# New Setup To Study Trapped Nano-Particles Using Synchrotron Radiation

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**Abstract.** A novel setup is presented that is suitable to investigate the change of the properties of a single trapped nanoparticle by charging it with monochromatic synchrotron radiation. The particles are stored for long time periods that reach up to days without any contact to a substrate in the center of a three dimensional electrodynamic quadrupole trap. The accurate $Q/M$ value is derived from the oscillatory motion of the particle in the trap recorded via scattering of visible light.

## INTRODUCTION

Properties of variable size matter have been investigated during the last decades. It is of fundamental interest to investigate size-dependent changes of matter in order to bridge the gap between the gas phase and the condensed phase. However, the number of atoms that is required to obtain macroscopic behavior of condensed matter depends sensitively on the properties of interest [1]. Size-dependent properties of matter have numerous possible applications in nanoscience, materials research, and other fields of applied research. Moreover, electrical charges changes these properties of matter, especially in weakly bonded clusters [1]. The number of charges that can be accommodated on a cluster or particle depends sensitively on its size. Small clusters as well as microparticles undergo immediate fission, if the Rayleigh stability limit is exceeded [1, 2].

Variable sized, single particles offer the unique possibility to investigate properties of matter that are beyond the size regime of small clusters, which also includes controlled charging. We present in this paper a novel experimental approach, that allows us to investigate trapped, single micro- and nano-particles in the gas phase over long time periods using monochromatic synchrotron radiation in the soft X-ray regime.

## EXPERIMENTAL

The experimental setup consists of a three-dimensional electrodynamic trap, which is located in an ultra-high vacuum chamber. Figures 1(a) and 1(b) show a schematic view of the trap. It consists of two conical cap electrodes (see Fig. 1(b)). There are around the center of the trap eight vertical rod electrodes which replace the ring electrode of a classical three electrode Paul-trap (for more details see [4]). This open geometry allows us to observe the stored particle at various angles, so that several detectors can be used simultaneously. The AC voltage of the driving field is applied to the cone electrodes. The boundary conditions of the apparent quadrupole term of the field expansion are shown as dashed contours (see Fig. 1(b) and refs. [5, 6]). A small loudspeaker is mounted below the trap, serving as particle reservoir as well as particle injector. It was filled with monodisperse $SiO_2$ particles of 500 nm diameter [7]. When an AC voltage of typically 1.4 kHz is applied to its membrane, it vibrates and ejects a swarm

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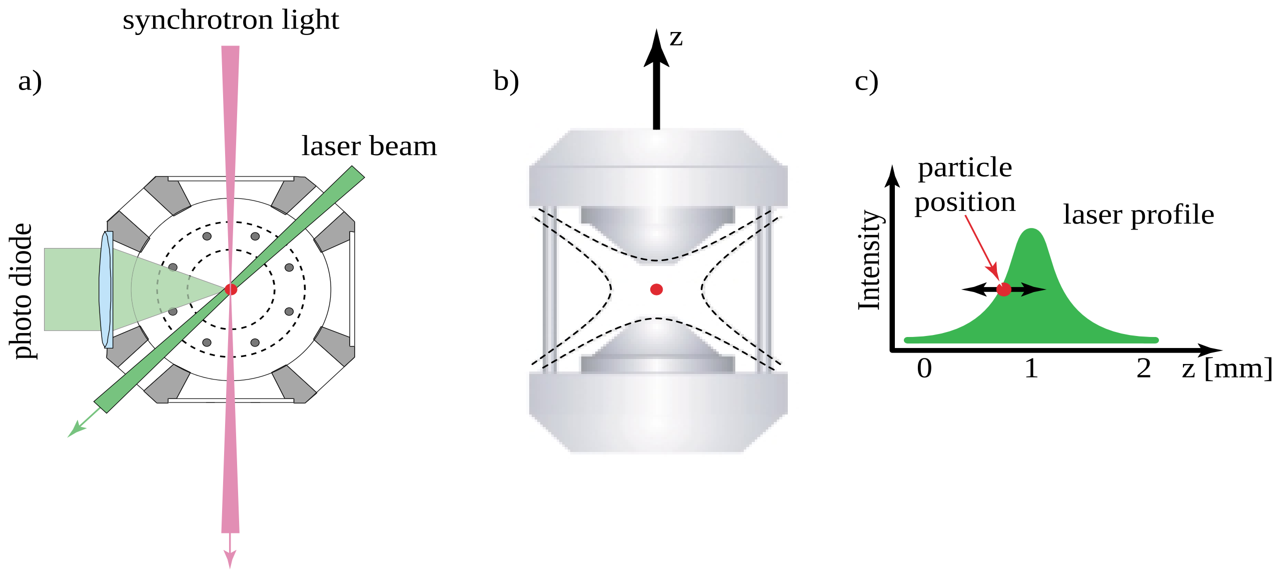

