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COHERENT EXCITATION OF DIPOLE MOMENTS BY RELATIVISTIC CHARGED P--ETC(U)

APR 78 H R ROBL, D DIALETIS DAAG29-77-G-0016

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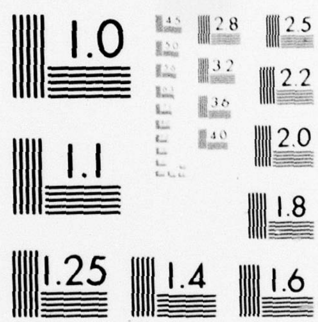

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The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This research project was concerned with a theoretical investigation of the generation of electromagnetic radiation in polarizable or conducting media by relativistic charged particles. Results are contained in the following papers: ~~I.~~ Generation of Coherent X-Rays by a Relativistic Charged Particle Traveling Through a Crystal; ~~II.~~ Generation of Coherent Radiation in a Resonant Medium by a Relativistic Charged Particle; ~~III.~~ Cerenkov Radiation at the Resonance Frequency of an Amplifying Medium, ~~IV.~~ Generation of Cerenkov Radiation at the Cyclotron Frequency of a Conducting Medium.

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20. ABSTRACT CONTINUED

~~V.~~ ;Set of Electric Dipoles Under the Influence of an External Field; and ~~VI.~~ Equivalence of the Ewald-Oseen Extinction Theorem as a Non-Local Boundary Value Problem with Maxwell's Equations and Boundary Conditions.

FINAL REPORT

1. ARO PROPOSAL NUMBER: P-14729-P

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5. NAME OF INSTITUTION: Duke University

6. AUTHOR(S) OF REPORT: Hermann R. Robl and Demos Dialetis

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

I. Generation of Coherent X-Rays by a Relativistic Charged Particle Traveling through a Crystal, D. Dialetis, Phys. Rev. A, March 1978.

II. Generation of Coherent Radiation in a Resonant Medium by a Relativisitic Charged Particle, D. Dialetis, submitted to Phys. Rev. A.

III. Čerenkov Radiation at the Resonance Frequency of an Amplifying Medium, D. Dialetis, submitted to Phys. Rev. A.

IV. Generation of Čerenkov Radiation at the Cyclotron Frequency of a Conducting Medium, D. Dialetis, Phys. Rev. A.

V. Set of Electric Dipoles Under the Influence of an External Field, D. Dialetis, submitted to Phys. Rev. A.

VI. Equivalence of the Ewald-Oseen Extinction Theorem as a Non-Local Boundary Value Problem with Maxwell's Equations and Boundary Conditions, D. Dialetis, submitted to the Journal of Optical Society of America.

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

Demos Dialetis, Research Associate

FINAL REPORT

1. This research project was concerned with a theoretical investigation of the generation of electromagnetic radiation in polarizable or conducting media by relativistic charged particles. Results are contained in six papers listed below.

I. Generation of Coherent X-Rays by a Relativistic Charged Particle Traveling Through a Crystal

II. Generation of Coherent Radiation in a Resonant Medium by a Relativistic Charged Particle

III. Čerenkov Radiation at the Resonance Frequency of an Amplifying Medium

IV. Generation of Čerenkov Radiation at the Cyclotron Frequency of a Conducting Medium

V. Set of Electric Dipoles Under the Influence of an External Field

VI. Equivalence of the Ewald-Oseen Extinction Theorem as a Non-Local Boundary Value Problem with Maxwell's Equations and Boundary Conditions

2. The common subject of papers I to IV is the excitation of dipole moments by the electric field of a single relativistic charged particle, and the radiation emitted by the dipoles. Specifically, I is concerned with the radiation of dipoles in a regular crystal lattice, while III describes the effect of an initial population inversion in an irregular medium. Radiation due to circular motion of carriers in the presence of a uniform magnetic field following excitation by a single relativistic charged particle is examined in IV. In the course of the work the need was recognized for a re-investigation of the response of a system of dipoles to an external electric field, and an alternate proof of the Ewald-Oseen extinction theorem. This is the subject of papers V and VI.

