Nuclear Instruments and Methods in Physics Research B xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Six decades of atomic collisions in solids

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ARTICLE INFO

Article history:
Received 5 August 2016
Received in revised form 18 October 2016
Accepted 1 December 2016
Available online xxxx

Keywords:
Atomic collisions
Channeling
Stopping power
Sputtering
Charge states

ABSTRACT

In response to an invitation by the organizers of the 27th international conference on atomic collisions in solids, a brief survey is presented, starting from the roots of the field in the 1950s and 1960s, of some major discoveries, longstanding problems, surprising findings and memorable controversies in topics covered by the conference. Considering the breadth of the field, the selection of topics is necessarily subjective, but with the emphasis on channeling, stopping and sputtering, three topical areas are discussed which have been active from the early 1960s until now.

1. Introduction

Atomic collisions in solids, also known as particle-solid interaction, is the common term for a branch of accelerator-based physics with a wide range of applications in science and technology. The roots of the field date back to the middle of the 19th century with the study of phenomena in gas discharges. Early in the 20th century, after the discovery of radioactivity, exploration of the penetration of charged particles in matter and their accompanying ionization phenomena became an active research area. During the first half of the 20th century it was not the least theoretical studies of atomic–collision processes which paved the way for the development after World War II.

Fig. 1 shows publication activity from 1945 until now in three major topical areas, radiation damage, stopping and sputtering[1].

The overall behavior is exponential over several decades, but there are significant differences between the three chosen fields. Radiation damage shows a very steep rise after 1950 and a more moderate slope from 1970 on. Sputtering shows a similar behavior, although the expansion rate is significantly higher than that of radiation damage from around 1975, with a publication rate of $\sim$ 5000 papers per year in 2015. Note, however, that both sets of data include activities that may be far from fundamental research in collision physics. A different behavior is seen in the field of stopping, where we see a constant activity level until $\sim$ 1965, the time of the first ICACS conference, a rapid rise until 1990, and a constant level at $\sim$ 150 publications per year ever since.

A few distinct events in the 1950s have contributed to mark a new era in collision physics,

- As a consequence of US president Eisenhower's legendary 'Atoms for Peace' speech in 1953, an international conference on peaceful use of atomic energy was called to Geneva in August 1955 [2]. It was in this period that wartime research in nuclear science and technology whad to be understood in terms of momentum transfer in atomic collisions or as local evaporation, 'Wehner spots' reflecting the crystal structure in the angular emission pattern of sputtered atoms were instantaneously taken as evidence supporting the dominating role of atomic collisions in the process. More on this point in Section 7.1.
- Already in 1951, N. O. Lassen [4] had reported measurements of the charges of fission fragments penetrating through matter, where he found significantly higher charges for penetration in solid than in gaseous targets (Fig. 3). These measurements marked the starting point of a new field of research, atomic physics with swift heavy ions, and their interpretation gave rise to a long-lasting controversy from the 1970s to the end of the past century. More on this point in Section 6.5.1.
- The last item to be mentioned here is Lindhard's [5] dielectric theory, which is an expansion of classical Drude-Lorentz electrodynamics of material media. Lindhard theory is based on quantum instead of classical mechanics and allows for rapidly varying electric and magnetic fields via a dielectric function

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[1] This graph is supposed to show qualitative trends, considering both the choice of keywords and wellknown weaknesses of the Web of Science [1].

http://dx.doi.org/10.1016/j.nimb.2016.12.004
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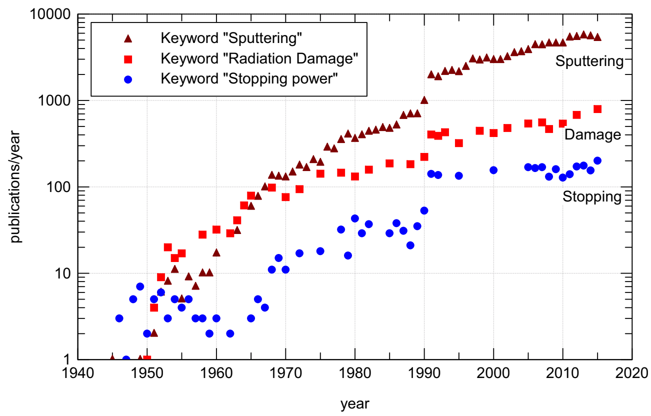

Fig. 1. Number of publications per year listed under keywords 'radiation damage', 'sputtering' and 'stopping power' in the Web of Science, June 2016.

