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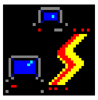

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JUNE 2005 **Volume 19 Number 2**

AOS NEWS

ARTICLES

Refereed Review Article

Regular Articles

DEPARTMENTS

Cover Picture: A Silicon sphere produced by CSIRO as part of a program to redefine Avogadro's constant. The roundness and absolute radius of the sphere have been measured in association with the Australian Measurement Institute (formerly NML) by a combination of methods using a precision contact probe and a phase shifting optical interferometer respectively, to an uncertainty of a few nm. Photo courtesy of Bob Oreb.

AUSTRALIAN OPTICAL SOCIETY

ABN 63 009 548 387

AOS News is the official news magazine of the Australian Optical Society. Formed in 1983, the Society is a non-profit organisation for the advancement of optics in Australia. Membership is open to all persons contributing to, or interested in, optics in the widest sense. See the back page (or the AOS website) for details on joining the Society.

AOS News - Editorial Board

Submission guidelines

The *AOS News* is always looking for contributions, especially from AOS members. Here is a short summary of how to make a submission.

What can you submit?

* ***Scientific Article***
A scientific paper in any area of optics.

* ***Review Article***
Simply give a run down of the work conducted at your laboratory, or some aspect of this work.

* ***Conference Report***

* ***News Item***

* ***Book Review***

* ***Cartoon or drawing***

Reviewing of papers

On submission of a scientific or review article you may request that the paper be refereed, and if subsequently accepted it will be identified as a refereed paper in the contents page. The refereeing process will be the same as for any of the regular peer reviewed scientific journals. Please bear in mind that refereeing takes time and the article should therefore be submitted well in advance of the publication date.

How can you submit?

⏭ The easiest way is by email. We accept nearly all file formats. (Famous last words!).

▸ Submitted articles will be imported into an Adobe Pagemaker file. It is best if the diagrams and other graphics are submitted as separate files. All common graphics formats are acceptable, but the resolution must be in excess of 300d.p.i.. Be aware that all colour diagrams will be rendered in grayscale, so if you do use colours, choose colours that show up well in grayscale.

▸ When using Greek letters and mathematical symbols, use font sets such as Symbol or MT Extra. Please avoid using symbols that are in Roman fonts, where the Option or Alt key is used; e.g. Opt-m in Times font on the Mac for the Greek letter mu.

▸ If using TeX, use a style file similar to that for Phys Rev. Letters (one column for the title, author and by-line, and two for the main body). The top and bottom margins must be at least 20mm and the side margins 25mm. Submit a pdf file with the diagrams included, as well as copies of the diagrams in their original format in separate files.

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President's Report

Optical science in Australia has received more reecognition recently with several members of the AOS being recognised for their achievements. Professor Chennupati Jagadish (Australian National University) was made a fellow of the Australian Academy of Science in March. Also in March, the Optical Society of America published a list of new OSA fellows that included Professors Min Gu (Swinburne), Lindsay Botten (University of Technology Sydney), Chennupati Jagadish (ANU), and Barry Sanders (Macquarie University and Univ. of Calgary). I would like to extend warmest congratulations to these people on behalf of the AOS.

On a less happy note, I was informed in February (while the previous issue was at the printers) of the death of Phil Ciddor, one of the stalwarts of the AOS. He made significant contributions in areas such as thin film modelling, optical length metrology and more recently in refractive index corrections for air and was active in research right up until he died. He has collaborated with a wide range of people, not only in optics but in the surveying community as well. He will be sadly missed by the Australian optical community.

Many of you may by now have noticed that the AOS news now has an ISSN number which will help to make it easier, for those of you who take the time and effort to write articles, to gain some kudos for this in the annual audit of research and scholarly output. While this isn't one of the high impact publications it is nevertheless important locally in helping to maintain a sense of community among people in optics. Such a sense of community is beneficial to all of us, as it is one of the intangibles that gives our field a profile. Your efforts are greatly appreciated and I would urge you all to keep the articles flowing. To make the proposition even more attractive we are introducing refereeing for the scientific and review articles, since refereed articles count for more in the above-mentioned audit. This will be on a voluntary basis and papers that are refereed will be identified as such.

The AOS will hold its AGM at 1pm on the 6th of July 2005, the venue being Star City in Sydney where the BGPP/ACOFT conference will be being held. Annual General Meetings are problematic for the AOS because of the timing and the need to get a quorum. We are required to hold one every year after the end of the financial year but before October (or thereabouts). However our main conferences tend to be in the summer. The ACOFT series of meetings has been held in July or August for the last few years, and have provided a venue for the AGM's. Sometimes it has required a bit of legwork and cajolery on the part of council members to get a quorum, so hopefully you will be reading this and heeding this unsubtle hint to attend the AGM, if you possibly can.

Murray Hamilton
President, Australian Optical Society
May 2005

Position Vacant
Australian Optical Society Newsletter

Editor

The AOS is seeking an editor for the newsletter. This is a quarterly publication conveying optics news, scientific articles and optics advertising to the Australian Optics community.

The editor will be paid an honorarium of $2000 p.a or $500 per issue.

Applications and enquiries for this position should be addressed to the President of the Society, Dr Murray Hamilton

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AOS Annual General Meeting 2005

The annual General Meeting of the Australian Optical Society will be held at 1pm on 6th July 2005, Star City, Sydney.

Bragg Gratings, Poling and Photosensitivity/ 30th Australian Conference on Optical Fibre Technology
4-9 July 2005, Star City, Sydney
http://www.bgppacoft2005.com/

Call for papers

Australasian Conference on Optics, Lasers and Spectroscopy 2005

December 6–9, 2005

Royal Lakeside Novotel
Rotorua, New Zealand

This conference is the 7th in the ACOLS series, bringing together students and researchers working in all aspects of optics, lasers, and spectroscopy. It incorporates the 18th Australian Optical Society Conference, the 12th Australian Laser Conference, and the 22nd Australian Spectroscopy Conference.

Submissions are now invited for papers to be presented at ACOLS'05, for scientific and technical work that falls within, but are not limited to, the following topics (as outlined on the ACOLS'05 web page):

- Atomic and molecular spectroscopy
- Lasers and laser applications
- Optical imaging
- Optical fibres and photonics
- Atom optics and BEC
- Quantum optics, quantum information, and quantum computing
- Instrumentation and standards
- Biophotonics

One-page abstracts should be prepared according to the templates that can be downloaded from the ACOLS'05 web site and must be submitted electronically either through the web page or via email to acols05.submit@auckland.ac.nz no later than Friday September 9, 2005.

Abstract submission deadline: Friday September 9, 2005

Authors will be notified on the status of their submission no later than October 10, 2005

http://www.cce.auckland.ac.nz/conferences/index.cfm?S=CCE_ACOLS

Announcing

The New Zealand and Australian Quantum-Atom Optics Workshop

Queenstown ~ New Zealand, 29 November to 1 December, 2005

This international meeting, a satellite to ACOLS 05 (Rotorua, NZ, 6 – 9 December), will feature prominent international and local speakers.

Early expressions of interest are requested: number of participants may need to be limited due to facility size.

Jointly hosted by the Australian Research Council Centre of Excellence for Quantum-Atom Optics (ACQAO), and its New Zealand partners.

Workshop chair: Professor Rob Ballagh, University of Otago

Further information is available at:
www.physics.otago.ac.nz/uca/conference

ARC COE FOR QUANTUM-ATOM OPTICS

Warsash/AOS Student Prize

A prize comprising up to $3000 worth of equipment, or a $3000 discount on the sale price of equipment whose retail price exceeds $3000, will be provided annually by Warsash Scientific Pty Ltd. for the best student research proposal meeting the criteria laid out below. The equipment will chosen by the winner from that equipment which is normally offered for sale by Warsash.

Eligibility

Students enrolled in a postgraduate degree by research in an Australasian university are eligible to apply for this prize. The student must be a member of the AOS and be in the first or second year of their candidature.

Application

The student must submit a research proposal (maximum 6 pages of 12pt font, including his/her CV) that sets out the aims , methodology, and significance of the proposed research. A brief description of how the Warsash equipment fits into the research plan must be part of the proposal. Two letters of support from an academic referees must accompany the application. One of these must be from the student's supervisor and must include confirmation that the equipment supplied by Warsash will be used appropriately in the proposed experiment. Applications should be sent to the Secretary. Applications will close on the 30th of June each year.

Judging

The applications will be judged on the basis of scientific merit by a panel of three AOS members, convened by the President or Vice-President.

The judging will be based on three factors:

- The general excellence of the candidate, as indicated by the CV and the letters of reference
- Whether the research proposal is thorough, exciting and clearly explains the impact of the research
- The reason why the particular piece(s) of equipment is(are) essential.

Ownership of equipment

Ownership of equipment that is awarded in this prize will lie with the university in which the student is enrolled.

Obituary - Philip Ciddor

Philip Ciddor passed away suddenly on 23 February 2005. It was a shock for everyone as he was a remarkably healthy 74 year old. One colleague commented that, “He was a real gentleman and scholar and just an all round good bloke. Phil, without any hesitation, helped me on many occasions when I had a problem”. The problems Philip helped with were difficult scientific issues to do with surveying, satellite ranging, measurement lasers, optical transmission, etc. There was very little that Philip wouldn't tackle and his good nature often led him down difficult technical paths.

Philip joined CSIRO in 1955 and retired 40 years later. He worked on optical standards for length measurement, playing an important role in the development of photoelectric microscopes and stabilised lasers. He led the Length standards project from 1982 to 1992 and represented Australia at the BIPM Consultative Committee for the Definition of the Metre (Paris 1982), where he played a role in developing the current definition for the metre. He continued to work in his retirement, extending the range of the Edlen refractive index equations (now adopted by the IAG). He also rewrote the Nation Standards Commission's Verifying Authorities Handbook, reviewed many papers and of course, helped many colleagues with numerous problems.

His colleagues will deeply miss him as a friend and advisor and send their condolences to his wife, two daughters and four grandchildren.

Nick Brown, National Measurement Institute

SPIE The International Society for Optical Engineering

SPIE was formed in 1955 as the Society for Photo-optical Instrumentation Engineers, and has been dedicated to providing the best possible service to the optical engineering community. SPIE is an international technical society dedicated to promoting the engineering and scientific applications of optical, photonic, imaging and optoelectronic technologies through its education and communications programs, meetings and publications.

SPIE offers

International Networking

Today SPIE is the largest international professional engineering society serving the practicing engineer and scientist in the field of optics and photonics. The Society serves the global technical and business communities, with over 14,000 individual, 320 corporate, and 3,000 technical group members in more than 75 countries worldwide. Advance professionally through networking and visibility among your peers. Learn from others and gain access to the voices, ideas, and the energy of a global community.

Meetings

Among the many services the Society offers are the sponsorship, planning, and execution of technical conferences, product exhibitions, and symposia. SPIE's technical meetings and symposia are internationally-acclaimed gatherings of engineers and scientists working in optics, optoelectronics, and many related fields. They take place in large and small venues, from specialised topics to cross-disciplinary information exchanges, complete with extensive programs including short courses, workshops, and other special activities.