3. Abstracts of the papers I to VI by D. Dialetis are attached to this report. The required number of reprints of all publications will be submitted to the Army Research Office.

4. A contributed paper entitled "Čerenkov and Transition Radiation at the Resonance Frequency of an Amplifying Medium" was presented at the APS meeting in November 1976 at Virginia Beach, Virginia.

5. H. Robl presented seminar lectures at the Physics Departments of of Columbia University and M. I. T., and an invited paper at the Physics of Quantum Electronics Conference at Telluride, Co., in August 1977. The subject of these presentations was coherent resonance radiation from thin foils, and the prediction of radiation intensities due to high current beams in which the location of individual particles is random.

ABSTRACT I.

The radiation due to the coherent excitation of the electric dipole moments of the atoms in a crystal has been studied. These dipole moments are induced by the electric field of a relativistic charged particle traveling through the crystal. In this context, coherent excitation refers to the correlation of the phases of the dipole moments which are induced by a single relativistic charged particle. The phases of dipole moments which are induced by different charged particles are, of course, uncorrelated. The electric field of the incident relativistic charged particle is analyzed into its frequency spectrum and the effect of each frequency component on the crystal is determined. Expressions for the fields, far away from the crystal, and the radiated energy are derived for transitions between bound states, for transitions from a bound state into the continuum and for the case where the frequency components are much larger than the ionization potentials of the atoms divided by Planck's constant. It is shown that the generated coherent radiation is emitted in the Bragg directions. Moreover, the polar and azimuthal angular spreads, as well as the frequency width, divided by the frequency of radiation, are of the order $1/\gamma$, where $\gamma = (1 - \beta^2)^{-1/2}$, $\beta = v/c$, v is the velocity of the incident charged particle and c is the velocity of light. A comparison is made with x-ray diffraction and it is shown that, for a small crystal, the radiated energy per incident charged particle is less than the radiated energy per incident photon by a factor approximately equal to $Q^2/\hbar c$, where Q is the charged of the particle and $\hbar$ is Planck's constant divided by 2π.

ABSTRACT II.

The radiation due to the coherent excitation of the electric dipole moments of the atoms which are embedded in a host medium with real dielectric constant ϵ has been studied. These dipole moments are induced by the electric field of a relativistic charged particle moving through the resonant medium. In this context, coherent excitation refers to the correlation of the phases of the dipole moments which are induced by a single relativistic charged particle. The phases of dipole moments which are induced by different charged particles are, of course, uncorrelated. The electric field of the incident relativistic charged particle is analyzed into its frequency spectrum and the effect of each frequency component on the embedded atoms is determined. Expressions for the fields, far away from the resonant medium, and the radiated energy are derived for transitions between bound states. Two cases are considered. In the first case, it is assumed that $\zeta = (1 - \epsilon\beta^2)^{-1/2}$ is real, where $\beta = v/c$, v is the velocity of the incident charged particle and c is the velocity of light. It is shown that if $\zeta >> 1$, the radiation is emitted in the direction of motion of the incident charged particle. In the second case, it is assumed that ζ is imaginary. Since the Čerenkov condition is satisfied, i.e., $\beta\sqrt{\epsilon} > 1$, there is a primary Čerenkov radiation in the host medium which excites coherently the embedded atoms at their resonance frequency. In spite of the fact that both the primary and stimulated radiations are emitted in the direction of the Čerenkov cone, it is shown that it is possible to detect the presence of the latter because of the finite lifetime of the embedded atoms. Therefore, the possibility arises for the manifestation of their coherent excitation by relativistic charged particles.

ABSTRACT III.