**FIGURE 1.** (a) Top view of the electrodynamic trap, where a single particle is stored in the center; (b) $z$-plane view of the trap; (c) Schematic drawing of the $Q/M$-measurement using the secular motion of the particle through the Gaussian laser beam profile (see text for further details).

of particles into the trap, until one of them gets caught. Trapping becomes quite efficient, when the AC trap voltage amplitude is set to $2V_0 = 1500\,\mathrm{V}$ at $\Omega/2\pi = 600\,\mathrm{Hz}$. The trapped particle typically carries initially some ten positive charges. It is illuminated by a frequency doubled Nd:YAG-laser ($P < 50\,\mathrm{mW}, \lambda = 532\,\mathrm{nm}$, cf. Fig. 1(a)). The scattered light from the particle is collected by a lens ($f = 25\,\mathrm{mm}$) and it is detected by an avalanche photodiode. The motion of the trapped particle through the Gaussian beam profile of the laser is schematically shown in Fig. 1(c). As a result, the scattered light is modulated by the secular motion frequencies $\omega_r$ and $\omega_z$ perpendicular and parallel to the trap axis, respectively. Both frequencies are obtained from a fast Fourier transform of the photodiode signal. This allows us to derive the charge-to-mass ratio $Q/M$ of the particle:

$$Q/M = \sqrt{2}\,\omega_r\,\Omega z_0^2/V_0, \tag{1}$$

where the driving frequency of the trap $\Omega$ and the high voltage amplitude $2V_0$ are known quantities and the geometrical factor $z_0$ corresponds to 5.50 mm. Firstly, one has to determine $Q/M$ of the stored particle. This is accomplished by changing the charge of the particle by using an electron gun. The kinetic energy of the electrons is typically set to some hundred eV, so that the positive charge of the particle increases by secondary electron emission. One observes at low electron current an increase by one or integer multiples of the elementary charge, leading to a stepwise change of the eigenfrequencies of the stored particle. The least common multiple of the frequency changes corresponds to the change of one elementary charge, corresponding to the smallest step height in a charging experiment. The absolute charge state and the mass of the particle are determined according to eq. (1) (see also ref. [5]). In this new experiment, monochromatic synchrotron radiation has been used to eject electrones from stored particles to study charging mechanisms at different photon energies. (see Fig. 2). The particle shown in Fig. 2 has a mass of $9.950 \cdot 10^{-17}$ kg. Assuming that the density $\rho_{\mathrm{SiO}_2} = 2.0 \pm 0.1\mathrm{g/cm}^3$, one obtains a particles diameter of $455 \pm 8$ nm. This value is close to the average particle size distribution specified by the manufacturer [7]. The particles are exposed after proper characterization to monochromatic synchrotron radiation in the soft X-ray regime, using the UE52-SGM beam line at the storage ring BESSY. First experiments focus on the controlled charging of the stored particles by soft X-rays.

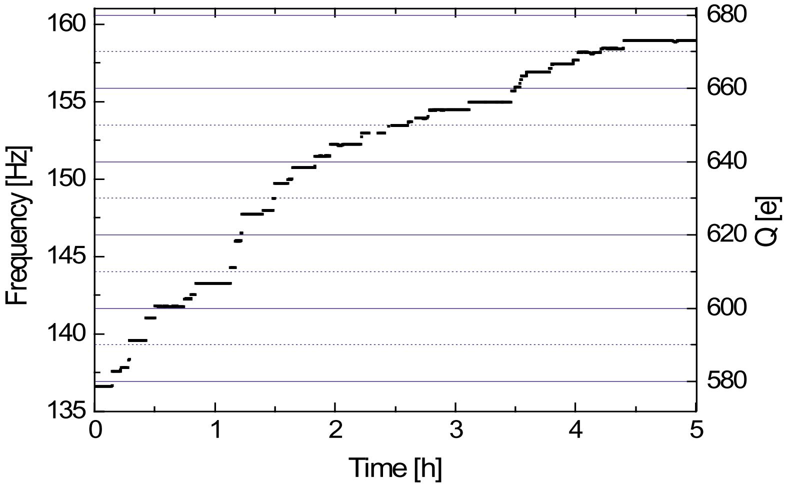

**FIGURE 2.** Charging curve of a single $SiO_2$ particle, when it is exposed to monochromatic synchrotron radiation at $h\nu = 500\,\mathrm{eV}$.

