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Hollow-atom probing of surfaces

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Document Version

Publisher's PDF, also known as Version of record

Publication date:

1996

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Limburg, J. (1996). *Hollow-atom probing of surfaces*. s.n.

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Hollow-Atom Probing of Surfaces

OMSLAG: *“Winter in Groningen”, KVI/PV De Kern schaatstoertocht, Winsum – Onderdendam – Baflo – Mensingeweer – Winsum, 1996.*

This work is sponsored by the “Stichting voor Fundamenteel Onderzoek der Materie” (FOM) which is financially supported by the “Nederlandse Organisatie voor Wetenschappelijk Onderzoek” (NWO).

Part of this work is sponsored by the EC program on Human Capital and Mobility, grant no. ERBCHRXCT930103.

DRUK: *Stichting drukkerij C. Regenboog, Groningen, augustus 1996.*

RIJKSUNIVERSITEIT GRONINGEN

Hollow-Atom Probing of Surfaces

Proefschrift

ter verkrijging van het doctoraat in de
Wiskunde en Natuurwetenschappen
aan de Rijksuniversiteit Groningen
op gezag van de Rector Magnificus, dr. F. van der Woude,
in het openbaar te verdedigen op vrijdag 30 augustus 1996
des namiddags te 2.45 uur precies

door

Johannes Limburg

geboren op 26 oktober 1966
te Delfzijl.

Promotor: Prof. dr. R. Morgenstern

Referent: Dr. ir. R. Hoekstra

Preface

“Meet the hollow atom – it has a bright future. Physicists think they can tap its energy to make everything, from X-ray holograms to CD’s”– **Ian Hughes and Ian Williams in New Scientist, #1980, (1995).**

THIS THESIS presents the results of a graduate study into the *interaction of highly charged ions with solid surfaces*. This study started the first of september 1992, when I entered the main building of the ‘Kernfysisch Versneller Instituut’ in Groningen – for the first time as a member of the “Atomic Physics Team”. During my undergraduate studies, I took numerous courses in computer science and electronics but only a very few which had something to do with the discipline of *atomic physics*. Despite this lack of knowledge, I realized that the “study of atomic phenomena” – probably having the longest standing tradition of all disciplines within physics – is a very active field of research. This, taken with the prospect to study the exciting creatures called “hollow atoms”, was a strong motivation to apply for a PhD. position within the group of professor Reinhard Morgenstern.

For those who are laymen as far as the discipline of atomic physics is concerned – as I was four years ago – the following text briefly introduces the background of the experiments discussed in this thesis.

Atomic physics

The great Greek philosopher and scientist Aristotle (384 - 312 B.C.) classified all known matter into four basic elements: soil, air, water, and fire. In his philosophy two forces acted on these elements: *weight*, the tendency of soil and water to fall down and *lightness*, the tendency of air and fire to rise

up. Aristotle believed that matter is continuous, that it can be split in two over and over. Other Greeks, like Democritus “*the Laughing Philosopher*” (circa 460 - 371 B.C.) thought that all matter is granular, built up of little grains.

If one could collect one gram of highly charged neon 9+ ions, this gram would contain about 10,000,000 Joules of potential energy. This is much more than the energy contained in a typical piece of Dutch cheese (1000 J/gram) but much less than the energy released during nuclear fission (100,000,000,000 J/gram).

These grains, or *atoms* were thought of as the basic building blocks of nature (Greek *átomos* literally means *undivided*). The dispute between both philosophies lasted for centuries until finally at the beginning of this era Einstein found strong support for the atomists' view. In a paper published a few weeks before his famous article on special relativity, he proved that Brownian motion – the irregular motion of small particles suspended in a liquid – is caused by collisions with fluid *atoms*. If the fluid were continuous, no such collisions could occur.

However, at this time it was already suspected that the atom itself has structure, i.e. is built up by smaller constituents. In 1911, the British physicist

Ernest Rutherford performed a famous experiment showing that atoms consist of a very small positively charged nucleus (made up of *protons* and *neutrons*), with a number of negatively charged electrons orbiting around it. The attraction imposed by the positively charged nucleus keeps the electrons in their orbits, just as solar gravity prevents the planets from drifting away into deep space. However, since the work of Hertz in the nineteenth century it was known that a current (i.e. electrons) running around in an electric field gives rise to *radiation*. The electrons running around in the nuclear electric field can be considered as tiny electric currents, therefore according to Hertz' law they should also radiate. Moreover, such radiation would occur at the expense of the electrons' velocity. This would eventually lead to a collapse of the atom at the moment the electrons have radiated all their energy. Such a collapse is not observed in reality. In contrast, atoms are very stable!

In 1913 this contradiction was (partly) solved by the Danish physicist Niels Bohr who proposed that the electrons are not allowed to have any kind of orbit around the nucleus but each of them rather rotates at a fixed distance. By this he was able to explain the structure of hydrogen, the simplest atom consisting of one proton and one electron.

