WIS-95/35/Aug.-PH

# IONIZATION MEASUREMENTS IN SMALL GAS SAMPLES BY SINGLE ION COUNTING

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## ABSTRACT

A new method for highly efficient measurements of the ionization statistics in small, wall-less, well-defined low density gas samples is proposed. It is based on counting ions, induced by radiation in a sensitive gas volume. The high resolution permits to measure spatial correlations between the number of ions induced in two distanced small sensitive volumes. Using tissue- or solid-equivalent gases, the method permits to accurately determine the ionization statistics in the corresponding sub-nanometer volume of condensed matter. These data are of relevance to the modeling of microscopic phenomena related to the interaction of radiation with matter, such as in nanodosimetry and studies of radiation damage to solid state devices.

*Submitted as a letter to* Nuclear Instruments and methods in Physics Research A.

The spatial distribution of damages, induced by energetic ionizing particles in condensed matter, is a subject of interest in different fields such as solid state physics, microelectronics, and radiobiology [1,2,3]. Of particular importance is the field of radiation protection and microdosimetry; the knowledge of the damage distribution and fluctuations in this distribution in living tissue is important for the understanding of biological radiation effects [3].

The relevant scale for the damage distribution varies, according to the application, from a micron in microelectronics down to a nanometer in the study of the damage to the DNA. For some applications the correlation between damage sites is of prime importance. For example, if the irradiated system has a built-in recovering mechanism for a single damage site, it may not recover from two or more correlated damage sites inside its basic cell. According to microdosimetry, the biologically significant damage distribution should be related to a living cell size or to that of its subsystems: $\sim 1\ \mu m$ for a chromosome and $\sim 1\ nm$ for the double-helix of the DNA [4]. The importance of the nanometric scale has been experimentally confirmed [5]. Moreover, some biological models [6,7] indicate that the maximum radiobiological damage is related to the coincidence of two ionization clusters, each having a few nanometer size and being a few tens of nanometers apart. Therefore, it is desirable to develop experimental methods enabling to measure the ionization statistics within volumes of a cubic nanometer and to measure the spatial correlations between such two distanced damage sites.

There is an approach for measuring ionization site distributions on small scales, which uses a gas phase as a model for the condensed matter sample under consideration. It relies on a scaling factor originating from the density ratio, with presumably some corrections to density effects [8]. In the case of the living tissue, a tissue-equivalent gas (TEG) is used. In spite of the evident roughness of this approach, which neglects some specific features of a living matter and others of a condensed matter, in microdosimetry it still provides useful results. The rigorous treatment of gas simulation of condensed matter is a subject for further investigations.

Many experimental works have tried to minimize the tissue-equivalent sample size, simulated by a low pressure (a few $Torr$) TEG. Among these are a cylindrical proportional gas counter [9], where the pulseheight reflects the ionization density, and a drift chamber coupled to a single-electron counter [10,11,12]. In the latter, the number of ionizations is measured by counting pulses induced by individual

electrons, originating from the ionization sites in the sensitive volume. However, the considerable electron diffusion at very low gas pressure seriously affects the spatial resolution. It limits the simulated (tissue-equivalent) sensitive volume, typically to about 10 nanometers. Furthermore, a reduction of the pressure below 1 *Torr* causes the electrons to undergo a quasi-ballistic transport, which inhibits the use of this approach [13].

We propose a new approach, based on the collection and counting of the radiation-induced positive ions, rather then electrons [14]. As explained below, it provides a spatial resolution, in the tissue-equivalent scale, down to 1 nanometer or less. The idea is shown in Fig. 1. An energetic charged particle traverses a low-pressure gas ionization cell, typically at 0.1 *Torr*. It induces ionizations around its track – directly and through the mediation of $\delta$-rays. Radiation-induced ions drift under an electric field $E_1$, through a narrow aperture, towards an ion detector (under $E_2$). The electric field configuration and the size of the aperture define the sensitive volume, shown in the figure. By displacing the aperture relative to the particle beam axis, the ionization distribution can be measured. The ion counter, a microchannel plate (MCP) or microsphere plate (MSP) [15], is vacuum operated. An appropriate differential pumping system can maintain the pressure difference between the two sides of the aperture. It should be noted that the MSP can operate at relatively moderate vacuum, of $10^{-3} - 10^{-4}$ *Torr*, which is an advantage in this application.