Publications

A major activity of SPIE is the publication and distribution of archival professional journals, full-manuscript conference proceedings, newsletters, and optics-related texts and monographs. SPIE publications deliver timely, high-quality technical information to the optics, imaging, and photonics communities worldwide. Membership includes a subscription to *OE Reports*, a monthly newspaper that provides news and commentary on cutting-edge technology.

Öand More

In addition, SPIE provides numerous services to its members, including on-line electronic databases, electronic bulletin board and networking services, and employment assistance. To further serve the public good, the Society sponsors a number of awards, scholarships, and educational grants every year, and publishes a comprehensive catalogue of educational resources in the optics field, *Optics Education*.

To join SPIE: Complete the online membership form at *www.spie.org/membership_form.html*, print and fax it to SPIE along with a copy of your AOS dues receipt. (Be sure to indicate that you are eligible for the US$20 discount as an AOS member). Any queries can be directed to Mr Paul Giusts at *membership@spie.org*

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Critical Tests of higher-order and many-body Quantum Electrodynamics (QED) theory in medium-Z and high-Z systems

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Of all fundamental physical theories, relativistic quantum electrodynamics, QED, has provided the most complete and celebrated agreement between theory and experiment. QED is the first outcome of second quantization, and the first application of Quantum Field Theoretic methods. Here, not only are the eigenvalues of energy of a Hamiltonian quantised, but it is also necessary to consider the radiation field as a quantised system. The combination of these two ideas has led to the field of quantum optics, whether used for laser development, interferometry, quantum entanglement, quantum computation or other investigations. Much attention is focused on these and other applications of QED; but it is less well understood that major issues remain with the fundamental basis itself. This article presents some of the key ideas and current excitement behind the field, and key questions which may be answerable in the near future.

The classic experimental test of bound-state QED is the measurement of the 2s-2p interval (the classical Lamb shift) in atomic hydrogen. The study of this single transition in hydrogen catalyzed a new field of research in the 1940's and led to the development of QED. The recent tests of the transitions of hydrogen itself, measuring the ultra-violet transition frequency between the 1s and 2s states of atomic hydrogen to an accuracy of 15 significant figures, proves QED as the best tested theory in nature (with general relativity) [1]. The breathtaking precision of this recent measurement by H‰nsch and collaborators has enabled the high precision measurement of the ground-state Lamb shift in hydrogen and has provided limits on the variation of the fine-structure constant over laboratory timescales. Subsequent advances in both theory and experiment now reveal a limitation of hydrogen transitions as a rigorous test of QED, due to uncertainties in the internal structure of the proton, the proton form factor and polarizability, that place fundamental limitations on the use of atomic hydrogen [2].

Other major tests of QED include the g-2 tests of an isolated or bound electrons' gyromagnetic ratio [3]. More recent key objects of investigation include the energy levels of positronium [4], antihydrogen and other exotic species [5], which continue to show significant discrepancy of theory from experiment. There are numerous complementary questions which must be asked of QED, electro-weak theory and CPT which as yet remain unaddressed, and this field remains challenging and exciting. Does QED apply to neutral atoms!?! Does QED converge? Where does it break down?

The spectacular success of QED evinced by Haensch et al. [1, an accuracy of 15 significant figures] has been achieved despite a number of fundamental problems which attract close scrutiny, because of the leading role played by QED in the description of all pure research and applied technologies involving the interactions of charged particles, photons, and electromagnetic fields. A well-known difficulty in the fundamental *basis* of QED is that the radius of convergence of all energy and wavefunction expansions in powers of the fine-structure constant, α, is known to be vanishingly small. The theory is not convergent, and at best possesses the mathematical characteristics of an asymptotic expansion. It works extraordinarily well for the first term or two in the α-expansion, but cannot be regarded as complete or internally consistent. In addition, QED (like its classical antecedent) admits the appearance of divergent, unphysical quantities, even for low-order terms in the α-expansion. These infinities are removed by a renormalization of the physical parameters of mass and charge, an ingenious, well-established, but ungainly aspect of the theory. Internationally, large efforts aim to test and investigate QED in complementary regimes. The complementarity should perhaps be emphasised: the different investigations probe different Feynman diagrams, series convergence, divergences, renormalisation and computational schemes and perhaps most importantly, different physics.

One of the most precise and sensitive tests of QED at high field strength is to compare theory and measurement of the classic Lamb shift in medium to high Z hydrogenic ions [6,7]. Recent measurements of transitions in hydrogenic and helium-like systems clearly indicate inconsistencies and inadequacies of existing theoretical treatments as well as the further need to eliminate systematic errors in experimental data which might reveal the dependence of many-body and radiative effects on the nuclear field strength. Experimental accuracies are now comparable to theoretical uncertainties. Experimental results for He^+ show a 7 standard deviation discrepancy from current theory [8]. This discrepancy may result from recent advances in theory and computation for higher-order terms [9], or may be due to experimental systematics [8].

While the fundamental principles of QED are clear, a number of interpretations and implementations of the theory exist, particularly in bound-state problems for which two general approaches may be identified. In the first of these appear two expansion parameters; α, which is a measure of the strength of the electron-electron interaction, and $Z\alpha$, which measures the strength of the electron-nucleus interaction. This approach is the historical formulation of QED, due to the pioneering studies in the 1940's and 1950's of electron self-energy and vacuum polarization (Lamb shift) effects, later extended to effects of higher order of perturbation theory. Work continues using this approach, which relies on the manipulation of the analytic properties of free-particle and non-relativistic wavefunctions. Revised estimates of QED effects in few-electron systems have been reported recently by its leading exponents, notably Drake, Cheng, Pachucki, Jentschura and their collaborators [10,11,12].

While $\alpha \sim 1/137$ is a small parameter, $Z\alpha$ approaches unity for heavy elements, and the terms in the expansion in $Z\alpha$ for large Z possess the qualities of an asymptotic expansion, where the terms increase in magnitude and alternate in sign. A second approach to the calculation of Lamb shift effects was therefore developed by Mohr within the Furry bound-state formalism of QED, in which the $Z\alpha$ expansion is replaced by a treatment in which the electron-nucleus interaction is absorbed within the definition of the electron-positron field amplitudes. Within this general approach, several variations have developed differing mainly in the method used to implement the mass renormalization program for the calculation of electron self-energy. The earliest work in this direction was made in the 1950's by Brown, Langer and Schaefer, but their approach used a non-covariant form of mass-renormalization and had difficulties in achieving sufficient numerical precision in the final results. Mohr's method is based on a parametric modification of the electromagnetic interaction in the ultraviolet limit. Subsequent developments include the use of dimensional regularization, and the introduction of parameter-free partial wave mass renormalization by Quiney and Grant [13], and by Lindgren, Persson and Salomonsson [14].

In the latter approaches, treating the electron binding to all orders in $Z\alpha$, only α appears as an expansion parameter; agreement exists within the various renormalization schemes for the calculation of effects involving the exchange of a single virtual photon. The challenge to theorists is to calculate combined effects of radiative and many-body corrections to provide a rigorous test of QED in medium- and high-Z systems and to verify the internal consistency of the various schemes. The calculation of many-body effects in few electron atomic systems has been made by the introduction of relativistic finite basis set methods, leading to new techniques in relativistic quantum and molecular physics.

A continuing effort across the international community has been directed to Lamb shift measurements in hydrogenic and helium-like systems by many independent groups (Chantler, Silver, Gillaspy, Hudson [e.g.

15,16,17,18,19]). Experimental medium-Z data may indicate the breakdown of QED anticipated in the limit of strong external fields.

Medium-Z measurements probe higher-order QED theory, and (due to the Z-scaling) are not limited by the nuclear form factor uncertainties which limit low-Z and high-Z measurements. Based on scaling of the terms of order $\alpha^2(Z\alpha))^6$, a relative accuracy of 1ppm [10^{-6}] in a medium-Z atomic system with Z=30 will be as sensitive to some of these terms as an experiment in hydrogen with a relative accuracy of 10^{-12} to 10^{-15}. Helium-like systems measure both correlation effects and two-electron QED, which are inaccessible to hydrogenic studies. These complementary investigations explore a range of fundamental issues. Modest increases in experimental precision over current work – by a factor of three in an appropriate system – will reveal the limitations of current theoretical approaches and suggest new directions for future developments.

For example, bound QED systems particularly test the very effective Furry formalism, and investigate the utility of QED applied to systems with high nuclear fields. As the nuclear charge (Z) is increased, the results of all Feynman diagrams for QED corrections become much larger, so that in principle tests become easier. For neutral atoms, however, the theoretical methods are not yet able to compute reliably accurate values for transition frequencies. In this area both hydrogenic systems (with a single electron, like hydrogen) and helium-like systems (with just two electrons, like helium) allow good determination of theoretical predictions and experimental results, to provide critical tests. In the past these hydrogenic and helium-like investigations primarily probed the lowest-order QED terms (the Lamb shift self-energy and vacuum polarisation contributions in lowest order). However some recent breakthroughs by researchers in Australia allow the possibility of direct and critical measurements of new QED contributions, including higher-order terms, excited-state QED, two-electron QED, and p-electron QED.

Past Australian efforts in few-electron QED measurements are restricted to two independent groups – that of the author and one at ANU [20]. The high precision measurement of energy levels in few electron systems is an active and continuing international field of research. We have developed state-of-the-art detector and spectrometer technology to pursue these goals. The data obtained from these studies are

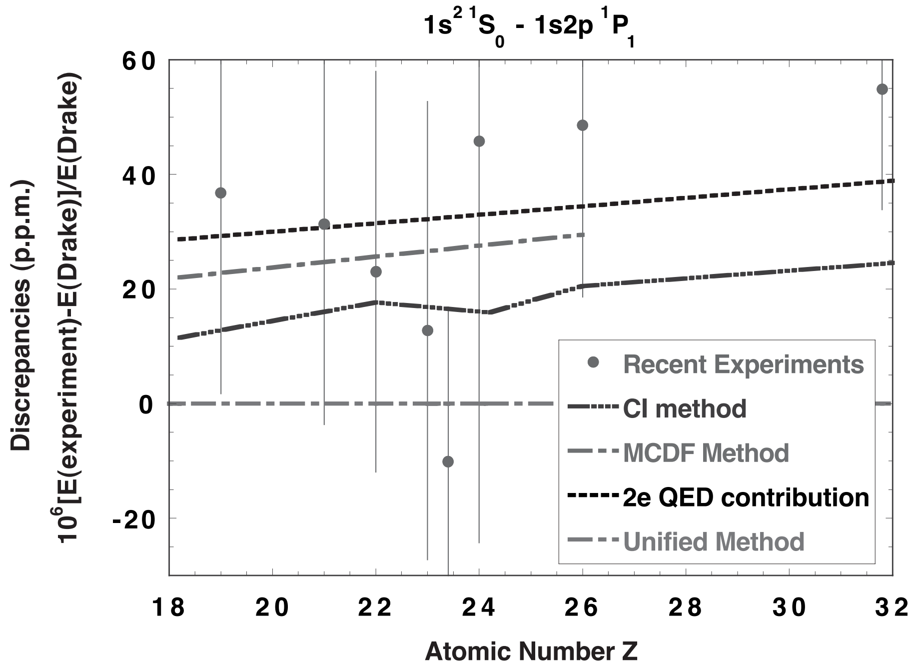


Figure 1: A problem of QED theory, computation, or experiment? Helium-like QED theory, Z = 18-32 (horizontal line through zero) versus (recent) PLT tokamak & EBIT measurements, and alternate computational formalisms as discussed in the text. Vertical scale is the discrepancy in parts per million (p.p.m.) from the theoretical results of the Unified Method of Drake [2]. Note the magnitude of the two-electron QED contribution is similar to the magnitude of the possible discrepancies.