$\epsilon(k,\omega)$ which depends on both frequency and wave number. This has proven to be a powerful and versatile formalism and acknowledged as a useful tool in many-body electron theory because of its conceptual simplicity. The original paper [5] offered applications both in condensed-matter physics and in particle penetration. The theory was exemplified on the Fermi gas, and its combination with the Thomas–Fermi principle, or local density approximation, provided a badly-needed tool for semi-quantitative calculations of energy losses in condensed matter for several decades.

In this report I have chosen to illustrate the development of the field of atomic collisions in solids on three topical areas, channeling, stopping and sputtering, which have been amongst the prime issues at all ICACS conferences over half a century. I have tried to focus on landmarks where either longstanding problems were solved or new activities opened. Considering the amount of acquired knowledge indicated by Fig. 1, I kindly ask the reader to bear over with the fact that both the choice of topical areas and selected landmarks to some degree reflects my own experience in the field, and the degree of detail reflects to some extent the time periods of my engagement.

2. Drivers of the development

The field of atomic collisions in solids is characterized by tight interaction between theory and experiment, as well as between basic and applied research.

Radiation damage in materials, particularly in graphite, had been identified as a prime topic to be concerned about in the construction of the first reactor during the Manhattan project in World War II. A report by Seitz [6] stimulated a wealth of experimental and theoretical studies, not only of radiation damage in numerous materials but, just as important, of a wider range of collision phenomena.

Another major driving force came from nuclear physics. In 1955, leading groups in isotope separation gathered at Harwell [7], discussing ion sources, target preparation and collection problems. By 1965, the time of the first ICACS conference [8], ion sources and target preparation had been studied widely and successfully, while collection problems, addressing the concentration of foreign atoms that could be incorporated into a material by implantation, needed fundamental knowledge of ion penetration, sputtering and radiation-enhanced diffusion which was still nonexistent.

The development of integrated microelectronic circuits has been a major driving force for basic research in collision physics from the mid 1960s, as documented already in the proceedings of ICACS-1 [8]. It was particularly developers of particle detectors who had the right mix of expertise in solid-state and accelerator physics to lead this development [9].

Numerous applications of atomic–collision phenomena in solids showed up in the following years. Materials science has been one of the main objects, in particular ion beam analysis by a variety of accelerator-based techniques, ion-beam modification of all kinds of materials, as well as basic research in diffusion phenomena. Ion-beam modification became the topic of a separate conference already in 1970, and ion-beam analysis followed in 1973.

An example of the opposite order of events is the discovery of organic mass spectrometry by particle bombardment, also called PDMS (plasma desorption mass spectrometry), by nuclear physicists [10] and subsequently discussed vividly in the atomic collisions in solids community for several years. Interest in that area decreased temporarily with the emergence of laser-based technologies but come up again more recently under the name 'MeV-SIMS'.

A particular feature is the phenomenon of sputtering which, during the 1960s, became more or less split between two topical areas, sputter emission or erosion on the one hand and sputter deposition on the other. Sputter emission is genuine atomic–collision physics and central to applications in basic and applied surface physics and chemistry. Sputter deposition is an important tool in thin-film technology. Research in sputter emission accounts for most activities in sputtering indicated in Fig. 1 until around 1975, while sputter deposition took over gradually and has been dominating from the late 1980s.

3. Experimental tools

Numerous experimental tools, developed in other branches of science and technology such as ultrahigh vacuum, particle accelerators and detectors as well as sample preparation, especially crystal growth, have become necessary ingredients in atomic–collision physics. In other areas such as structure analysis, electronics and computers there was also substantial feedback in the opposite direction.

Several types of particle accelerators were developed initially for protons, alpha particles or electrons. Experiments involving other ions required special ion sources. The major challenge in experimental research on atomic collisions was the development of ion sources enabling acceleration of an arbitrary isotope of an arbitrary element up to a well defined energy. That development took place from the mid 1950s over most of the 1960s. The energy range available for acceleration of heavy ions increased gradually from ∼100 keV in 1960 to the TeV regime at the turn of the century.

Beams of molecular ions had been employed early on, mostly with the aim of decreasing the beam velocity for a given acceleration voltage, but from the early 1970s molecular beams were used to investigate new physics [11,12].

Antiprotons, discovered in 1955, result from nuclear reactions at high-energy accelerators. Hence, instead of an accelerator a source of antiprotons for atomic–collision studies is typically a decelerator. While the prime motivation for building such facilities is the study of antimatter, limited access has been provided from the late 1980s to atomic–collision experiments with both gas and solid targets [13].

4. Theoretical aspects

Here I wish to mention two features in the development that are common to all topical areas in consideration.

Please cite this article in press as: P. Sigmund, Six decades of atomic collisions in solids, Nucl. Instr. Meth. B (2016), http://dx.doi.org/10.1016/j.nimb.2016.12.004