Topics for Honours & Higher Degree Students
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Quantum Electrodynamics, X-ray optics and atomic physics
and The X-ray Laboratories in the School of Physics

Quantum Electrodynamics is one of the two best-tested theories in physics and science. Yet certain problems in its formulation lead people like Roger Penrose to assume that there are fundamental flaws in the theory which may be revealed by an appropriate experiment. The type of experiment pursued by our group may reveal such an inadequacy, by being more sensitive to important terms and interactions than other available tests. QED is the primary explanation of the interaction of light and charge, and is fundamental to much of the physics which we assume and rely on in the world today. Experimental and theoretical developments in 1998 – 2003 are questioning the current theoretical approaches.

X-ray optics and atomic physics are very accessible to simultaneous theoretical and experimental investigations. Available projects in this field, for this year, include pure theoretical topics, pure experimental topics, and mixed theory, computation and experimental projects. Pure theory and pure experimental topics can be pursued in X-ray optics and atomic physics [and the optics group] without losing sight of the direct link to the other. A Doctorate will link these threads together in a coherent whole. The synchrotron announced in Melbourne has a close link with both Keith Nugent & Chris Chantler, in the highest profile synchrotron physics group in Australia. The local laboratories also allow development of tools and technology in-house, as well as asking fundamental questions about the universe and matter.

The Web sites: http://optics.ph.unimelb.edu.au/~chantler/home.html & http://optics.ph.unimelb.edu.au/xrayopt/xrayopt.html give background information on some of our current research projects. More recent updates and recent papers can be collected from Chris Chantler.

Current topics for honours and higher degrees:

1 Atomic Physics Theory: a particular area of theoretical investigation is the development of theory of atomic scattering of X-rays. A major form factor tabulation and theoretical basis has been published.[1] There is a need to extend and develop the computation & theory of atomic scattering, particularly in the X-ray regime. Applications of this theory include precision measurements, crystallography, medical physics, tomography and fundamental X-ray experiments like new types of test of Quantum Electro-Dynamics.

1.1 Theory and computation of atomic form factors (scattering of X-rays/diffraction/atomic structure). **[Hons Project*]** Particularly interesting questions relate to high-energy limits, analytic formulations, S-matrix field theory and implementations of correlated perturbation theory. This can develop directly into publications and higher degrees. An honours student recently worked on new analytic calculations of relativistic atomic form factors and was awarded school physics prizes for honours.

1.2 XAFS, Isolated Particle Approximation models and near-edge structure (scattering, atomic structure & crystals). Theory of near-edge structure can explain a number of anomalies in current experimental data from synchrotron research. **[Hons Project*]** Within an honours project, a student would analyze and develop models based on existing work, leading to publications; this would also lead to higher degree projects where new self-consistent theory would be developed. Post-doctoral students are working in this area & an honours student has been working on this in 2003.

1.3 Dynamical diffraction from curved crystals (diffraction / mosaicity). Developments of theory of mosaicity and mosaic diffraction of X-rays is necessary in high-efficiency diffraction experiments in the X-ray regime. We have published the first dynamical theory of X-ray diffraction for non-ideally imperfect curved crystals. Mosaic crystals are crystals where the lattice plane orientation (or phase relationship) is not constant throughout the crystal but instead varies with position or depth. This is a promising area for further research. Recent post-doctoral students have also contributed significantly to this area of research. The link between diffraction and electron density mapping to uinderstand bonding is becoming more important in current world research.

2 X-ray measurement of atomic form factors f and tests of QED: We have developed techniques to test our theories and others available in the literature. Accurate measurements of these coefficients probe atomic physics, the latest theory, and several interesting issues, in addition to probing new structure investigated only in the last few years (XAFS). This has opened up a new field and initiated questions about relativistic, QED and other theoretical contributions to observed interactions. The form factor is directly related to the refractive index (RI) used in visible optics.

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[1] C.T. Chantler, *Theoretical form factor, attenuation and scattering tabulation for Z=1-92 from E=1-10 eV to E=0.4-1.0 MeV*, J.Phys.Chem.Ref.Data 24, 71-643, 1995; C.T. Chantler, *Detailed new tabulation of atomic form factors and attenuation coefficients in the near-edge soft X-ray regime (Z=30-36, Z=60-89, E=0.1 keV – 8 keV), addressing convergence issues of earlier work*, J. Phys. Chem. Ref. Data. 29 (2000)

2.1 High-accuracy measurement of the imaginary component f″. Accurate f″ measurements are experimentally challenging. Our synchrotron techniques have surpassed the previous world's best result by some two orders of magnitude in accuracy and precision and have been announced as amongst the top five experiments this year on two separate beam-lines at one of the three largest synchrotrons in the world. **[Hons Project*]** A recent honours student made great progress towards new high-precision measurements at the X-ray lab Rotating Anode source on level 5. We have the first high-power, high-frequency CE Rotating Anode X-ray source in the world. Earlier experiments have generally been unable to test critical differences between theories. Local and international experiments could follow work done in honours as part of a higher degree. Doctoral students [Chanh Tran & Martin de Jonge] have worked on international experiments relating to this area.