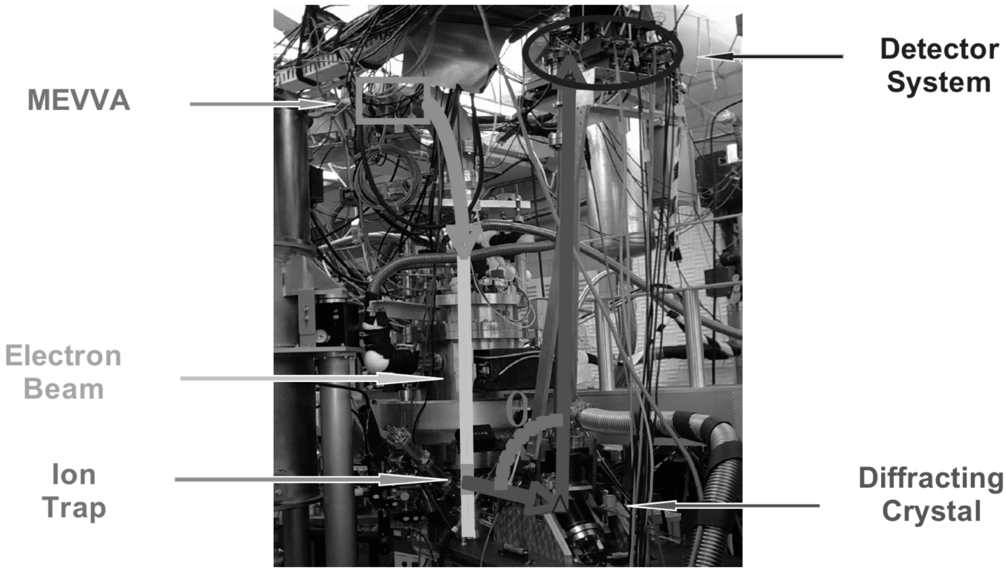


Figure 2: The NIST Electron Beam ion Trap and key components for QED tests

used in fundamental studies of electronic structure as well as the determination of fundamental constants and quantum metrology, including application to opacity studies of astrophysical interest.

Measurements for medium-Z atoms critically sensitive to two-electron QED, and tests of QED in this region accurate to 1%, will allow new insight into two-electron systems, theoretical approaches, and recent observed discrepancies between QED theory and experiment (see, for example [21]). We already have the situation that alternative theoretical approaches to QED yield different results [10,22,23,24]. These may then be tested both in medium-Z and high-Z systems. High-precision measurements and state-of-the-art theoretical investigations of transition energies in two-electron medium- and high-Z ions will allow critical assessment of the accuracy of current theoretical calculations of relativistic, many-body, nuclear structure, and quantum electrodynamical effects in these systems. Note that these (one- and two-electron bound systems) are the *simplest possible systems* for studying electronic structure and allow the simplest and *most direct* tests of QED and particularly higher-order terms.

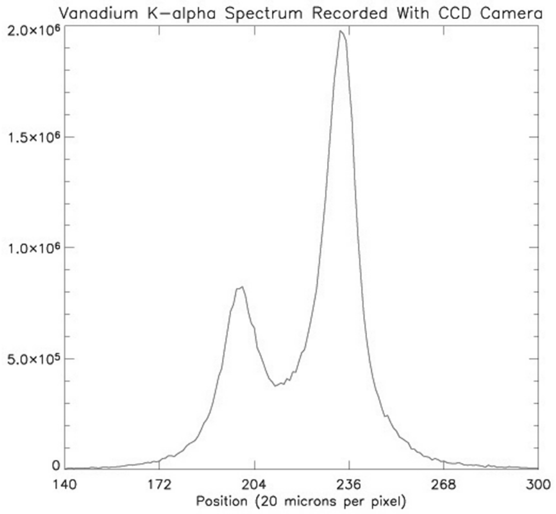
Our techniques are sensitive to two-electron QED. Two electron QED is the QED contribution due to two-electron Feynman diagrams, but also due to the difference between one-electron diagrams in the different (one versus two electron) potential. Different theoretical approaches yield quite different estimates of this QED contribution. Our experiments isolate one of the most difficult questions regarding QED theoretical implementation to atomic systems. Currently only three measurements claim to be sensitive to two-electron QED for the 1s Lamb shift in medium-Z atoms. Our earlier work on vanadium is one of these three, and the other two, for quite different Z, are sensitive to 2e QED at the 50% level but have neglected certain systematic contributions in their analyses (curved crystal dynamical diffraction shifts, crystal defects, absolute calibration, theoretical uncertainty, decay lengths) [25,26,27]. We address these systematics using a robust absolute calibration method proven in earlier experiments, and work in progress can achieving an improvement in experimental uncertainty over all earlier work (including our own) by a factor of two or three, and possibly much more.

For Z=26, theory differs by 30 ppm from one another [28,29,30]. This level is consistent across the range of medium-Z. The variation between theories across this range is one or two standard deviations of experimental results. The ability to significantly reduce the current experimental error budget will lead to a critical investigation of theory.

The data displayed in Figure 1 provide an indication of the state of this field. There is a suggestion of a systematic deviation between theory and experiment in the range $15<Z<40$. Part of this discrepancy may relate to the computational methods used in the theory, or to experimental systematics, and part may show an intrinsic limitation of all current theoretical approaches.

Several of the recent developments have involved the development of new high-precision experimental Electron Beam Ion Trap (EBIT) techniques. We refer to [31] for a detailed discussion of EBIT operation, but Figure 2 illustrates the NIST EBIT and key experimental components for our investigations. EBIT sources trap ions in a weak radial and longitudinal potential trap, with negligible thermal motion. Most QED measurements have employed beam-foil or plasma-based spectroscopy at accelerator facilities, for which the most significant limitation on the precision of the measurements is the Doppler shift uncertainties due the use of fast beams. By generating the target systems in an EBIT, we avoid this fundamental limitation. The limiting experimental precision available then comes from other controllable contributions. This feature of EBIT sources has made the technology especially attractive in studies of systems of astrophysical interest, plasma diagnostics, and laser research.

The ongoing development of EBIT resources offers the possibility of performing critical measurements of many-body



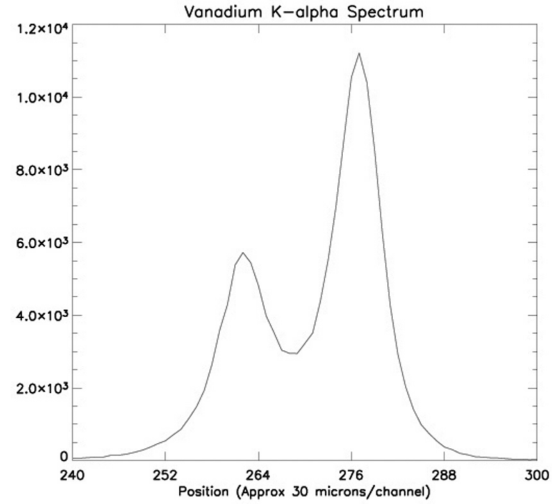


Fig. 3 The comparison of CCD and our detector technology from our 2004 experiment at NIST (Chantler, Mark Kinnane, Justin Kimpton, George Christodoulou, Larry Hudson, John Gillaspy and international collaborators): the V K-a doublet is equally well resolved by both detector systems, but the new detector has the advantages of (1) Pseudo-event mode operation to analyse systematics of all types, including those previously considered to be random or statistical errors; (2) Faster processing, for higher statistics on monitoring processes and temporal fluctuations; (3) Larger area detector to increase throughput, efficiency & statistics; (4) Improved resolution and efficiency of detector technology; & (5) Clean discrimination against cosmic rays. The spectra were unobtainable with alternative spectrometers at NIST. The spectrometer shows potential to provide (1) Thermal control to 1ppm; (2) Mechanical stability to 1-2ppm; (3) angles monitored by clinometry to 1-5 ppm; (4) mechanical strain and Bragg angles monitored to same accuracy; (5) Closer approach of spectrometer crystal to source; (6) Stronger, more flexible calibration source target and arrangement; & (7) Optimisation of Rowland Circle positioning for minimisation of effects of dispersion function (limitations of dynamical diffraction theory circa 1-5 ppm depending upon geometry and statistics).

and QED effects in few-electron systems, and of investigating whether apparent discrepancies between theory and experiment are due to systematic failures of QED in the presence of strong external fields, or to unresolved systematic errors in the available energy level measurements. The group's earlier work has yielded results for vanadium at the new limit of 27 ppm [15]. This has led the field by including several systematic error corrections that had been neglected in earlier studies by other investigators. This research will be driven towards investigations of systems with higher nuclear charges, and will require further innovation for each system, built on the experience obtained from vanadium and titanium.

Earlier studies by the author and collaborators have provided new results regarding polarization of X-rays from EBITs and comparisons to various models [31]. The investigation is advancing theoretical and computational approaches to relativistic QED in atomic, molecular and solid-state systems, (Quiney and Grant [32]).

We observe 4-8 keV X rays relative to local K± sources using a Johann curved crystal spectrometer calibrated across a wide energy range (Figure 3, & references in preparation [33]). This controls many potential systematics. The measured transition energy then corresponds to a measurement of the QED component of the transition.

Past research has often employed calibration lines in a different order of diffraction, using curved crystals with significant (30-200 ppm) uncertainty in the theoretical shift due to dynamical diffraction theory. We have published seminal papers on the theory and calculation of these shifts [34]. Spectroscopic principles involve major modifications to successful earlier QED investigations [15,35,36]. This work has constrained errors using different orders of diffraction to approximately 30 ppm in conditions using appropriate geometry. Several significant systematics have been computed for the first time by Chantler and Paterson [15,37]. Asymmetric line profiles and refractive index shifts contribute 100-300 ppm shifts in this energy regime.

Our current techniques use calibration lines in the same order of diffraction and hence should therefore only be limited at the 1-3 ppm level by theory and the literature calibration spectra. This is an enormous advance on the present status.