Though Bohr's assumptions initially seemed rather strange and artificial, his ideas were proven right by the newly developed theory of quantum mechanics a few years later. According to quantum mechanics, an electron orbiting around a nucleus can be considered as a travelling wave, the wavelength of which is inversely proportional to the *energy* of its movement. In order to survive in a certain orbit, the electron wavelength must fit exactly an integer number of times. Otherwise the wave would quench itself (by a process called destructive interference). Furthermore it was shown that no two electrons can be in exactly the same orbit ('level') at the same time. This eventually led to the *shell* model of the atom, in which the atom is pictured as a nucleus surrounded by electrons in specific orbits or shells. The every day atom is in the ground state, that is, the electron shells are filled up step by step, starting with the one closest to the nucleus.

What are "hollow atoms"?

Ground state atoms can be *excited*. That is, an electron can be moved into a higher orbit (by a collision with another atom for instance) leaving a hole in its former shell. Or they can be *ionized*, when one or more electrons are completely removed from the atom. But, like throwing up a stone, this costs energy. *A hollow atom is an atom with many (or all) of its electrons far away from the nucleus, in 'highly excited shells'.* Consequently, a lot of space is present in the shells closer to the nucleus.

Just like a thrown-up stone has a tendency to fall back to the earth, an electron in a high shell can drop back into the hole it left in a deeper shell. When such a *transition* occurs, the potential energy the electron gained when it was moved away from the nucleus becomes available again. There are basically two mechanisms available by which an electron can release its potential energy; by emission of a photon (light) or by kicking another electron out of the hollow atom. The latter process is called an "Auger transition".

The large amount of potential energy carried by hollow atoms makes

Part of the work presented in this thesis has been sponsored by a European Human Capital and Mobility network which became operational in 1993. The network was based at the Hahn-Meitner Institute in Berlin, the residence of network 'chief' dr. Nico Stollerfoht. All contributors are listed in the figure. Much of the work in this thesis has been done in close collaboration with the groups in Osnabrück, Vienna, and San Sebastián.

them interesting species for study. Firstly as subject of fundamental studies. The potential energy is released very rapidly, and measurement of the resulting photons or electrons can reveal the processes governing this rapid energy release. But also possible technological applications of the energy stored in the hollow atoms has been a strong motivation for study.

How are hollow atoms created?

Hollow atoms are made in laboratories in a rather peculiar way. The creation of a hollow atom starts in an ion source. In such a machine, electrons are removed from atoms (the atoms are *ionized*). The ions are then extracted from the source and guided toward an experimental set-up. The last decades very powerful ion sources have been developed, by which virtually any number of electrons can be removed from atoms. This way, intense beams of ions have been produced, ranging from singly charged hydrogen (a proton without the electron) up to fully stripped U^{92+} (an uranium atom without its 92 electrons)!

When such highly reactive ions collide with other atoms, molecules or even solid surfaces, their large positive charge strongly attracts electrons. During a collision, electrons can be removed from the collision partner and captured by the ion. Metal surfaces are of specific interest as collision partner since a metal, being a conductor, can supply a virtually infinite number of electrons to the incoming ion. Already at a large distance in front of such a surface a highly charged ion quenches its thirst for electrons by rapidly ‘pulling out’ loosely bound electrons from the solid. These electrons are mainly captured into highly excited shells of the ion, simply because these shells have large radii and are closest to the surface. *This way the hollow atom is formed.* The principle of hollow atom formation in front of surfaces was already described theoretically in 1973 by the Russian scientist Arifov and his coworkers. It took, however, 17 years until their existence became evident when in 1990 the group of J.P. Briand measured photons emitted by hollow argon atoms created in front of a silicon surface.

Here the surfaces come in

In 1979, Bitenskiĭ and coworkers developed the so called “Coulomb explosion” model. A *slow* highly charged ion approaching a surface might attract so many electrons out of the solid that a severe charging up of the solid takes place. If this charge is localized to a very small spot on the surface, the formed ions will repel each other strongly leading to a small scale explosion by which a tiny crater is formed on the surface. This way, highly charged ions might be used to create (‘etch’) structures on the surface. Such structures would have much smaller size than those created using conventional

Coulomb explosion according to Johannes Eilander, the designer of the KVI surface physics set-up.

techniques. The promising possibility of creating surface structures on an *atomic* scale has been a strong motivation to investigate highly charged ion-surface collisions. In view of such possibilities it is important to localize where and how the potential energy of the highly charged is dissipated. Energy release far away from the surface or after the ion has penetrated the solid too deep, probably has no effect on the surface itself. But potential energy dissipation close to or even *at* the surface, might lead to modification of the surface on the aforementioned atomic scale.

The localization of the potential energy dissipation which accompanies the interaction of highly charged ions with surfaces and a mapping of the underlying physical mechanisms are the basic topics discussed in this thesis. In a literal sence, Hughes' and Williams' quote cited in the preface perfectly summarizes the objectives at the root of this thesis: *What is the future (fate) of a hollow atom formed in front of a surface? How 'brightly' can it be observed? Is there any chance of surface modification?*

The discussion is presented in twelve chapters, eight of which handle results from experiments performed at the KVI. Chapters 1 to 3 are introductory and in chapter 12 some conclusions will be drawn.

Groningen, August 1996.