To estimate the sensitive volume size and shape, in the simplest case of an homogeneous electric field, we used the known diffusion model [16]. Using the general expression for the rms displacement of an ion during its drift under an electric field, and the Einstein relation between the ion mobility and the diffusion coefficient, we derive the rms ion displacement $\bar{x}_{ion}$:

$$\bar{x}_{ion} = \sqrt{\frac{2kT}{eE_1}}\sqrt{L} \ , \tag{1}$$

where $k$ is the Boltzmann constant, $T$ the gas temperature, $L$ the drift length, $e$ the electron charge magnitude and $E_1$ the the electric field strength.

It should be noted that relation (1) is valid if the ions are close to being in thermal equilibrium with the gas molecules. This condition is fulfilled, even for very low gas pressures, under the assumption, that the initial energies of the induced ions are thermal. It is completely valid for noble gases and only partly

valid in the case of molecular gases, where some fractions of ions of dissociative energy are produced. The initial energies of the ionization electrons, in contrary, significantly exceed both the thermal and the dissociative ion energies, and this leads to the above mentioned limitations in the the electron counting method at very low gas pressures [13]. We use relation (1) for semi-quantitative estimations of the proposed ion counting method.

The transverse spread of the ions during their drift was assumed to be Gaussian with the above rms value. The distributions of the ion collection efficiency over the entire ionization cell, calculated for $E_1 = 15V/cm$ and $T = 200K$, are shown in Fig. 2 *a*, *b*. The results do not depend on the pressure, which should be taken into account only in the scaling to the condensed matter simulated sizes. One can see that a region, from which the ions are collected with a high efficiency, is extended along the electric field direction, and its characteristic transverse size is about the slit width. Fig. 2 *b* shows the variations of the transverse efficiency distribution with the slit width. Larger silt width leads to a higher efficiency and a better definition of the sensitive volume (more "square" distribution). The scaling factors to the simulated condensed matter volume depend on the type and pressure of the gas. For example, for propane, the main component of a TEG, it is 2.4 $nm/mm \cdot Torr$. Thus, using 0.2 $Torr$ of propane and 2 $mm$ slit, one can reach, with a reasonable efficiency, a simulated transverse sample size of about 1 $nm$. An additional reduction of the sensitive volume size can be made by measuring the ion arrival time with respect to the primary particle crossing moment. By selecting a given time interval, a corresponding section of the sensitive volume is sampled. This is a simple task due to the relatively low ion drift velocity.

Due to the high expected resolution of this technique, it can be extended to include two or more aperture/detector elements, measuring the ionization from separated sensitive volumes in coincidence. This may uniquely provide the correlations between ionizations in small distanced volumes.

The nearest aim of the suggested method is to satisfy the requirements of nanodosimetry. It may permit, for the first time, to measure biologically significant data in tissue-equivalent sub-nanometer volumes, corresponding to the sizes of the finest units of the biological structure. Both spatial ionization distributions and their correlations can be obtained. This method can be applied also to the modeling of radiation-induced ionizations in other species of condensed matter, such as submicron solid-state electronic devices.

The new technique promises to provide a qualitatively new experimental information, important for understanding fine features in the interaction between radiation and condensed matter.

This work was supported by the Foundation Mordoh Mijan de Salonique and the Basic Research Foundation of the Israel Academy of Sciences and Humanities. S. S. is grateful to the Israel Ministry of Absorption for his partial support. A. B. is the W. P. Reuther Professor of Research in the peaceful uses of Atomic Energy.

