, similar to the ones suggested by Franson, and by Horne, Shimony and Zeilinger, in two recent *Physical Review Letters* (62, 2205 and 2209 (1989)), in order to observe a purely quantal Berry's phase.

We successfully observed coincidences from the above two-photon light source in the Spring of 1989. We also constucted a nonplanar Mach-Zehnder interferometer to observe Berry's phase at the classical level. We set up and aligned a system incorporating a white-light-fringe Michelson interferometer.

We also set up a two-photon interferometer, similar to the ones suggested by Franson, and by Horne, Shimony and Zeilinger, in two recent *Physical Review Letters* (62, 2205 and 2209 (1989)), in order to observe a purely quantal Berry's phase. As a first step, we have successfully observed the dynamical phase of two entangled photons (Phys. Rev. A41, 2910 (1990)), and improved our apparatus so that the visibility of our two-photon fringes seen in coincidence exceeded 50%, at which point our results became nonclassical. After obtaining a visibility in excess of 71%, we violated Bell's inequalities, and our results became nonlocal. We also set up and observed the first nonclassical Berry's phase, in the form of Pancharatnam's phase, by means of two zero-order quarter wave plates placed in one arm of a Michelson interferometer. This was done in conjunction with a triple coincidence counting technique, and is described in "Observation of a Nonclassical Berry's Phase for the Photon," which was published shortly after the termination date of this contract in *Physical Review Letters* 66, 588 (1991).

The 15 publications which resulted from this contract were:

"Geometrical Phases from Global Gauge Invariance of Nonlinear Classical Field Theories" (with J. C. Garrison) Phys. Rev. Lett. **60**, 165 (1988).

"Observation of a Topological Phase by Means of a Nonplanar Mach-Zehnder Interferometer" (with A. Antaramian, K. M. Ganga, H. Jiao, S. R. Wilkinson and H. Nathel) Phys. Rev. Lett. **60**, 1214 (1988).

"Lorentz-Group Berry's Phases in Squeezed Light," (with T. F. Jordan) Phys. Lett. **A132**, 77 (1988).

"Two Topological Phases in Optics by means of a Nonplanar Mach-Zehnder Interferometer", (with H. Jiao, S. R. Wilkinson and H. Nathel) Phys. Rev. **A39**, 3475 (1989).

"Berry's Phases in Optics: Aharonov-Bohm-like Effects and Gauge Structures in Surprising Contexts", Nuclear Physics B (Proc. Suppl.) **6**, 298 (1989).

"Lorentz-Group Berry Phases in Squeezed Light", Nuclear Physics B (Proc. Suppl.) **6**, 327 (1989).

"Time-Reversal of Berry's Phase by Optical Phase Conjugation", (with W. R. Tompkin, M. S. Malcuit and R. W. Boyd) J. Opt. Soc. Am. **B7**, 230 (1990).

"Correlated Two-Photon Interference in a Dual-Beam Michelson Interferometer", (with P. G. Kwiat, W. A. Vareka, C. K. Hong and H. Nathel) Phys. Rev. **A41**, 2910 (1990).

"Berry's Phases in Optics", in Analogies in Optics and Microelectronics, W. Van Haeringen and D. Lenstra, eds., Kluwer Academic Publishers, Dordrecht, the Netherlands, 1990, p. 151.

"Optical Manifestations of Berry's Topological Phases: Aharonov-Bohm-like Effects for the Photon", in the Proceedings of the Third International Symposium on Foundations of Quantum Mechanics in Light of New Technology, S. Kobayashi, H. Ezawa, Y. Murayama, and S. Nomura, The Physical Society of Japan, Tokyo, 1990, p. 80.

"Optical Manifestations of Berry's Topological Phase: Classical and Quantum Aspects", (with C. K. Hong, P. G. Kwiat, H. Nathel, and W. A. Vareka) in Coherence and Quantum Optics VI, J. H. Eberly *et al.*, eds., Plenum Press, New York, New York, 1990.

"Observation of a Nonclassical Berry's Phase for the Photon", (with P. G. Kwiat) Phys. Rev. Lett. **66**, 588 (1991).

"Two-Photon Bound State in Self-Focusing Media", (with I. H. Deutsch and J. C. Garrison) Phys. Rev. Lett. **67**, 1399 (1991).

"Analogies between Electron and Photon Tunneling: a Proposed Experiment to Measure Photon Tunneling Times", (with P. G. Kwiat and A. M. Steinberg) Physica B **175**, 257 (1991).

"The Energy-Time Uncertainty Principle and the EPR Paradox: Experiments Involving Correlated Two-Photon Emission in Parametric Down-Conversion", (with P. G. Kwiat and A. M. Steinberg) in Workshop on Squeezed States and Uncertainty Relations, D. Han *et al.*, eds., NASA Conference Publication 3135, NASA, Washington, DC, 1991.