The propagation of Čerenkov radiation through a medium in which the population of two energy levels is inverted has been studied. The population inversion is represented by an imaginary part of the index of refraction of the medium at the resonance frequency. The resonant atoms are embedded in a host medium which has the shape of a slab of finite width L and dielectric constant ϵ_h. The slab is covered by a mirror on each of its surfaces and the medium outside the slab and the mirrors has dielectric constant ϵ_1 ($\epsilon_1 = 1$ for vacuum). While each individual charged particle can stimulate coherent emission by different resonant atoms, the phase of radiation which is due to different particles is uncorrelated. It is shown, however, that radiation of high intensity in the direction of the Čerenkov cone can be produced by high-current particle beams. Exact expressions, in integral form, are obtained for the electromagnetic field everywhere in space. Using the method of stationary phase, approximate expressions are derived for the Čerenkov fields as well as the radiated energy in the forward and backward direction, far away from the slab.

ABSTRACT IV.

The excitation of coherent cyclotron radiation by a relativistic charged particle moving through a conducting medium has been studied. The medium consists of free electrons embedded in a host medium which has the shape of a slab of finite width L and dielectric constant ϵ_h (for example, the medium could be either a semiconductor or a plasma). It is well known that such a medium in the presence of a uniform magnetic field, which, for simplicity, is taken normal to the sides of the slab, behaves like an anisotropic uniaxial crystal. From Maxwell's equations and boundary conditions, exact expressions, in integral form, are obtained for the the electromagnetic field everywhere in space. It is shown that there are two components associated with the electromagnetic field inside the slab, namely, the ordinary and extraordinary components, as it is expected from the anisotropy of the medium. It is also shown from the corresponding dispersion relations for the ordinary and extraordinary indices of refraction that the extraordinary component of the electromagnetic field corresponds to the propagation of Čerenkov radiation inside the slab for frequency components close to the cyclotron frequency. In contrast, the ordinary component is absorbed within a few wavelengths from the trajectory of the incident relativistic charged particle. Using the method of stationary phase, approximate expressions are derived for the Čerenkov fields and radiated energy in the forward and backward direction, far away from the slab.

ABSTRACT V.

The coherent radiation of N electric dipoles under the influence of a time-dependent external field is studied in the special case of a resonant transition and under the assumption that the dipoles occupy the sites of a cubic lattice and they are located within a sphere. The linear theory for a discrete set of dipoles as well as the linear classical continuum theory are developed for the above configuration. Both theories lead to identical results for the fields and the radiated and absorbed energies in the case of a dilute sample with radius much smaller than the radiation wavelength. Exact expressions are obtained for the polarization, the fields, and the radiated and absorbed energies, for a sample of arbitrary radius, in the linear classical continuum theory. It is assumed that the external field propagates in a fixed direction with a constant phase velocity. In the special case of a dense sample with radius much smaller than the radiation wavelength, it is shown that a broadening of the original resonant line and a shift of the resonance frequency occur. The frequency shift is independent of position inside the sample.

ABSTRACT VI.

It has been shown in the past that the Ewald-Oseen extinction theorem can be generalized into a non-local boundary value problem and that the scattering of an electromagnetic wave on a medium of arbitrary response can be described in terms of this boundary value problem. The scattered field inside the medium (the interior scattering problem) is determined, without any reference to the scattered field outside the medium, by solving a set of coupled partial differential equations, subject to certain non-local boundary conditions which are generalizations of the Ewald-Oseen extinction theorem. Once the field on the boundary of the medium is known, the exterior field (the exterior scattering problem) is evaluated by direct integration. Moreover, a hypothesis was put forward according to which these non-local boundary conditions completely and uniquely specify the solution of the interior scattering problem. In this paper, it is shown that this hypothesis is true. The equivalence of the interior and exterior scattering problems to Maxwell's equations and boundary conditions is proven. For simplicity, the proof is confined to non-magnetic media. Thus, if Maxwell's equations and boundary conditions have a unique solution, the interior scattering problem will also have a unique solution, namely, that obtained from the former. Some illustrative examples are presented in the special case of a linear medium.