A unique feature of this research is the measurement in an EBIT source of *absolute energies* with respect to robust standard calibration sources. X-rays from the EBIT source are focused by a curved diffracting crystal in an energy-dispersive Johann geometry, onto a two-dimensional detector. The Lamb shift varies from 300 ppm of the Lyman-± X-ray transition energy at Z=16 to 900 ppm at Z=36, and to 1500 ppm at Z=54 (xenon). The precision of these new experiments should yield a final accuracy of about 3-10 ppm. New computations of systematic effects in theory should improve the result further [38]. This will yield the best QED measurements in the medium-Z regime. Predicted higher-order contributions vary with theoretical approach, of order 2 eV [60 ppm] for He-like Xe and 1.5 ppm to 70 ppm [39] for hydrogenic Xe.

The use of *curved crystals* (Johann geometry) dramatically increases the statistics, and also makes the experiment insensitive to positional misalignment of 5–500 microns (major limitations of other techniques). We have recently designed and constructed two-dimensional backgammon detectors in Melbourne (based on NIST precursors) promising the best performance (resolution and area) of this flexible type of X-ray detector. New CCD detectors have excellent two-dimensional resolution and are useful alternatives to our

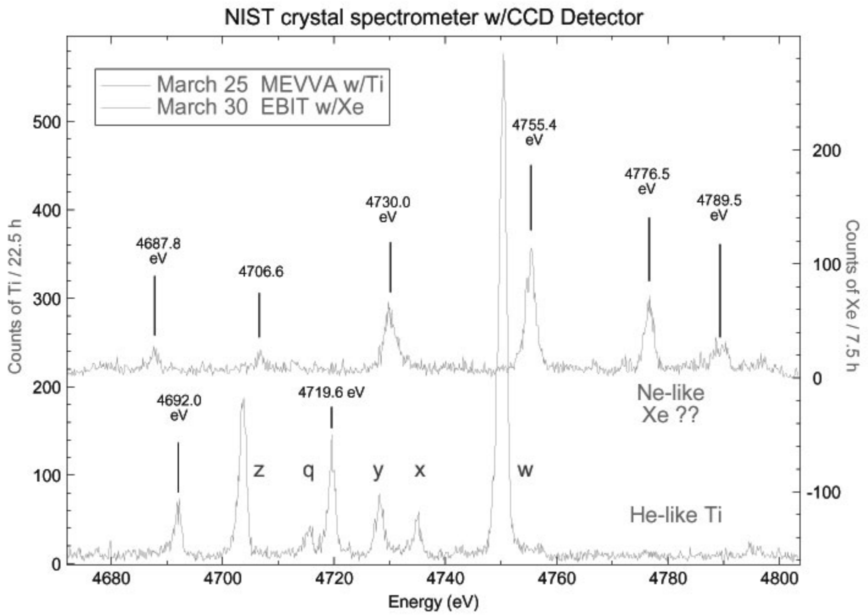


Fig. 4 The new spectrometer with a CCD detector; preliminary analysis from our 2004 experiment at NIST (Chantler, Mark Kinnane, Justin Kimpton, George Christodoulou, Larry Hudson, John Gillaspy and international collaborators). The key spectral components have good statistics and excellent resolution. Transitions are labelled: w :He-like Ti ($^1S_0$-$^1P_1$); x :He-like Ti ($^1S_0$-$^3P_2$); y :He-like Ti ($^1S_0$-$^3P_1$); q :Li-like Ti($^2P^0_{1/2}$-$^2D_{3/2}$); z :He-like Ti ($^1S_0$-$^3S_1$).

backgammon prototypes, and are also investigated by the collaboration.

SUMMARY OF SOME MEDIUM-TERM GOALS

The aims of this research are to develop new experimental approaches to make original tests of aspects of QED (Quantum Electrodynamics), and hence to

Resolve several standard deviation discrepancies of theory from experiment, for helium-like transitions;

Make the first measurements for medium-Z systems critically sensitive to two-electron QED;

Measure QED Lamb shifts to 1% in hydrogenic and helium-like medium-Z systems;

Test both lowest order QED and higher order corrections;

Directly investigate the interaction of light with charge in regions of high effective coupling strength, where QED interactions can be treated as perturbations only with major concerns. This will indicate directions for improvement of correlation and many-body effects in complex systems.

Innovative theoretical approaches will be developed to identify experimental sensitivities to interesting theoretical questions. Correlated and many-body QED is well developed but Figure 1 reveals key limitations of current approaches.

State-of-the-art detector and spectrometer technology are being developed for this research, with much wider applications for other high-precision experiments.

Specific scientific goals provide insight into systematic effects in X-ray diffraction, which is a key technique used in the development of frontier technologies. Improved understanding of X-ray optical systems is fundamental to micro-lithography, XAFS and synchrotron investigations of surfaces and crystals. Scientific corollaries of this research include X-ray detector development, spectrometry and shielding advances.

The xenon Lyman series represents an upper limit to spectroscopy using Bragg X-ray diffraction methods, and optimisation of flux and resolution for this is crucial. For example, if we can maintain the calibration accuracy suggested by the precision and the calibration transfer method we are developing (e.g. circa 1-6 ppm compared to 27 – 50 ppm) then the accuracy of a titanium or vanadium study could improve by a factor of three or more and the factor for the QED investigation for Xenon could increase by an additional factor of 8. This would represent an enormous breakthrough in the field. Some of these limits can be achieved or exceeded by developing an EBIT source in Australia and setting it up on the coming synchrotron beam-line. In that case the calibration and statistical goals can be even higher than suggested here.

The developments outlined above including the design and construction of new detector technologies for X-ray physics, which has direct application for radiation safety and testing, for possible development into (medical) imaging technologies and for industrial and commercial testing and process optimisation. The detector and spectrometer technologies realised in 2004 point the way towards commercializable outcomes.

Past work by the author in this area has led to patents and economic benefits for US corporations involved in medical research and mammography with diagnostic accuracies improved by two orders of magnitude. This promises safer and earlier detection for millions of at-risk patients. These results are spin-offs of the fundamental research pursued and an example of the process of scientific discovery at work. One of the collaborators has developed a multi-million dollar company based on an understanding of fundamental physics applied to third world vision needs. Another collaborator has led US security mail testing and sterilisation methodologies as a consequence of his expertise in fundamental science and standards research.

Synchrotron research is not a part of this research, but key new opportunities in world materials science and pharmaceutical research in synchrotron technologies also benefit directly from the skills, technologies and training described. Australia is poised to develop the Australian synchrotron, and the development of skills and technologies for such an opportunity is therefore critical. The development of high-precision experimental techniques in X-ray spectroscopy and sophisticated methods for constructing detailed models of systems containing heavy elements will make important contributions to the Australian Synchrotron Project. When it is operational in 2007, this national facility will be of enormous benefit to the development of science and technology in Australia and will have a measurable impact on the Australian economy and all manner of optical investigations.

ACKNOWLEDGEMENTS

The results presented here (and especially Figures 3 and 4) have been the results of a major international collaboration involving the author's group, and especially Mark Kinnane, Justin Kimpton and George Christodoulou, and several international groups under Larry Hudson, John Gillaspy and Endre Takacs. Without this team the developments discussed would not have been possible.

ABOUT THE AUTHOR

Chantler has been a key developer of X-ray investigations at the NIST EBIT, and has a long term experience in investigating and using EBIT sources. He has extensive experience with parallel investigations at accelerators in Oxford, GSI, Lawrence Berkeley Laboratory and Argonne. Groups from NIST, GSI, University of Paris, University of Lisbon, University of Leipzig and Oxford University have been involved for several years in collaborative research towards testing QED in highly charged ions.

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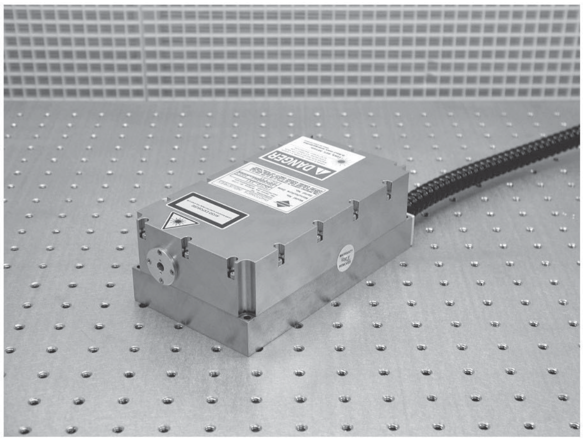

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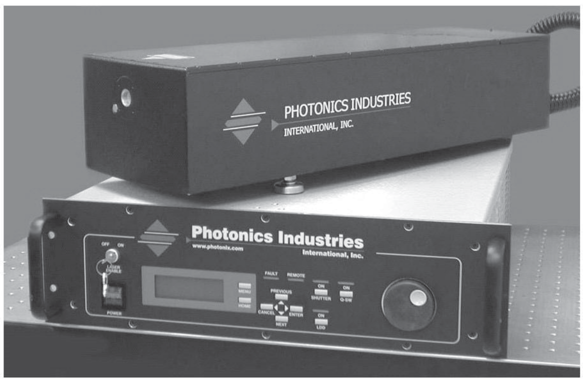

