Nuclear Inst. and Methods in Physics Research, A 911 (2018) 15–18

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

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

# Penetration of gases by fission fragments—Comparison between selected models and the data

Jan Grzegorz Hajnrych [a], Philippe Filliatre [a,*], Benoît Geslot [b]

[a] CEA, DEN, DER, Instrumentation Sensors and Dosimetry Laboratory, Cadarache, F-13108 St-Paul-lez-Durance, France
[b] CEA, DEN, DER, Laboratory of Experimental Programs and Safety Tests, Cadarache, F-13108 St-Paul-lez-Durance, France

ARTICLE INFO

*Keywords:*
Gas-filled counters
Stopping power
Instrumentation
Electrical phenomena in gases
Ionization of atoms by atom

ABSTRACT

A comparison between a few models of fission fragment penetration in several gases used in fission chambers is presented. To verify the energy loss of fission fragments, a comparison methodology was developed. It is based on comparative analysis of range experiments from third party publications with currently available models. We compared results from the SRIM code, the ICRU parametrization model implemented in Geant-4 and the LSS model. Albeit they are based on different hypotheses about the underlying physics that are not specific to fission fragments, those models reproduce fairly well the trend and order of magnitude of experimental data. Thanks to effective use of semi-empirical correlation fitted over large number of points, the SRIM code gives the closest results to experimental data: thus it is the model of choice for predicting and interpreting fission chambers' signal.

## 1. Introduction

Fission chambers [1–4] are nuclear detectors that are widely used to deliver on-line neutron flux measurements for mock-up reactors and material testing reactors. Their versatility allows applications such as characterization of experimental conditions, reactor monitoring and safety, hence a wide range of constraints. As a consequence, designing a specific fission chamber and measuring chain for a given application is a demanding task. It can be achieved by a combination of experimental feedback and simulation tools, the latter being based on a comprehensive understanding of the underlying physics. For more than a decade, our team has undertaken such an effort [5–11].

In a fission chamber, the neutrons induce fission events in a fissile layer, the resulting fission fragments then ionize a filling gas between electrodes, hence perform the conversion between the incoming neutron flux and an measurable electric current. However, a key issue in fission chamber modelling lies in the way the fission fragments lose their energy in the gas. This problem belongs to the more general problem of heavy ion penetration in gases, which has been addressed by theoretical or empirical modellings [12–15] and few experimental studies as well [16–18]. However, fission fragments are specific ions in several ways. Most of them are unstable radioisotopes. More important, their charge state is initially large and unknown, and may change after every interaction. Experimental data are rather scarce, because they are obtained from a dedicated apparatus involving a spontaneous fission source such as $^{252}$Cf.

The purpose of this article is to compare selected theoretical and phenomenological models of fission fragment penetration in gases with available experimental data [19–21]. As such, this article is a generalization of our previous article which was limited to the SRIM model [22,23]. In the present work, we propose an indirect method to compare the ranges of fission fragments. This comparison will make it possible to choose, in the framework of fission chamber modelling, the most adequate model of fission fragment penetration given the available data, and to assess a rough estimate of the associated bias.

The papers is organized as follows: we briefly review the physics of fission fragment energy loss process along with the models that will be tested thereafter (Section 2); we describe the experimental data and a method to simulate them with the models (Section 3); we give the results and discuss them in the framework of fission chamber modelling (Section 4); then we conclude (Section 5).

## 2. Fission fragment energy loss modelling

### 2.1. Stopping power and range

The stopping power $dE/dx$ is the amount of kinetic energy $E$ that an incoming particle (e.g. an ion) loses in average per unit of length of the target medium. In this paper only gaseous targets are considered. For usual conditions of pressure (including pressures reigning in fission chambers, i.e. a few bars), there are only binary collisions between fission fragments and gas molecules. The energy loss by unit of length is thus proportional to the gas density [24]. Hence the stopping power can be written as:

$$\frac{dE}{dx} = NS(E) \tag{1}$$

* Corresponding author.
*E-mail address:* philippe.filliatre@cea.fr (P. Filliatre).

https://doi.org/10.1016/j.nima.2018.09.118
Received 29 June 2018; Received in revised form 21 September 2018; Accepted 25 September 2018
Available online xxxx

where $N$ is the atomic density of the target medium, and $S$ the stopping cross section.

The total stopping power of heavy ions is the sum of two interaction regimes: electronic and nuclear. They are decorrelated, so that:

$$S = S_e + S_n \tag{2}$$

The electronic interaction regime is predominantly composed of small-angle elastic and inelastic ionizing or non-ionizing collision, while the nuclear interaction regime is mostly responsible for direction-changing elastic scattering. For fission fragments in gases, the electronic regime is dominant as long as their kinetic energy is above a few MeV [15].

The range of a particle can be calculated by integrating the inverse of the stopping power over its kinetic energy from its initial energy $E_{init}$ to its absorption, according to Eq. (3).

$$R(E_{init}) = \frac{1}{N}\int_0^{E_{init}} S(E)^{-1} dE \tag{3}$$

As the slowing down of the incoming particles by a series of collisions is inherently a stochastic process, the range $R$ is indeed a value that is averaged over identical particles.

