THE PHYSICS OF STORED LASER COOLED ION CLUSTERS:

PHASE TRANSITIONS IN A SYSTEM WITH ONLY A FEW DEGREES OF FREEDOM

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Laser cooled stored ions offer a number of intriguing possibilities as an experimental tool for contemporary atomic physics research. Confined by "walls of pure energy" the ions are free from any unwanted contact with the surface of the confining vessel. This is an ideal situation for spectroscopy, for storing antimatter, or even a combination of both: antimatter spectroscopy. Moreover, a single laser cooled ion might well be the core of future high accuracy frequency standards, several orders more accurate than present day Cs atomic clocks /1/. The basic idea of storing and cooling of ions might also find useful applications in analytical chemistry, where the idea could be further developed into a tool which is sensitive on the single ion level. Recently an additional dimension was added to the physics of laser cooled ions. It was conjectured that crystallized ion beams, cooled by electrons or lasers might exist in accelerators and storage rings /2/ with far reaching consequences for elementary particle physics. The new type of crystallized beams surpass by orders of magnitude the quality of "traditional" beams as far as beam diameter and emittance are concerned. These features result in a considerably increased luminosity implying that atomic and elementary particle processes with cross sections too tiny and therefore too costly to be measured with present day technology would now be within the experimental reach.

In this article we describe yet another interesting aspect of laser cooled stored ions, namely their application to the physics of few body dynamical systems. In extension of earlier work on stored aluminum particles /3/ it was demonstrated only recently /4/ that laser cooled ions in a Paul-trap/5,6/ can be found in essentially two stable phases: a "crystalline" phase in which the ions arrange themselves in highly symmetric geometrical patterns, and a "cloud" phase in which the motion of the ions appears irregular and chaotic. In certain ranges of the trap control parameters both phases are stable, i.e., the ions show bistability and hysteresis /4/. As a function of the laser power, e.g., transitions between the two phases were observed both experimentally and theoretically by modelling the experimental situation on a large computer /7/. In order for the ion clouds to be stable, a heating mechanism is necessary which is provided

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by the time varying storage field of the trap itself. Although this mechanism was known to the experimentalists for already a long time /6/ its origin was rather uncertain and, e.g., attributed to collisions with rest gas atoms or the heating effect of the laser cooling photons. Only very recently it was revealed that the heating mechanism, the "rf heating", is actually due to a purely dynamical effect, namely the occurrence of deterministic chaos in the stored ions system /8,9/.

Thinking about it for a moment, this "discovery" is not so unexpected since ions in a trap are very similar to a miniature planetary system interacting via an inverse square force law. The sign of the Coulomb force, sure, is opposite to the sign of the gravitational force, but otherwise the few body ionic system resembles closely the celebrated three- and more-body planetary systems which are known to be non-integrable and exhibiting deterministic chaos in certain domains of phase space.

A close investigation of a five ion situation showed that ions stored in a Paul-trap exhibit four dynamical regimes /7/: The first regime is a single point in phase space and corresponds to the minimal energy "crystalline" configuration whose existence was proved experimentally by direct observation with a photon sensitive imaging camera (see e.g. cover page of Physics Today, Sept. 1988, or Nature, vol. 334, 1988). The second regime is a small region in phase space around the minimal energy point and represents the "quasi periodic" regime. In this regime, the ions perform a quasi periodic motion, i.e., the Fourier transform of their positions or their velocities shows a discrete frequency spectrum. The crystalline phase and the quasi periodic phase are the "non-heating" phases since the trap field, representing a mono-chromatic drive, cannot couple resonantly to any of these discrete frequencies unless it hits one of them "right on top", which is extremely unlikely. The quasi periodic region in phase space is separated from the chaotic region by a fractal boundary /7/. In the chaotic regime, the third dynamical regime, the Fourier transform of the positions and velocities of the ions exhibits continuous bands in frequency /7/ and due to the continuous nature of the possible frequencies of the ionic motion, the trap field always finds "its" frequency to which it can couple resonantly and deposit energy which results in heating of the chaotic phase ("rf heating"). The heating eventually stops as soon as the ions have gathered so much energy that their mean separation is so large that the Coulomb force can be neglected. This means that the non-linearities in the problem are too small to lead to chaos, the motion is integrable again, and since in this regime the ions behave nearly like independent particles, this regime has been dubbed the "Mathieu" regime since the motion of single ions in the Paul-trap is governed by the Mathieu equation /6/.

The existence of these four regimes of the ion dynamics leads naturally to a physical picture for the explanation of the observed "phase transitions" from the cloud state to the crystalline state. When the ions are loaded into the trap, they possess a considerable kinetic energy and are most likely to be found in the Mathieu regime. Switching on the cooling laser takes out kinetic energy from the system and the ion cloud contracts until an equilibrium is reached between the powers of laser cooling and rf heating. Since in a smaller cloud the ions explore more of the non-linearities of the Coulomb interaction, a small ion cloud is "more chaotic" and thus heats more than a larger cloud. The heating power of the cloud thus rises with smaller cloud size, and an increasing cooling laser power will therefore be counter balanced by the increased heating power of the smaller cloud. The cloud's maximal heating power, however, is limited. There comes the point where, as a function of increasing laser power, the cloud is forced to such a small diameter that it enters the quasi periodic region in phase space, where, as a result of the discrete frequency spectrum in this region, all the heating power is lost and the cloud collapses to the crystalline phase. The picture of the four dynamical regimes thus explains very naturally the sharpness of the cloud $\rightarrow$ crystal phase transitions.

In the absence of external noise, a crystal $\rightarrow$ cloud transition does not occur in the Paul-trap since the crystalline configuration is always surrounded by the quasi periodic regime, and both phases are non-heating. This is confirmed by experiment /7/ and theoretical calculations /7/. The crystals, however, can be destroyed by external sources of noise /7/. Noise induced transitions from the quasi periodic regime to the cloud phase, as a function of the trap voltage, were reported by Dr. DeVoe in this conference. The average location of the crystal $\rightarrow$ cloud transition points depend on the "temperature" of the crystal, i.e., the crystal's average excitation energy /8/.

Returning to the problem of phase transitions as a function of the laser cooling power, it should be pointed out that "spontaneous" transitions from the cloud phase to the crystalline phase are possible with a probability which reflects the ions' probability of occupying regular (non-heating) and irregular (heating) phase space domains. This ratio is particularly large in the few ion case and also shortly before the cross-over from the cloud- to the crystalline state occurs as a function of increasing laser power. It is therefore expected that for a small number, N, of ions, the probability distribution of the location of the transition points has a fairly large width which narrows in the limit $N \rightarrow \infty$. The narrowing, however, is expected to be very fast for increasing N, and already in the case of N=5 ions it was demonstrated /7,9/ that the transition points are very well defined.

Summarizing the above results, we can say that the physics of laser cooled ions in a Paul-trap is fairly well understood on a global qualitative level. Considerably more work has to be done on the detailed quantitative level to get, e.g., analytical estimates for the locations of the various phase transition points. Since recent experiments with a single stored ion already hit the quantum limit /10/, it might also be desirable to work out the quantum theory for ions stored in a Paul-trap. Given the occurrence of classical chaos in this storage device, the manifestations of "quantum chaos" should show up for $N \geq 2$.

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