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RADIATIVE PROPERTIES OF STRONGLY
MAGNETIZED PLASMAS

Progress Report

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PROGRESS DURING THE PRESENT BUDGET PERIOD

The influence of strong magnetic fields on quantum phenomena continues to be a topic of much interest to physicists and astronomers investigating a wide array of problems — the formation of high energy-density plasmas in pulsed power experiments, the crustal structure and radiative properties of neutron stars, transport coefficients of matter irradiated by sub-picosecond lasers, the spectroscopy of magnetic white dwarf stars, the quantum Hall effect, etc. (References on these and other issues can be found in the proceedings of the 6th International Conf. on Megagauss Fields, Albuquerque, NM, Nov. 1992.) The passage of time finds more questions being asked than being answered in this subject, where even the hydrogen atom "paradigm" remains a major challenge.

This theoretical program consists of two distinct parts: (1) investigation into the structure and transport properties of many-electron atoms in fields $B > 10^8$ Gauss; and (2) extension of spectral lineshape methods for diagnosing fields in strongly magnetized plasmas. Research during the past year continued to be focused on the first topic, primarily because of the interests and skills of Dr. E. P. Lief, the postdoctoral research associate who was hired to work on the proposal. Unfortunately, Dr. Lief has just left Rice University to accept a more secure position in medical physics at the Memorial Sloan-Kettering Cancer Center; a prompt search for his replacement will be conducted as soon as this proposal is approved for renewal. (In the meantime, the PI is continuing the research with an advanced graduate student from Cornell who, fortuitously, is working part time in Houston this year.)

1. THEORETICAL ANALYSIS

During the first year of the proposal, Lief and the PI developed a new statistical model of multi-electron atoms in strong fields ($B \sim B_0 = 2.35 \times 10^9$ Gauss), one which exhibits the correct axial symmetry. This represents a fundamental improvement over Kadomtsev's original extension of statistical, Thomas-Fermi (TF) theory to the case of large magnetic fields. (His model requires strongly magnetized atoms to still be spherical.) By working with the atomic electrons'

density $n(\mathbf{r})$ instead of the electrostatic potential $\Phi(\mathbf{r})$, as is usually done in TF theory, we could introduce an *ansatz*,

$$n(\mathbf{r}) = n(\rho, z) = n_\rho(\rho) \cdot n_z(\rho; z) \quad (1)$$

that imposes the correct symmetry on the solution. The "price" one pays is that now, instead of a non-linear second-order ordinary differential equation, one must solve a non-linear second-order partial differential equation,

$$\partial^2 n_z^2 / \partial z^2 + \partial^2 n_z^2 / \partial \rho^2 + C(\rho) \partial n_z^2 / \partial \rho = - A(\rho) n_z^2 + D(\rho) n_z, \quad (2)$$

where A , C , and D are specified functions of n_ρ (see Lief and Weisheit, *Contrib. to Plasma Phys.*, Dec 1993, for further details).

We construct the factor n_ρ from occupied Landau orbitals for (free) electrons in a quantizing magnetic field, but the determination of which orbitals are occupied is not trivial: One must identify which set of occupation numbers yields the most tightly bound atom, and so far we have had to do this on a case-by-case basis, by numerical methods described in the next section.

The atomic binding energy E_b is the difference between the energy E_{atom} that the electrons and nucleus have in the presence of both the field $\mathbf{B}$ and their pair-wise Coulomb interactions (energies V_{en} and V_{ee}), and the energy E_{free} that all these charges have when they are in the field but do not interact with each other, i. e., when they are free. The adoption of Landau orbitals implies that motion perpendicular to the field is completely regulated by the field itself. Hence, only motion parallel to the field (energy $T_{||}$) contributes to the binding energy,

$$E_{\text{bind}} = E_{\text{atom}} - E_{\text{free}} = \langle T_{||} + V_{en} + V_{ee} \rangle. \quad (3)$$

The parallel kinetic energy $T_{||}$ should be eliminated to give a binding energy in terms of just the electrostatic quantities V_{en} and V_{ee} which are straightforward to compute. However, we recognized in the course of this work that the usual Virial Theorem results for spherical atoms cannot be used here. Instead, one needs to appeal to density functional theory to yield another relation between these mean energy terms,

$$\langle 3T_{||} + V_{en} + 2V_{ee} \rangle = 0, \quad (4)$$

and from these two equations get the working definition of E_b .

2. NUMERICAL ANALYSIS

During the past year, most of our efforts have focused on the development of numerical procedures to solve the equation for $n_z(p;z)$. The present code uses an implicit finite difference scheme which, for a 50x50 spatial (p-z) grid, leads to a $50^2 \times 50^2$ matrix that must be inverted. (This is about the maximum size that can be accommodated straightforwardly on our SUN Sparcstation II.) An unusual aspect of our approach is that, to achieve proper normalization, the behavior of n_z at large z-values must be adjusted so that the integrated charge density equals the number of bound electrons. No more than few hours computation time is needed to calculate an atomic charge distribution numerically accurate to 1 or 2%.

We have already reported a set of energy calculations for carbon atoms in strong fields, and those results indicate that atoms can become much more tightly bound when the constraint of spherical symmetry is dropped. A new set of calculations have just been carried out for helium. Even though two electrons make for a poor statistical atom, we are encouraged by the results:

B/B ₀	0.1	1	10	10 ²	10 ⁴
E _b [He] (au)	1.03	2.83	6.93	17.6	139

At the lowest field strengths appropriate to our statistical method ($B \sim B_0$), the energy is close to the adiabatic bounds published by Park and Starace [Phys. Rev. A29, 442, (1984)]. There is some possibility that J. Feagin (also funded by OBES) will be able to explore the He problem further, using techniques he has developed to study the Coulomb 3-body problem, but this time in an external field.

At the present time, work is in progress to develop a better numerical scheme to take advantage of the sparseness of the large matrix described above, and to automate the search for the Landau orbital populations that yield the most tightly bound atom.

3. PRESENTATIONS

This research is being well received by the atomic/plasma physics community, and the following presentations were made during the past year.

- May 1993 meeting of APS Atomic, Molec. and Optical Phys Div.(Reno, NV) — poster presentation by Lief
- Aug. 1993 symposium of Rice Quantum Institute (Houston, TX — poster presentation by Lief and Weisheit
- Sept. 1993 APS Topical Conf. on Atomic Processes in Plasmas (San Antonio, TX) — poster presentation by Lief and Weisheit
- Sept. 1993 at VII Internat'l Workshop on Non-Ideal Plasmas (Rostock, Germany) — invited address by Weisheit
- Oct. 1993 at Joint Us-Russia Workshop on Dense Plasmas (Moscow, Russia) — invited address by Weisheit

4. PUBLICATIONS

- "On the Structure of Atoms in Strong Magnetic Fields," E.P. Lief and J.C. Weisheit, *Contrib. to Plasma Phys.*, to be publ., Dec 1993 issue.

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