### 2.2. LSS model

The LSS model was developed by Lindhard and his colleagues in the 60 s (see [12] and references therein). It gives an approximation for $S_e$ that is valid when the velocity $v_p$ of the penetrating ion is low enough:

$$v_p < v_0 Z_p^{2/3} \tag{4}$$

where $v_0$ is the Bohr velocity ($v_0 = e^2/\hbar$, where $e$ is the charge of the electron in atomic units, numerically $v_0 = 2 \cdot 10^6\,\mathrm{m/s}$), $Z_p$ the atomic number of the penetrating ion. One of the most commonly emitted fission fragment, $^{96}$Sr, is released with a kinetic energy of about 115 MeV after the fission of a $^{235}$U nucleus. This corresponds to a velocity of $v_p = 18 \cdot 10^6\,\mathrm{m/s}$, below $v_0 Z_p^{2/3} = 25 \cdot 10^6\,\mathrm{m/s}$, so that condition 4 is met.

It is convenient to introduce the dimensionless energy and range:

$$\epsilon = \frac{a_u M_t}{Z_p Z_t e^2 \left(M_p + M_t\right)} E \tag{5}$$

$$\rho = 4\pi a_u^2 \frac{M_p M_t}{\left(M_p + M_t\right)^2} N R \tag{6}$$

where $M$ refers to the mass, the subscripts $p$ and $t$ to the penetrating ion and to the target. The parameter $a_u$ can be interpreted as the screening parameter of the inter-atomic potential between the ion and the target. In LSS model, the following was used:

$$a_u = 0.8853 \cdot a_0 \left(Z_p^{2/3} + Z_t^{2/3}\right)^{-1/2} \tag{7}$$

with $a_0$ being the Bohr radius ($\hbar/me^2$). Then the electronic stopping power is given by:

$$\left(\frac{d\epsilon}{d\rho}\right)_e = \kappa \epsilon^{1/2} \tag{8}$$

where $\kappa$ is a constant that does not depend on energy, but only on the atomic numbers and masses:

$$\kappa = \xi_e \frac{0.0793 Z_p^{1/2} Z_t^{1/2} (A_t + A_p)^{3/2}}{(Z_p^{2/3} + Z_t^{2/3})^{3/4} A_p^{3/2} A_t^{1/2}} \tag{9}$$

In the original LSS model, $\xi_e$ was about $Z_p^{1/6}$. However, it is possible to consider $\xi_e$ (or directly $\kappa$) as being empirical, hence to be fitted to an experimental data set. Thereafter, this will be referred to as the LSS⋆ model.

### 2.3. SRIM model

SRIM [22] is a code for heavy ion penetration which can be used for calculating the stopping power and range. SRIM is free to use, however it is not open source. To assess the electronic stopping power, the main idea is to scale the stopping cross section of the heavy ion to the one of the proton of alpha particle. The scaling factor is the effective charge: this concept takes into account the fact that when slowing down an ion picks up electrons from the medium, hence its charge is no longer $Z_p$ (this would be a bare ion). This effective charge can be calculated with the Brandt–Kitagawa theory [25,26], which states that, within a solid target medium, an ion is stripped off its electrons when its velocity is greater that the Fermi velocity of the medium. The approach of SRIM is empirical: the effective charge is scaled on data, a correction is applied for gaseous media.

The nuclear stopping power in SRIM is modelled by using effective inter-atomic potential [22] and Coulomb scattering integral. This procedure leads to the development of the universal stopping power formula:

$$S_n(\epsilon) = \frac{\ln(1+\alpha\epsilon)}{2(\epsilon + \beta\epsilon^{\gamma} + \delta\epsilon^{1/2})} \tag{10}$$

Where $\alpha$, $\beta$, $\gamma$, $\delta$ are empirically adjusted parameters and $\epsilon$ is the reduced energy defined in Eq. (5). However, the screening parameter $a_u$ is different:

$$a_u = 0.8854 \frac{a_0}{Z_p^{0.23} + Z_t^{0.23}} \tag{11}$$

A major advantage of SRIM is the fact that beyond using relatively simple formulation of the stopping problem it is improved by the use of phenomenological charge state formulas. Its collision model is based on several empirical modifications of previous binary models. As those modifications are related to microscopic properties like charge-state and inter-atomic potential, SRIM can be called a semi-empirical code.

### 2.4. ICRU/Geant-4 model

For the energy range of 1 keV to 1 MeV per nucleon (which is the order of magnitude for fission fragments), Geant-4 standard heavy ion collision module uses ICRU parametrization and stopping tables [27,28]. Several known combinations of projectiles and targets are directly tabulated, however they do not include stopping powers of fission fragments in gases. Stopping powers for ion-material pairs, not included in [15], are computed by applying a scaling factor on a reference stopping power (the one of iron) using an effective charge expression:

$$S_p(Z_p, v_p) = \frac{\left[\gamma(v_p Z_{ref}) \cdot Z_{ref}\right]^2}{\left[\gamma(v_p Z_p) \cdot Z_{ref}\right]^2} \cdot S_{ref}(v_p) \tag{12}$$

where the subscript $ref$ points to the reference projectile in the same target medium and $\gamma$ the ratio between the effective charge , given by the Brandt–Kitagawa theory, and the atomic number of the ion.

## 3. Experimental methodology in third party data sets used for the comparison

### 3.1. Summary of the experiments

In our comparison, we analysed experiments aiming at determining the range of various fission fragments. In those experiments [19–21], a very thin Californium-252 source was placed in front of a high purity gas target. Thanks to the experimental set-up geometry, the source emitted a collimated beam of fission fragments. Those ions penetrated into the surrounding gas losing their energy until they hit the back wall or are completely stopped. In [21], to check whether particles penetrated the gas or were stopped inside it, a foil absorber (called catcher) was