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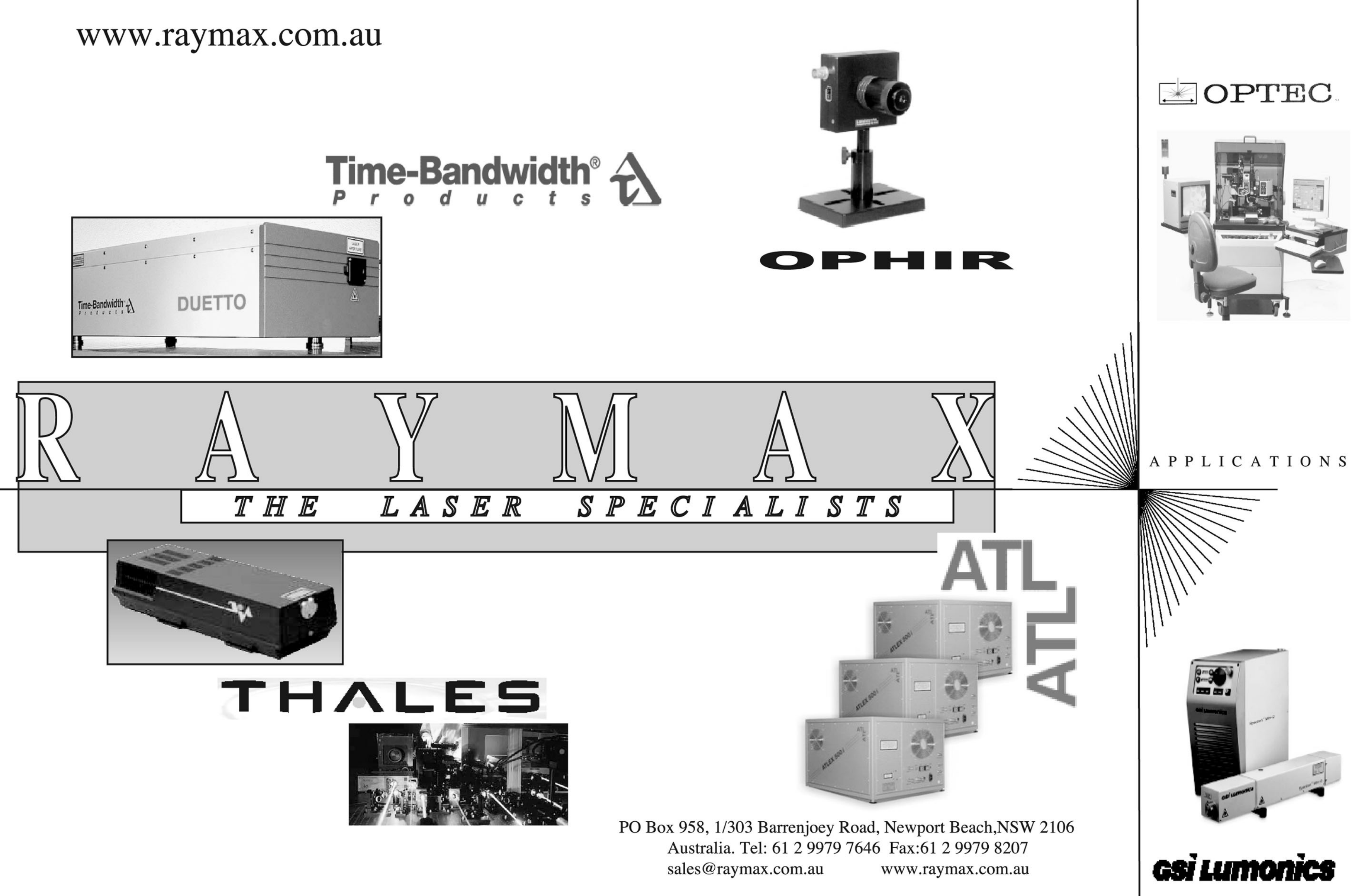
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Atom Chip Bose-Einstein Condensate

On the 15th of March physicists at the Swinburne University of Technology node of the ARC Centre of Excellence for Quantum-Atom Optics created a Bose Einstein condensate (BEC) of rubidium atoms using an atom chip. An atom chip is a surface containing fabricated elements (current carrying wires, magnetic materials) which allow the creation of magnetic potentials for the confinement and manipulation of ultra cold atoms. One advantage of atom chips is that the atoms are in close proximity to the elements which generate the magnetic potential, resulting in a very tightly confining trap. Tighter confinement means a faster in-trap collision rate, leading to more rapid evaporative cooling and a simplification of traditional BEC apparatus. The real attraction of atom chips, however, is that intricate potentials can be created for the coherent control of matter waves, leading to the development of novel devices including atom interferometers and test beds for quantum information processing.

In this case the atom chip is a hybrid construction of micro machined conducting wires embedded beneath a permanently magnetized magneto-optical film. Current carrying wires allow the flexibility of temporal control of the magnetic fields they produce, while the magnetic film provides a very stable, short range magnetic field that has no intrinsic current noise. The initial goal of this distinctive design is to test the feasibility of thin magnetic films as suitable elements for future experiments. For further information please visit our website,

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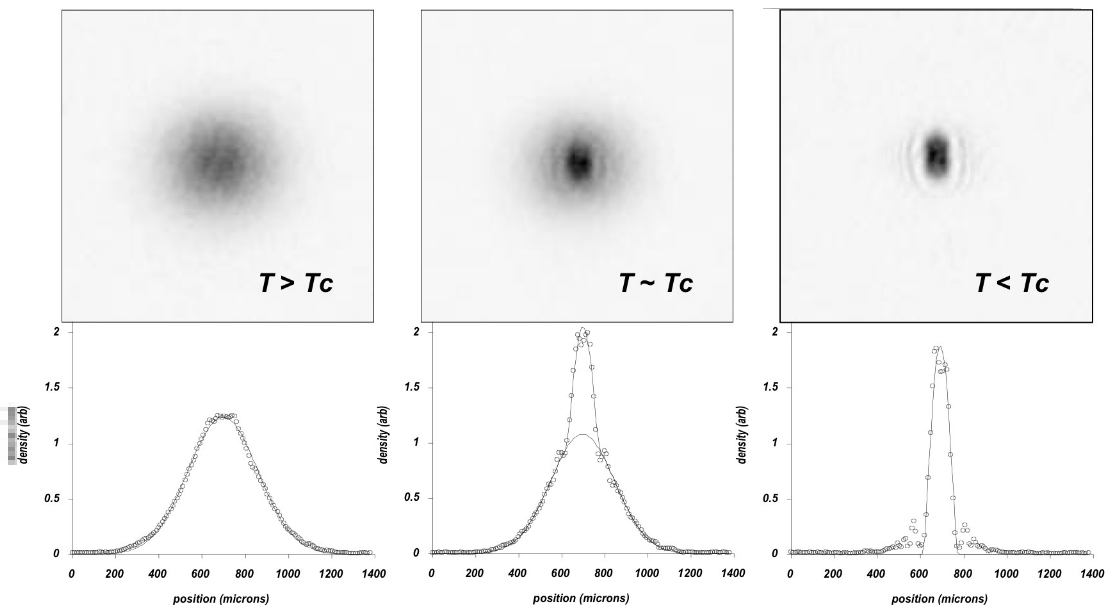

The above figure shows absorption images (top) of a falling rubidium cloud after 15 ms of free expansion. Density profiles of the clouds (below) show a Gaussian distribution (left), a two component (thermal and BEC - centre) and pure condensate (right). The pure condensate has ~ 50,000 atoms and the critical temperature was ~ 270 nK.

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Quantum science will play a major role in future technology and eventually our daily lives.

One area will be optics and wave effects for both light and atoms. Scientifically we are now able to investigate the quantum behaviour of larger objects, involving thousands and even millions of atoms, and see the transition from the microscopic world of a few particles to the macroscopic world of classical effects.

Technically we are now able to use the process of entanglement that was just a concept in the 1930s, and employ it in practical applications, such as communication systems.

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The funding and support provided by the Australian Research Council, the three Universities ANU, UQ and SUT and the Queensland and Australian Capital Territory governments will allow us to tackle ambitious Outreach projects, to have an intensive exchange of people, to provide opportunities for young scientists and to build the required research facilities.

James Gregory's Other Telescope.

Ian Bruce. Physics Dept. Adelaide University.

James Gregory (1638 - 1675) was an outstanding 17th century Scottish mathematician and astronomer[1]. In optical circles he is best remembered as one of the first to suggest a design for a reflecting telescope. This was set out in his *Optica Promota* [2](1663) in an epilogue, as an application of the main thrust of his little book, which was a theory of imaging by ellipsoidal and hyperbolic lenses and mirrors. Gregory did not live to see his telescope constructed, but eventually the design caught the attention of Robert Hooke, a skilled practitioner in optics, and it went on to become a popular astronomical telescope in the 18th century[3]. Meanwhile, Newton had simplified the design and made the first model reflector, while Cassegrain had also modified the design[4]. Gregory may hence be credited with generating some of the enthusiasm around at that time for making a reflecting telescope, as well as providing insight into image formation. In addition, Gregory had a design for a novel solid single lens refracting telescope, set out in *Prop. 59* of the *Promota,* and it is this device we shall discuss here, taken from the Latin original which the writer of this note has translated - and about which apparently nothing significant has ever been said or done.

Prop. 59: To build a telescope from a single lens, with the aid of which the far-sighted or relaxed eye may perceive distinctly a remote object with a greatly enlarged subtended angle.

'Let AEB be the angle of vision of a distant visible object; and let a telescope be constructed from a single lens, with the help of which a long-sighted [or relaxed] eye at O can see the image of a distant object distinctly, with an enlarged angle of vision AOB... '

We will not continue with Gregory's narrative, which accompanied the original ray diagram in Fig. 1, but give instead a modern commentary on Prop. 59. Gregory was unaware of Snell's law in the form we know it, and had derived his own version that involved the ratio of the sine of the angle of incidence to the sine of the angle of deviation, that yields the same results when applied to conic sections, apart from the parabola. In this version applied to the ellipse, if the eccentricity is set equal the inverse of the refractive index (in modern terms), then rays parallel to the axis of the ellipse pass through the far focus.