## RESULTS AND DISCUSSION

We have measured the charging of 500 nm $SiO_2$ particles, when they are exposed to soft X-rays at various photon energies. Such experiments require to reduce the number of photons impinging on the particle in order to avoid multiple photon absorption processes and to keep the absolute charge state low $(Q < 1000\,\mathrm{e})$. This is accomplished by narrowing the exit slit of the monochromator, detuning the undulator, and working off the focal point of the monochromator. The results are shown in Figs. 2 and 3. Each charging event is due to electron emission. The measurement starts at a charge state of 579 positiv elementary charges. In a period of 5 hours 94 electrons are emitted (Fig. 2). Fig. 3 shows that charging of the particle per absorbed photon is smaller at 84 eV than at 500 eV, corresponding to different step heights (cf. Fig. 2). This is due to changes in multiple ionization processes as a function of photon energy. Single ionization dominates at 84 eV and there should be smaller contributions from direct double and multiple ionization. However, the cross sections of these processes are expected to be low. At 500 eV there are enhanced contributions from multiple ionization, reaching up to the emission of 7 charges per absorbed photon. Multiple ionization in the Si $2p$-continuum can occur via normal or multiple Auger processes as well as secondary electron impact ionization by Auger electron in the bulk, explaining the lower probability of single ionization at this photon energy. The analysis of the step sizes allows us to determine the probability to eject a given number of electrons with one photon. This measured function has been fitted using a Poisson distribution (see Fig. 3). The distribution function shows that there is a finite probability of no charging at both photon energies, even though one would expect that the quantum yield of ionization should be greater than unity at both photon energies. The maximum of the Poisson distributions changes from $\delta = 1.3$ at 84 eV to $\delta = 2.3$ at 500 eV. This agrees very well with values from standard tables [8] for kinetic energies of the primary electron impact ionization close to the respective photon energy. The average number of charges produced per absorbed photon is expected to increase with photon energy, similar to the ionization yield of atoms [9]. Moreover, the emission of low kinetic energy electrons depends on the charge state of the particle, so that from highly charged particles only high kinetic energy electrons can escape. This may explain that there is already at low charge states a certain probability for no change in charge state, according to the distribution functions.

## CONCLUSIONS

Soft X-rays from the storage ring BESSY are shown to charge efficiently stored particles. Charging occurs at low photon flux in steps of single or integer multiples of the elementary charge. The absolute charge state $Q$ is accurately determined by an optical detection technique. In addition, probability distributions for the emission of electrons are reported, showing a distinct dependence on the photon energy. We expect that this distribution depends sensitively on

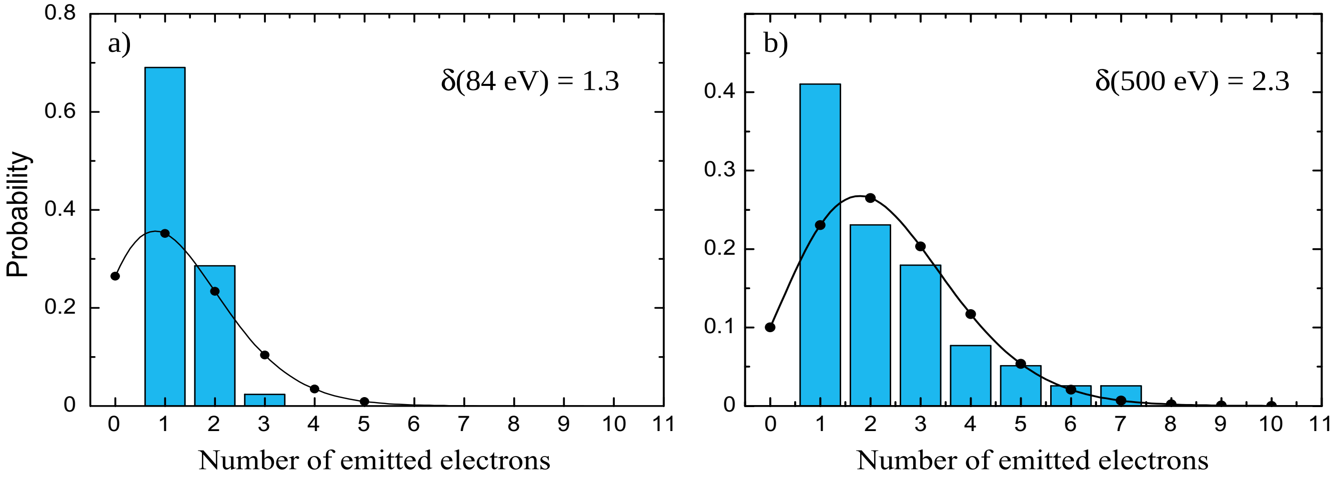

**FIGURE 3.** Electron emission probability of a $SiO_2$ particle at different photon energies: (a) 84 eV and (b) 500 eV. See text for further details.

the absolute charge state of the particle. Another advantage of the present approach is, that one can fully control the charge state of the sample, which is of importance for investigations of electronic properties of insulators.

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