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## Figure captures

Fig. 1 A conceptual diagram of the proposed single ion counting method. Ions, released by a charged particle in a low-pressure ionization cell, drift through an aperture and after acceleration, are counted in a vacuum-operated device.

Fig. 2 Spatial distributions of the collection efficiency for a long slit aperture. The electric field is 15 $V/cm$, the gas temperature is 300 $K$.
a) Equal efficiency contours for a slit width of 2 $mm$.
b) Transverse efficiency distributions for slit widths of 0.5, 1, 2 and 6 $mm$, at a fixed relative distance from the slit plane equal to 2.5 of the slit width. The lower scale is the real distance from the slit plane in a laboratory setup; the upper scale corresponds to the simulated tissue length for 0.2 $Torr$ of propane.

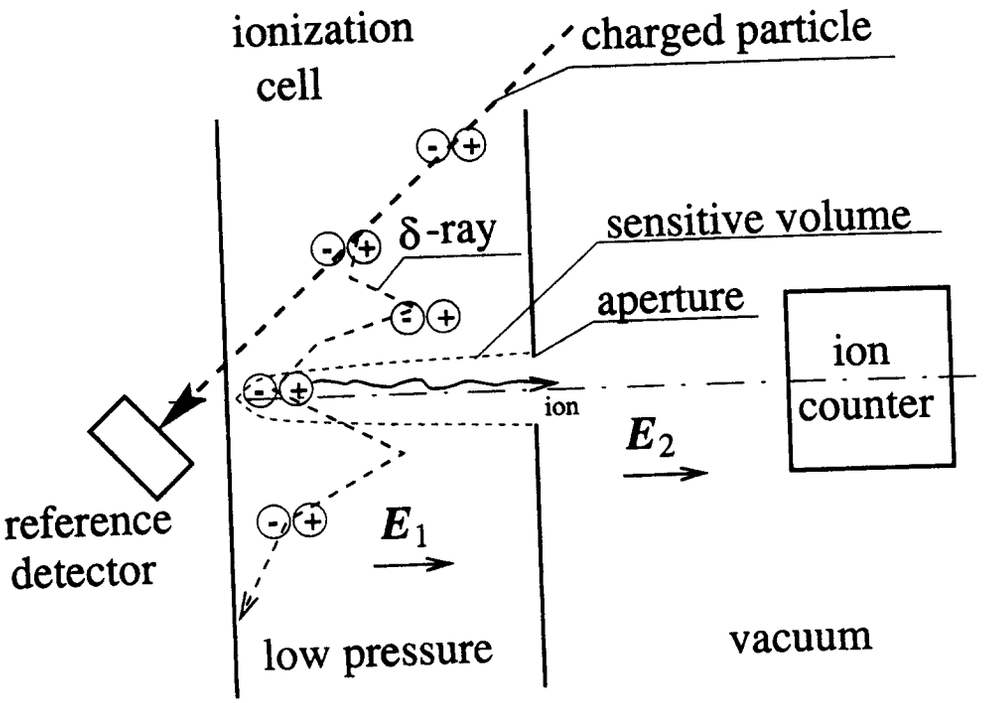
ionization
cell
charged particle
δ-ray
sensitive volume
aperture
ion
counter
ion
$E_2$
reference
detector
$E_1$
low pressure
vacuum