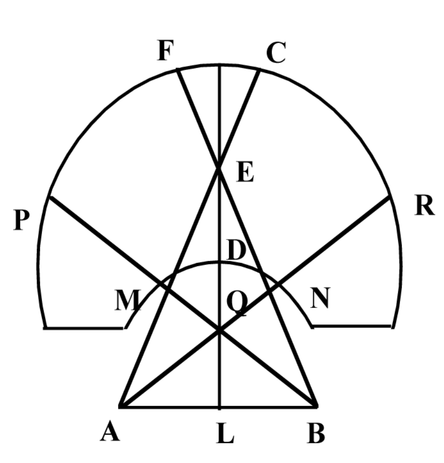

Figure 1

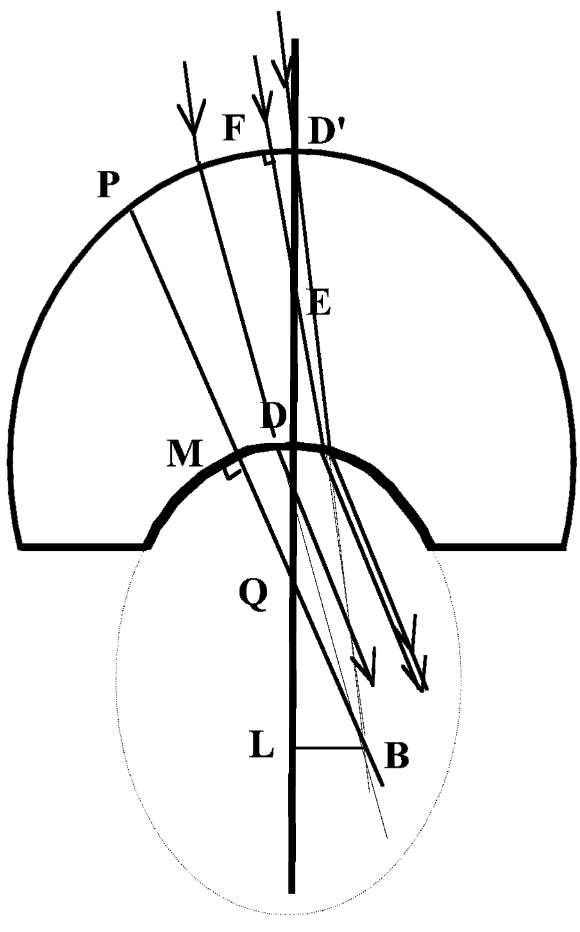

Figure 2

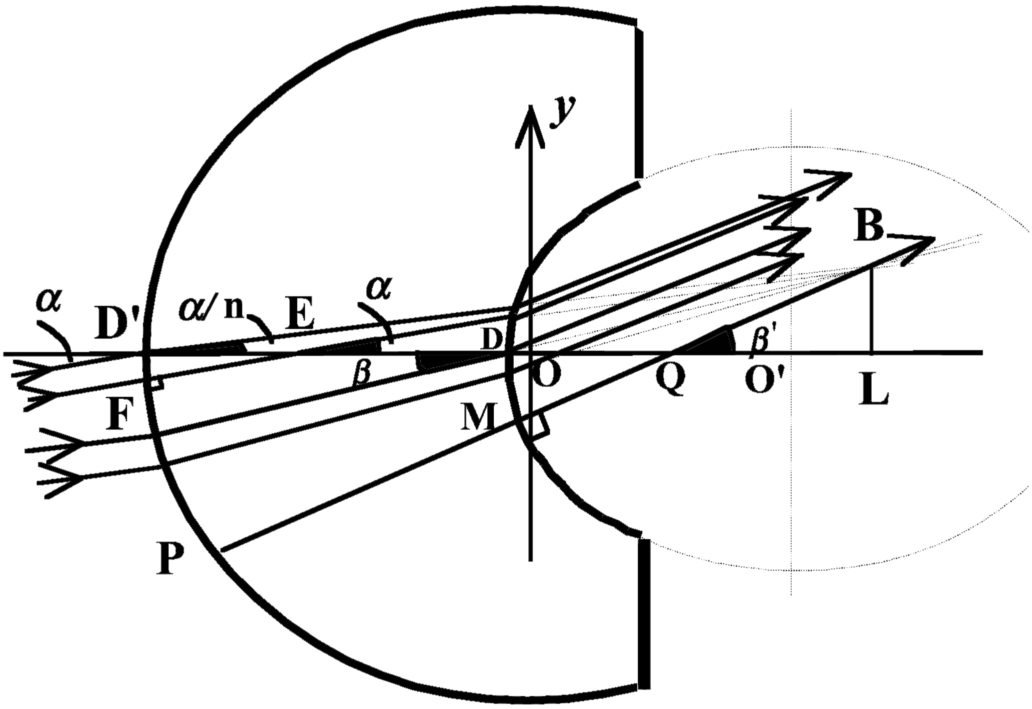

Figure 3

We are to imagine an ellipse, in two dimensions as in Fig. 2, made of the denser material, with the far focus at L and E a point on the axis, but with part of the ellipse truncated as shown. Rays are drawn from a distant object, initially parallel to the ray through E, which suffers no refraction as it is chosen perpendicular to the surface of the ellipse at F. Thus, the ray FE forms an auxiliary axis for the paraxial rays of the larger ellipse These paraxial rays converge to a point B as shown, on the perpendicular line LB passing through the focus L. However, a line MB can be drawn passing through the point Q of the other confocal 'air' ellipse and normal to the surface at M. MB is the auxiliary axis for parallel rays of the smaller ellipse with the same off-centre focus B. Hence the pencil of rays incident on B is rendered parallel to MB on refraction. One may also consider the reversed bundle of rays parallel to BM to be refracted at the inner surface, and to diverge from B. Note that the rays are drawn at much greater angles than would really occur, for clarity, as the paraxial approximation is to apply. Hence, the initial angle BEL subtended by the distant object has been replaced by the enlarged angle BQL, and the ratio of the two gives the angular magnification.

Analytically, the magnification is readily found from Fig.3 : The point B lies in the far focal plane of the larger ellipse of eccentricity e and semi-axis a, and BL = $a(1 + e)\alpha/n$, where α is the angle made by the optical axis to the incident parallel rays and n is the refractive index. The equation of the auxiliary axis FB with origin of coordinates at O is given by :

$$y - a(1+e)\alpha / n = \alpha(x - ae),$$

and hence the distance OE = ae^2, independent of α. Hence, if we have another ellipse of the same eccentricity with centre O' and semi-diameter a', where $a' < a$ and confocal with the first ellipse at L, then DL = $a'(1 + e)$, and β = BL/DL = $a/a' . \alpha/n$: in which case the angle of emergence of the refracted rays is $n\beta' = a/a' . \alpha$. These rays are parallel to the new auxiliary axis BP, and the angular magnification becomes a/a'. Also, as before, O'Q = $a'e^2$. Thus a magnification of the order 5 - 10 should be possible with such a device, if constructed.

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Optical coherence tomography

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INTRODUCTION

Optical coherence tomography (OCT) combines low-coherence interferometry with lateral point beam scanning to produce two- or three-dimensional images [1]. The low (temporal) coherence is provided by broadband light and endows the technique with an axial optical sectioning capability – a 'coherence gate'. This capability is similar to that provided by confocal microscopy but the coherence gate does not depend on the aperture of the optical system. OCT's penetration of highly scattering tissues is limited to a few millimetres, which is lower than ultrasound, magnetic resonance imaging, and x-ray computed tomography, but its resolution for *in vivo* imaging is higher than these modalities: routinely at around 10 μm, sufficient to display clinically relevant morphology, and potentially around 1 μm. OCT has been primarily targeted at *in vivo* imaging through thick biological sections, particularly in the human body. Largely transparent tissues such as the human eye and developmental biological models such as tadpoles and frogs, as well as highly scattering tissues, such as in the human gastrointestinal tract and cardiovascular system, have attracted the most attention. A number of recent works reviewing OCT have appeared [2,3,4,5]. After more than a decade of research, OCT is in the early phases of establishing a niche as a medical imaging technology for routine clinical use. Areas widely recognized as offering comparative advantage are imaging of the eye, primarily the retina, and endoscopic imaging of the gastro-intestinal and cardiovascular systems. Meanwhile, OCT remains the subject of intense research, both into its technology and into medical applications, many of which are in their infancy. In this article, we briefly describe the technology and its origins before highlighting our own work in two areas – the current push to achieve ultra-high resolution and the clinical application of OCT to monitoring the human upper airway during sleep.

BASIC DESCRIPTION

Figure 1 shows a schematic diagram of an OCT system in its most basic form. The key components are a Michelson interferometer and a light source with a very broad bandwidth (and correspondingly short coherence time). The broad bandwidth may be produced by a source with either continuous-wave or short-pulse output.

In the Michelson interferometer, light from the source is split into two paths. In its simplest form, the reference path or arm is terminated by a mirror, which is translated to vary the group delay. In the sample path, light is weakly focussed into a sample and a small fraction of it is backscattered (or back-reflected) within the aperture of the sample-path optics and captured. This component combines in a detector with light reflected from the reference path mirror. For identical polarisations, coherent interference occurs only when the round-trip group delays of the two components are matched to within the small range of axial delay determined by the coherence time of the light. The magnitude of the coherent interference is measured as a function of the reference axial pathlength, which is scanned by translating the mirror. This corresponds to longitudinal (axial) optical sectioning of the sample, and provides the reflectivity of the sample as a function of group delay. To determine the reflectivity as a function of true physical depth, the group refractive index of the sample medium must be known over the path taken by the wave. As described thus far, the technique is usually known as low-coherence interferometry or optical coherence-domain reflectometry.

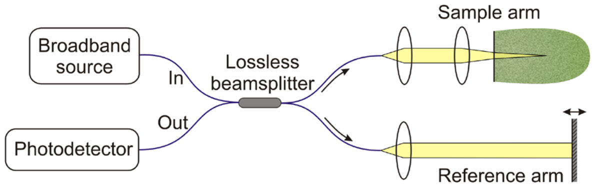

Fig. 1. Time-domain OCT schematic, showing an optical fibre-based Michelson interferometer.

To construct an image, the beam is then laterally shifted, *e.g.*, by reflection from a tilted mirror in the sample arm, and the axial scan repeated. In this way a two-dimensional slice, *i.e.*, an optical coherence tomograph of the reflectivity profile of a sample is recorded. A three-dimensional image may be recorded by including a second lateral scan mirror in the sample arm.

Some of the nomenclature used in OCT has been borrowed from ultrasound imaging [6]. An axial line scan is referred to as an A-scan, and when combined with lateral scanning, is referred to as a B-scan or B-mode imaging. Thus, the OCT scan plane is analogous to ultrasound B-mode, and the terms A-scan and B-mode or B-scan are used in the OCT literature. The OCT B-mode image plane is orthogonal to that obtained using confocal microscopy, which we refer to as the *en face* orientation. The OCT scanning engine can, in principle, be configured to record any two-dimensional surface within a sample and is not limited to raster scanning, but *en face* (usually in the form of optical coherence microscopy) and B-mode are the most common modes. B-mode is more common for two reasons: it provides a depth slice though tissue that is matched to common histological sections; and it is the least technically demanding configuration to build.

EARLY HISTORY AND RELATED TECHNIQUES

OCT may be described as the extension of low-coherence interferometry to tomographic imaging, primarily of biological objects. The term 'optical coherence tomography' was coined in J. G. Fujimoto and co-authors' seminal paper published in *Science* in 1991 [1]. With the benefit of hindsight, the addition of beam scanning to low-coherence interferometry seems an obvious extension, and one which could have been made much earlier, but was not. The huge consequence of this seemingly modest extension has been the creation of a major new branch of medical imaging, which is now finding clinical application.

Early work on low-coherence interferometry took place more or less contemporaneously with work on time-of-flight reflectometry employing short pulses. The application of short-pulse techniques to biological systems was suggested as early as 1971 [7]. Pulse time-of-flight techniques, however, have several disadvantages compared with coherence-domain techniques. The main one, independent of the details of the method employed, is the limit on the time resolution set by the optical pulse width. Until recently, the 100 fs to 10 ps-pulse widths of readily available sources have greatly exceeded the few-to-50 fs coherence times of continuous-wave sources, conveying upon time-of-flight techniques much poorer resolution.

Although not intrinsically a fibre-optic technique, low-coherence interferometry has exploited the development of optical fibre and related photonic technologies since its inception. Low-coherence interferometry was first proposed and demonstrated for micron-resolution optical ranging by three groups in 1987 [8,9,10]. The motivation for such systems was the characterisation of micro-optical components used in optical fibre communication systems. Low-coherence interferometry was applied to the eye as early as 1988 [11,12] and to arteries in 1992 [13]. The first report of OCT [1] contained images of *in vitro* eye and artery. *In vivo* measurements using low-coherence reflectometry had already been conducted on the eye [11]. The first *in vivo* images obtained using OCT were reported in 1993 soon after its initial development [14].

