Haggai Landa – Final Scientific and Personal Report

Chateaubriand Fellowship 2013-2014

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Purpose of the project

The guiding purpose of the project is to study the interaction of trapped ions with ultracold atoms and molecules. The project is currently focused on a single ion trapped in a time-dependent potential of a Paul trap, and interacting with an ultracold atom. In the second phase, utilizing solutions of the system of a single ion and single atom, the analysis will be extended to include a crystal of a few ions (and possibly even tens of ions or more), interacting with a gas of ultracold atoms or molecules, condensed into a Bose-Einstein condensate.

Description of the work carried out

The Chateaubriand fellow has started by studying the theory and main tools which are required in order to analyze the polarization interaction of ions with atoms, namely scattering theory and the Gross-Pitaevskii equation for the mean-field wavefunction of an interacting Bose gas. The past years have seen some notable advances in the understanding of such interactions, with an important tool being quantum defect theory, applied to long-range interactions. These tools have in general so far been applied to free (as opposed to trapped) particles, and within a time-*in*dependent framework.

Therefore, we have formulated a model for an ion trapped in a time-dependent trap and interacting with an atom, and the theory goes beyond current approximations used in the literature in a few respects. The motion of the ion is described by classical equations of motion within a time-dependent Paul trap, and a term describing the interaction of the ion and atom is added, which depends on the state of the atom. In this respect the model is novel because it accounts for the back-action of the atom on the time-dependent motion of the ion in its trap potential. The atom's motion is described quantum-mechanically, as a scattering problem (for the atom) in a time-dependent potential (the ion's prescribed motion). This problem is unsolvable in general and we have developed a complex scheme which allows to solve it reliably, going beyond existing treatments. The ion and atom's solutions are to be obtained self-

consistently. We are currently performing extensive numerical calculations in an effort to obtain solutions of the formulated model.

Ongoing and future work

The theory we have developed is expected to give accurate results, which can be confirmed experimentally. In fact, there is an ongoing debate in the community on the existence of bound states of ultracold atoms and ions trapped in Paul traps, and the possibility of observing such states has been doubted. Initial results which follow from the current project indicate that such states exist and potentially could be observed. The states which are predicted by these results are strongly time-dependent, and could not have been anticipated by the previously employed approximations.

Thus, if these results are confirmed they will present a significant advance of existing understanding of the possibilities for studying interactions of particles trapped in time-dependent fields (trapped ions being just one case). We will be able to apply the tools developed to more complex problems. In the next phases of the project, that will continue with funding by a Marie Curie Intra European Fellowship within the 7th European Community Framework Programme, we will study the generalization of the problem to the interaction of many ions (in a crystal) interacting with many atoms (condensed into a degenerate quantum state). Also, the technique which we have developed for solving the time-dependent scattering problem can be applied to completely different systems, such as trapped polar molecules, which present a rich system that has attracted a lot of attention recently.

Collaborations and planned projects

During the period of the fellowship a few collaborations have been initiated, and a few contacts have been established which are expected to mature to collaborations in the near future.

A collaboration has been started with the experimental ion trapping group at NIST, Boulder, led by Dave Wineland and Didi Leibfried. The purpose of this collaboration is to study jointly the chaotic motion and heating mechanisms of ions trapped in a surface Paul trap. Although the current experiment being held at NIST does not involve directly an interaction of the ions with atoms, the heating of trapped ions is currently the most significant limiting factor

in all experiments involving trapped ions. The formed collaboration will address this fundamental problem using novel tools developed for study of time-dependent problems (as stands at the heart of the fellow's Chateaubriand project). Involved in this collaboration is also Prof. Denis Ullmo from LPTMS, who contributes from his expertise in the field of dynamical systems and chaos, and this is a direct result of the fellow's stay at LPTMS.

The fellow has also initiated contact with a few experimental groups which are performing experiments specifically on the interaction of trapped ions and atoms – namely with the groups at the Freiburg University in Germany (headed by Prof. Tobias Schaetz), at the University of Ulm in Germany (headed by Prof. Johannes Hecker-Denschlag), and with the group of Prof. Roee Ozeri at the Weizmann Institute in Israel. The results expected within the fellowship project are of primary interest to those groups (and others who run the same system), and they all have expressed their interest in collaborating in the near future.

Finally, within the fellow's project for the upcoming two years, to be funded by the European Commission, the fellow has started an attempt to initiate an outreach activity which will involve high-school students in both France and Israel. Within the project, to be undertaken during a period of one year (approximately), the high-school students will be guided by Ph.D. students and will study scientific techniques of research, culminating in a small-scale study of a problem which is related to modern research carried in laboratories that they will visit. Within the proposed project, students from France and students from Israel will work on similar problems, and could form a "mini-collaboration" by electronic exchange of ideas and opinions on the problem at hand, with eventually meeting in a scientific congress for youth. In France, a few French-speaking Ph.D. students at LPTMS have already joined this initiative and therefore it is currently being presented at a few high-schools by personnel of Université Paris-Sud (Responsable du pôle "communication et diffusion des sciences d'Orsay"). The fellow will begin similar attempts In Israel soon.

Benefits and Challenges of the Fellowship

The fellowship and the extensive support by the French Institute at Tel Aviv has allowed me to move together with my family to Paris, and cope with the difficulties of the transit. From this respect, the efforts that have been made have greatly helped to make my relocation to Paris as smooth as possible. Also from the financial point of view, the fellowship has answered all

expectations and even exceeded them. One challenge which I have encountered during my stay was the fact that the fellowship includes a designated private insurance only for the fellow, which does not cover the family (and in particular not the children). It turns out to be impossibly difficult to obtain social security rights for the family (in fact, my wife has not succeeded in that until now). However, I wish to emphasize that this challenge did not affect my overall experience of the migration to France, and I perceive the possibility to live and perform my research in the Paris metropolitan area as a great opportunity. The abundant cultural richness allows me to still feel like a tourist on the weekends, when I go to explore Paris or the French countryside.

To conclude, the Chateaubriand fellowship has allowed me a continuous transit from my Ph.D. studies to a postdoc position, and in fact, to what has become at least a three-year postdoc position at LPTMS. In this respect the fellowship has inevitably set the course of my postgraduate research, and therefore, possibly, of my entire professional life. On a personal note, I wish to relate my deepest appreciation for the funding and for the support that I received from the personnel at the French Institute at Tel Aviv, which has allowed me to face the welcome and challenging changes in my life, and the life of my family.