Fig. 1

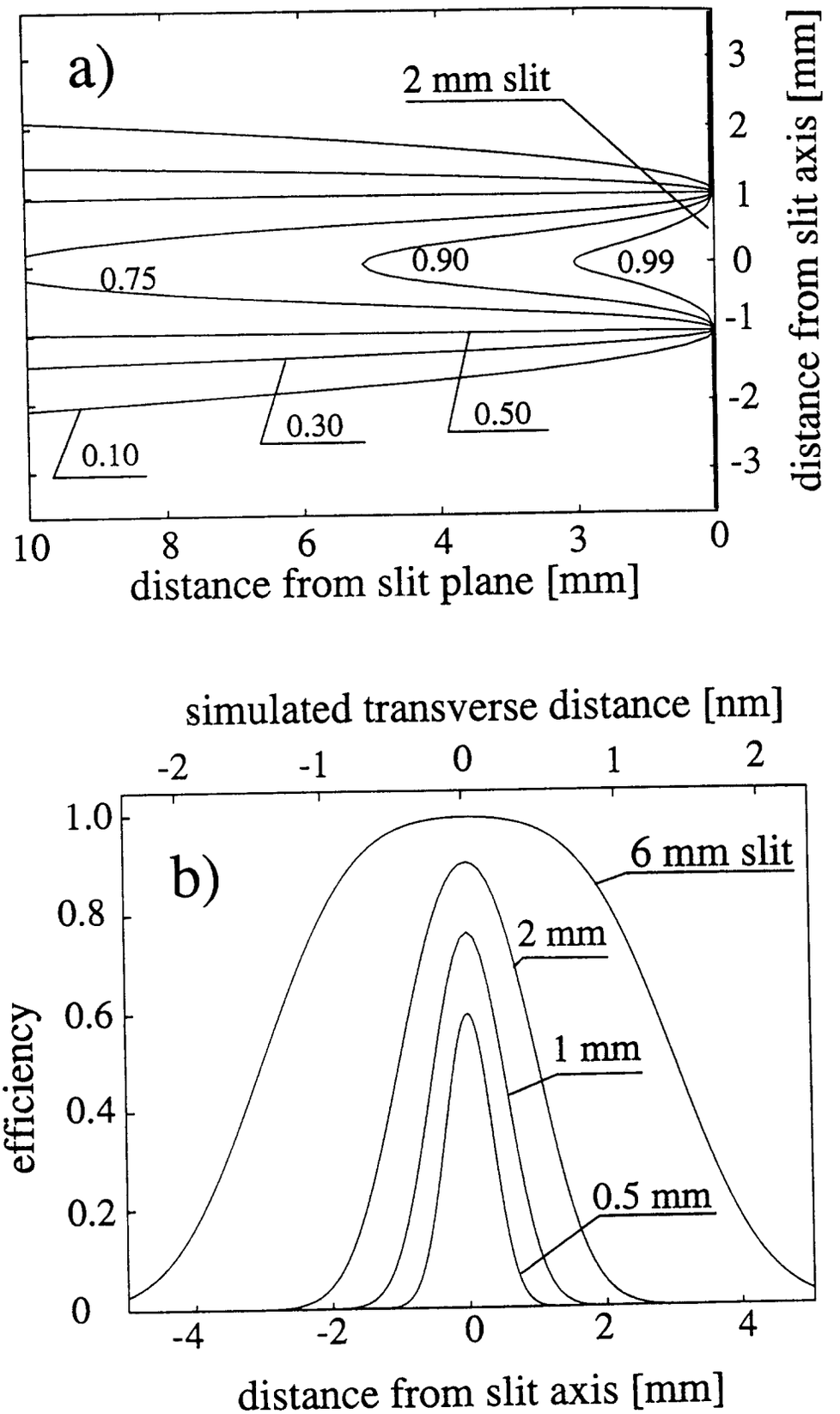
a)
2 mm slit
0.75
0.90
0.99
0.10
0.30
0.50
3
2
1
0
-1
-2
-3
distance from slit axis [mm]
10
8
6
4
3
0
distance from slit plane [mm]
simulated transverse distance [nm]
-2
-1
0
1
2
b)
6 mm slit
2 mm
1 mm
0.5 mm
1.0
0.8
0.6
0.4
0.2
0
efficiency
-4
-2
0
2
4
distance from slit axis [mm]

Fig. 2