Although OCT may have arisen from low-coherence interferometry, there are a number of other very closely related coherent microscopies [5]. An alternative description of the version of OCT employing a high-numerical aperture objective in an *en face* configuration is as a confocal interference microscope employing a low-coherence source. Confocal interference microscopy was first demonstrated in 1979 in transmission [15] and in 1982 in reflection [16], but with highly coherent lasers. Much more recently, confocal microscopy has been demonstrated using a low-coherence source [17], but the principles of interference and low-coherence were never brought together prior to the introduction of OCT in 1991. An important distinction must be made between OCT and confocal microscopy – OCT has typically employed a *low* numerical aperture. The resulting weak confocal effect permits axial scanning to be performed without undue attenuation of the beam at the endpoints of the scan, enabling axial tomographs in which coherence provides the basis for axial sectioning rather than the confocal effect. Early work on the confocal interference microscope did not demonstrate this mode of operation. The combination of OCT with a strong confocal effect, which was demonstrated in 1994 and termed 'optical coherence microscopy' [18], then introduces for B-mode operation the problematic requirement of synchronous scanning of the confocal and coherence optical sections or 'gates'.

Before continuing it is worth summarising the main advantages and disadvantages of OCT. The following are its main advantages.

- The strength of the optical sectioning is conveyed by heterodyne interferometric detection. Because of this, OCT can image to greater depths than confocal microscopy in highly scattering tissues.
- The axial resolution of the optical section is not dependent on the numerical aperture of the optical system, which bestows an advantage when the numerical aperture is limited, *e.g.*, in the human eye or in endoscopic imaging.
- Point scanning avoids crosstalk from neighbouring lateral sites in the sample.
- In common with confocal microscopy, high-speed scanners make real-time operation at video rates feasible.
- Images in depth, which match the orientation of conventional histological sections in many fields of medicine, are readily produced, often making OCT images more readily interpretable by clinicians than *en face* images.
- The point-scanning feature can be implemented in fibre optics, which makes endoscopic and catheter-based imaging possible.

The following is its main disadvantage:

- OCT images are subject to the corrupting effects of speckle, *i.e.*, the coherent interference of multiple lightwaves, which can limit image fidelity and resolution, as well as depth.

ULTRAHIGH RESOLUTION

To shift the axial resolution of OCT from around 10 μm, which is typically accessible with current generation semiconductor sources, to around 1 μm, requires (assuming a Gaussian lineshape) a corresponding increase in system bandwidth from 75 nm to 750 nm at a centre wavelength of 1300 nm, or from 28 nm to 280 nm at a centre wavelength of 800 nm, neglecting any complicating effects. The required bandwidth versus centre wavelength for a variety of axial resolutions is shown in Figure 2. Early promise of high resolution was shown by Kerr-lens mode-locked Ti:Al_2O_3 lasers [19] and their performance was significantly enhanced in 1999 [20], with the realisation of an extremely well dispersion-compensated laser resonator yielding a spectral width of 260 nm and suitably broadband OCT components, which enabled the axial resolution to reach 1.5 μm, and was soon applied to delineating the layers of the retina [21]. Since then, there has been a high level of activity in ultrahigh-resolution OCT, as recently reviewed by Drexler [22] and by us [23], mainly in the development and deployment of a variety of sources, primarily based on supercontinuum generation in various forms of optical fibre. Primary goals have been: to push the resolution as low as possible, with the record currently standing at 0.75 μm [24]; to cover the main OCT range from 700 nm to 1400 nm; and to reduce the complexity, cost, and size of such sources. A compact, user-friendly prototype has already been deployed in ophthalmologic clinical studies [25].

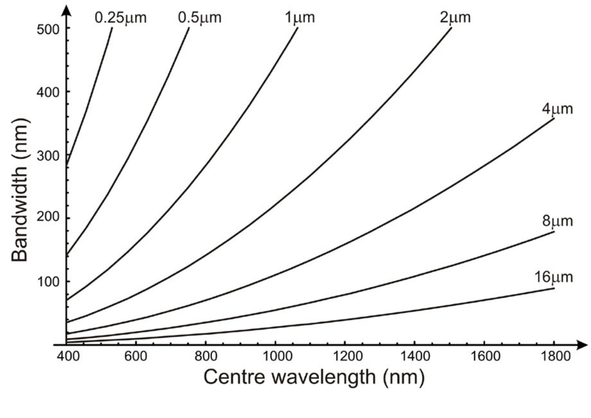

Fig. 2. Plots showing the relationship between centre wavelength and spectral bandwidth required to achieve the specified axial resolutions.

A number of issues have emerged as impediments to achieving micron-resolution *in vivo* histological OCT imaging:

1) Spectral shape: The spectral shape of most reported sources has been far from Gaussian, which causes sidelobes in the OCT axial response. There is no consensus on the maximum permissible value of side lobes, and this is no doubt dependent upon the specific sample and intended purpose. Many reported sources have incorporated passive filtering to improve the spectral shape. As we have demonstrated [26], registration of the full interferogram enables the coherence function to be modified in post-processing, but such modification in real time remains challenging.
2) Noise: Supercontinua often produce intensity noise many tens of decibels above the noise of the pump [27]. While much of this noise can potentially be cancelled by balanced detection [5], performance degradation is likely. This aspect of the new generation of broadband sources has been little studied in OCT but an encouraging sign is the recent demonstration that a 139 nm-band width supercontinuum generated from a high-numerical aperture fibre did not add noise to the pump light [28].
3) Dynamic focussing and high-speed imaging: To achieve a transverse resolution comparable with the enhanced axial resolution requires numerical apertures of 0.14 for 5 μm resolution and 0.57 for 1 μm resolution at a mean wavelength of 1300 nm, with associated depths of focus of 60 μm and 2.4 μm, respectively, in the sample. These depths of focus require the use of dynamic focussing (the axial co-location of focus and coherence gate in B-mode imaging), severely limiting image acquisition rates to the scan rate of the focus. This limitation suggests *en face* scanning as an alternative for real-time operation, which in turn requires wideband phase modulation to generate a carrier, a further challenge. It has been demonstrated that the frequency-domain delay could be used to achieve this [29] and this mode of operation has recently been used in *en face* scanning [30].
4) Visualising cells: Cells and their nuclei have been clearly visualised in transparent animal models and *in vitro* [24]. Some images show exquisitely fine morphological detail, but the visualisation of cells and their constituents at ultrahigh resolution deep in non-transparent tissue *in vivo* has not yet been achieved [22].
5) Sample dispersion and absorption: At the large optical bandwidths utilised for ultrahigh-resolution OCT, the effect of uncompensated dispersion and absorption on axial resolution and sensitivity become much more significant. The effect on a 1-μm resolution OCT signal of an uncompensated 1 mm section of water in the sample arm is to broaden it by a factor of 15 at 800 nm and 17 at 1300 nm. Compensation to high order of the 25-mm length of the eye becomes particularly critical for OCT imaging of the retina *in vivo* [22]. We have shown that sample dispersion may be dynamically compensated during fast axial scanning by an appropriate modification of the frequency-domain optical delay line [31].

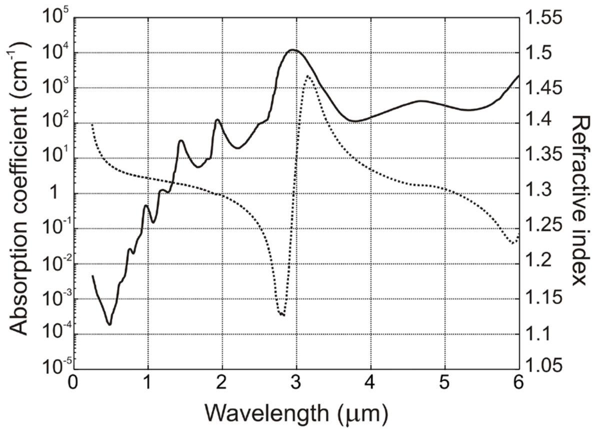

Fig. 3. Absorption (solid curve) and refractive index (dotted curve) spectrum of water, due to Segelstein.

More recently, we have examined the limitations on achieving ultrahigh resolution set by the simple fact that the sample comprises 70-80% water [32]. Figure 3 shows the absorption coefficient and refractive index of water over the wavelength range 0.25 to 6 μm [33]. In principle, the effects of dispersion can be perfectly compensated, but the effects of absorption cannot. The distorting effects on the broadband spectrum become increasingly pronounced as one approaches the local absorption peak of water at 1440 nm, effectively limiting the longest centre wavelength at which one may achieve 1 micron resolution to ~900 nm, which falls significantly short of the commonly used 1300 nm band. However, such performance assumes perfect compensation of dispersion, *i.e.*, the dispersion in the sample and reference arms of the interferometer are perfectly matched. This is difficult enough to achieve at a single depth in the sample, but must be achieved at all depths in B-mode OCT. Typically, dispersion effects are minimised by operating at the dispersion zero of water, close to 1000 nm [34], but as one increases the bandwidth in order to enable micron resolution, the need to compensate to higher dispersion orders rapidly arises. This can be seen in Figure 4, which plots the spectra and interferogram envelopes resulting from propagation through 1 mm of water for representative centre wavelengths and bandwidths. Note the broadening and distortion at the 1300†nm centre wavelength even with perfect dispersion compensation.

ENDOSCOPIC PROFILING OF THE HUMAN UPPER AIRWAY

At the other end of the length scale, we have been applying OCT to profiling human internal organs, which requires only modest resolution of perhaps 100 μm, but extended ranges of 50 mm or more. Video endoscopy of the internal surface of hollow organ systems is widely used in medical practice. A limitation has been the inability to easily quantify internal dimensions during these examinations. Such objective measurements would be particularly valuable in understanding the behaviour of the human airway. Repetitive collapse of the upper airway during sleep is the hallmark of obstructive sleep apnoea, a common condition affecting 2-4% of middle-aged adults. Current understanding of the pathogenesis of this condition has been constrained by the absence of techniques capable of quantitatively evaluating upper airway dimensions over significant periods of time during sleep. Radiographic (X-ray) computed tomography

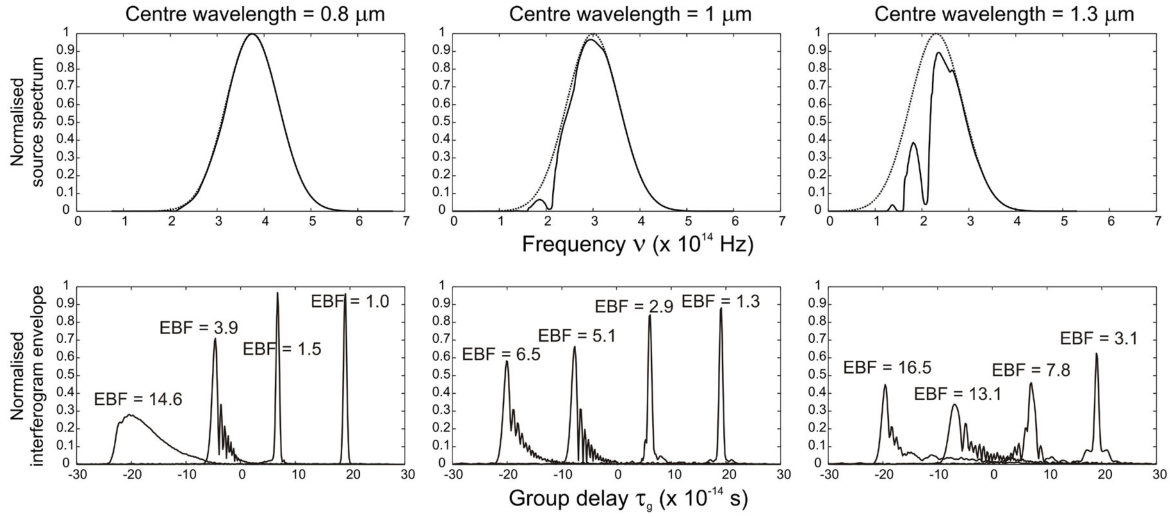

Fig. 4. Plots of interferograms due to the effects of dispersion and absorption. The source resolution is 1ºm. Top row: Dotted curve represents undistorted source power spectral density; solid curve represents absorption-distorted power spectral density. Bottom row: Normalized interferogram envelopes under various dispersion-compensation conditions. In each panel, from left to right, curves represent: no dispersion compensation; compensation of 2nd-order dispersion only; compensation of 2nd and 3rd-order dispersion only; full dispersion compensation. The envelope broadening factor (EBF) is given for all plots.