2.2 Absolute measurement of absorption coefficients of copper and silver using local and international sources [Zwi Barnea & Chris Chantler]. We have the best data in the world to investigate new physics in XAFS (near edge atomic and solid state structure), and this can be addressed in current projects.

2.3 Investigation of X-ray scattering and fluorescence distributions. These are needed for f' measurements [the real component of the atomic form factor], and investigate the radial electron density in atomic systems. **[Hons Project*]** An honours project will use existing facilities in the X-ray lab to investigate assumptions currently made about these processes. Post-doctoral students are working in this area.

2.4 Development and design of X-ray spectrometers for high-precision measurement in X-ray physics and QED. [Hons Project *] Current doctoral students & post-docs have made significant progress here. This is directly related to new tests of QED. We have just made the highest precision tests of QED for Vanadium atoms (Z=23) using a new device called an Electron Beam Ion Trap.[2] We are able to investigate discrepancies in QED at the level of 2×10^{-5} (or 20 parts per million) in medium-Z ions, and are developing state-of-the-art detector and spectrometer equipment to improve upon this and ask whether current discrepancies from theory may be fundamental insights into the laws of physics.

2.5 X-ray extended face crystal measurement of absolute intensities for extinction and bonding redistribution of electron density [Zwi Barnea with Chris Chantler]. Diffraction processes require careful measurements on an absolute scale to avoid significant error. The X-ray facility can address these issues directly. Associate Professor Barnea developed these techniques and there are many interesting questions of current international interest which can be resolved.

2.6 Models of X-ray source distributions. X-ray sources produce spectra which are relied on around the world; but theory is unable to predict experimental observed distributions. This area was initiated by a doctoral student [Chanh Tran], and can be developed theoretically and tested experimentally.

2.7 Measurement of reflectivity. Details of reflectivity profiles can test dynamical diffraction theory and investigate surface roughness in materials. **[Hons Project*]** This is complementary to the theory project 1.3 above. This increases our understanding of crystal structure & diffraction, in order to design X-ray-optical instruments for specific fundamental experiments. A doctoral student has developed experimental tools to investigate the effect of mosaicity on reflectivity.

All topics lead to higher degrees; all can lead to research papers within an Honours project; most can lead to or improve

- precision tests of QED (in systems such as He-like Vanadium & H-like Nickel) &/or
- fundamental X-ray spectroscopy. (How accurate is atomic physics for a real atom?)

Each of these experimental topics is a fundamental research area. Critical tests of these important theories have significant implications in understanding physics. Questions like 'How do X-rays diffract and scatter from crystals?', 'How much do we know about radial electron densities?', and 'Do we understand the fundamental forces between charges?' are addressed. This work is both in-house and in collaboration with NIST (Washington DC), the University of Oxford & Synchrotrons (Japan, Chicago).

Other research on X-ray photographic theory & experimental measurement[3] has links with industry. Projects linked with medicine and mammography have yielded publications and patents. Interests include coherence issues at synchrotrons (what new information can you get from interference, and how can you diagnose it?). We have recently installed and tested major new facilities suitable for all these projects and have the first 160 kV, 5μm spot Feinfocus X-ray source in Australia. We lead international collaborations with Chicago, Japan, Washington DC, Oxford and elsewhere.

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[2] J.D. Gillaspy, Y. Aglitskiy, E.W. Bell, C.M. Brown, C.T. Chantler, R.D. Deslattes, U. Feldman, L.T. Hudson, J.M. Laming, E.S. Meyer, C.A. Morgan, A.I. Pikin, J.R. Roberts, L.P. Ratliff, F.G. Serpa, J. Sugar, E. Takacs, *Overview of the EBIT Program at NIST*, Physica Scripta, **T59**, 392-395, 1995; C.T. Chantler, D. Paterson, L.T. Hudson, F.G. Serpa, J.D. Gillaspy, E. Takacs, *Absolute measurement of the resonance lines in heliumlike vanadium on an electon-beam ion trap*, Phys. Rev. A 29 (2000).

[3] C.T.Chantler, *Photographic response to X-ray irradiation I: Estimation of the photographic error statistic, and development of analytic density-intensity relations*, Applied Optics **32** 2371-2397, 1993.