(CT) scans involve potentially hazardous ionising radiation, as do plain radiographs and fluoroscopy. Magnetic resonance imaging (MRI) is cumbersome and expensive, the environment is noisy and cramped/claustrophobic. The routine use of CT, MRI, radiography and fluoroscopy is impractical for overnight sleep studies. The advantages of optical techniques are high patient safety and long permissible patient exposure times from the use of low-intensity, non-ionising radiation, as well as relatively low-cost and portable operation. A quantitative optical ranging technique such as OCT could provide continuous and dynamic measures of upper airway size and shape over lengthy periods.

Our catheter-based long-range OCT system is shown in Figure 5 [35]. The interferometer is in a Mach-Zehnder configuration, with three-port circulators in both reference and sample arms for maximum power efficiency, a phase modulator for serrodyne modulation of the interference signal to allow bandpass detection, and double-balanced detection to eliminate excess intensity noise. The scanning optical delay line employs a galvanometer mirror driven by a triangular waveform at 250 Hz, which results in a constant delay scan speed of 13.5 m/s. The endoscopic arm of the interferometer consists of a rotating catheter-mounted probe, which is connected to the system by a fibre-pigtailed optical rotary joint. The distal end of the probe consists of a GRIN lens of 1.0-mm diameter attached to the optical fibre, with a 0.7-mm right-angle prism attached to the lens to deflect the beam transverse to the probe. The probe launches 4 mW of optical

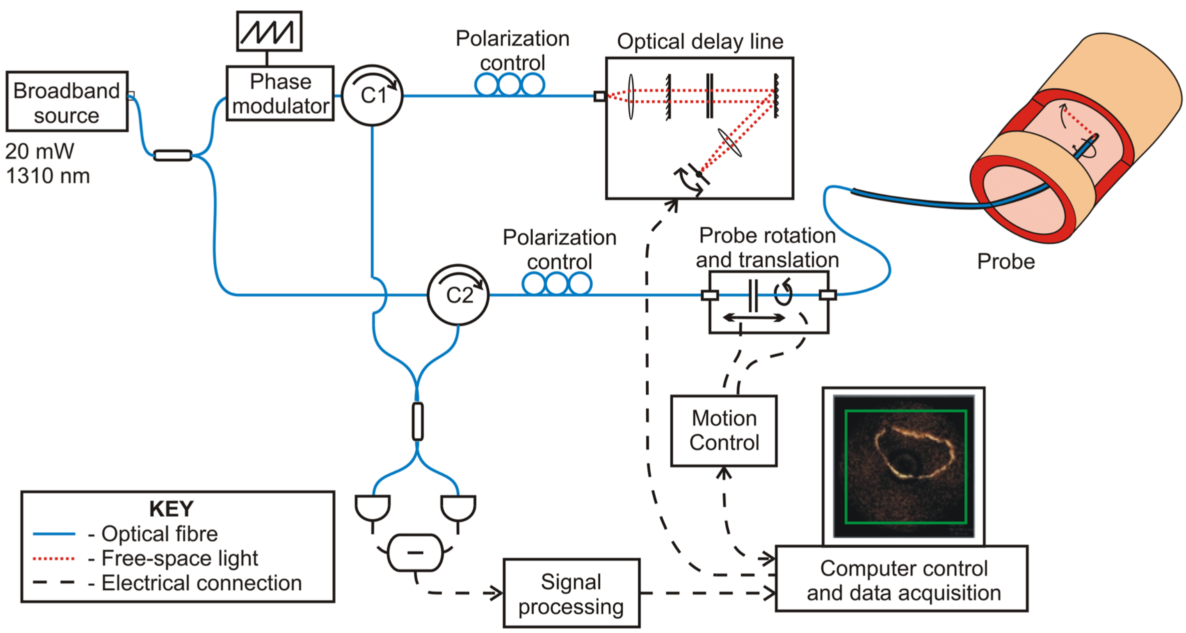

Fig. 5: Schematic of the long-range endoscopic OCT system.

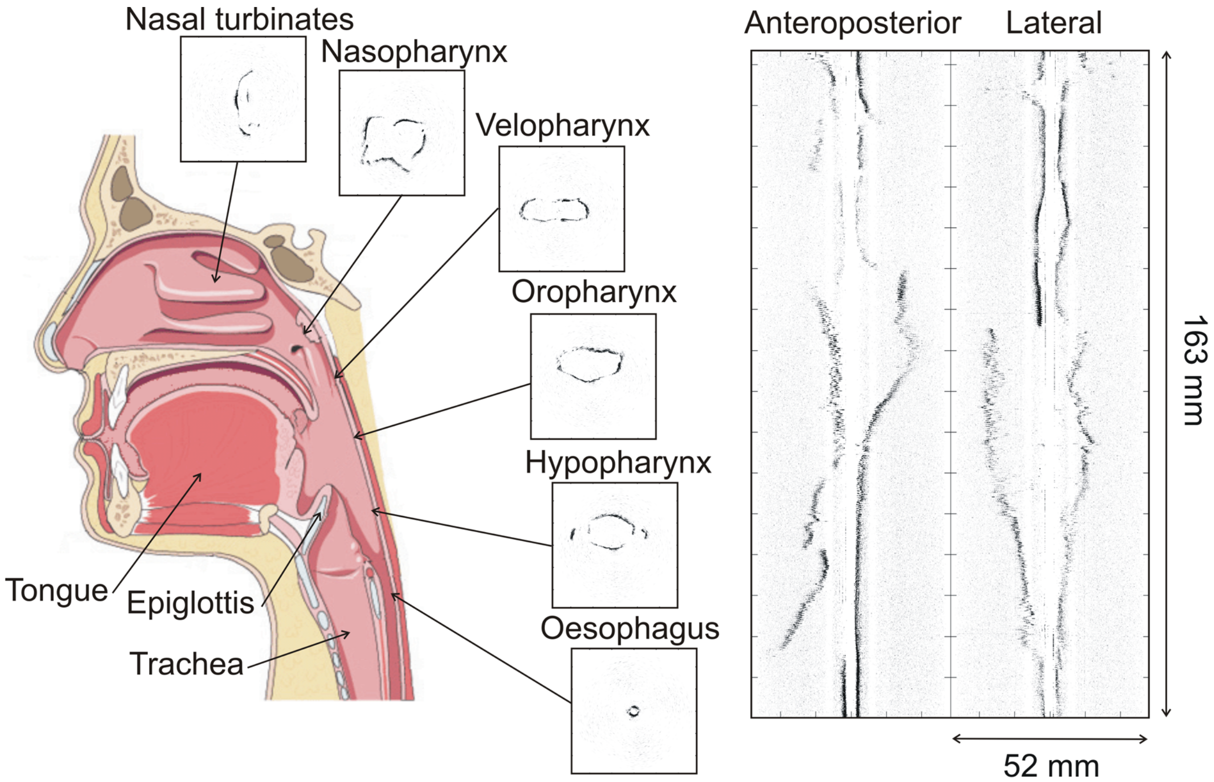

Fig. 6: Selected measured cross-sections (52x52 mm) of the upper airway of an awake human volunteer, and two longitudinal sections, relative to the catheter, reconstructed from a whole-airway scan.

power, and the system is sensitive to reflected power corresponding to a return loss of as low as -98 dB, which is 4 dB worse than the theoretical value of -102 dB. For *in vivo* profiling of the upper airway, a sealed, transparent naso-oesophageal catheter is passed through the external nares (nostrils) traversing the pharynx until the tip is positioned in the middle third of the oesophagus. The rotary joint is mounted on a motorized translation stage, which allows the probe to be automatically moved to various locations along the catheter. This has the benefit that, in addition to its ability to capture cross-sectional images at fixed locations, it is also possible for the probe to move along the catheter while simultaneously capturing images, thus, enabling longitudinal cross-sectional or three-dimensional reconstructions of the airway.

Figure 6 shows the anatomy of the human upper airway with representative measured cross-sectional images. The figure also shows typical left-right and anteroposterior longitudinal sections. From such images it is possible to directly assess airway narrowing; the current gold standard is indirect monitoring via polysomnography, in which changes in airway calibre and site of obstruction are not directly assessed. The availability of an OCT instrument at the bedside could simplify the diagnostic process and make it more specific, allowing better treatments to be derived on the basis of individual airway characteristics. The ability to dynamically examine the upper airway and its behaviour during sleep could have an immediate impact on the clinical care of patients by identifying the offending upper airway segment with subsequent therapeutic targeting. While we have concentrated on the upper airway, OCT is applicable to measurement of the internal dimensions of any hollow organ system accessible by an endoscope.

CONCLUSION

Optical coherence tomography is already a feature of worldwide clinical practice in ophthalmology – retinal imaging was the pioneering application. Commercial clinical applications in endoscopy will no doubt soon follow. The cornerstone research on the retina was done in the first half of the 1990s, providing an indicative timeframe for uptake in clinical practice. A topic of great current interest is the improvement of axial resolution towards 1 μm. Our work provides a framework in which to assess the feasibility of reaching this goal; it is clear that it will not be easy to perform subsurface histology on opaque tissues. OCT is providing new medical capability in a variety of areas and we have highlighted one at the other end of the length scale. The dynamic anatomical study of the upper airway should significantly impact on sleep research and ultimately on clinical treatment of obstructive sleep apnoea. No doubt many other compelling clinical applications of OCT will emerge in time.

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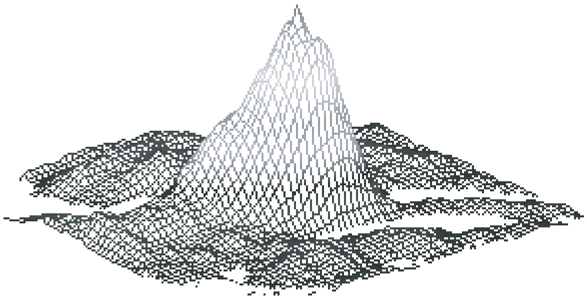

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