The Effect of Space Charge due to the Auto-Ionization of Neutral, Hydrogenic States in Point-Contact Germanium Detectors at MilliKelvin Temperatures

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A class of advanced, semiconducting radiation detectors, when operated at temperatures T~50mK, are able to simultaneously measure both the ionization and phonons created by particle interactions (Fig.1). This has direct application to the search for particle dark matter, as it allows for strong discrimination of the potential signature of dark matter interactions with lattice ions from electromagnetic background. Such detectors currently under research may take the form, for instance, of a P-type Point Contact (PPC) detector (Fig. 2) [1]. In this work, we explore the effect of space charge accumulation in a germanium PPC detector.

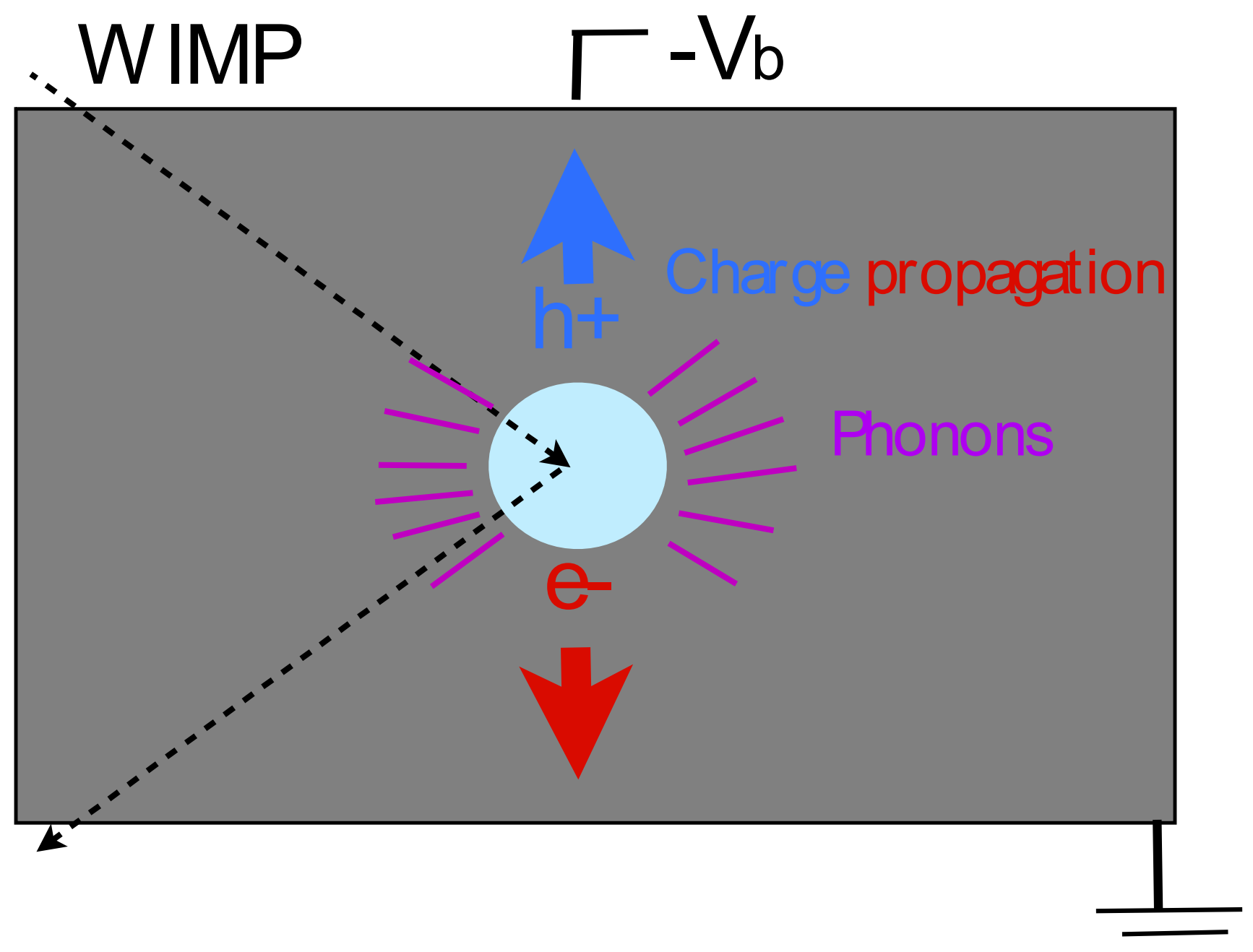


Figure 1. Ionization and phonons, generated by a potential interaction with a dark matter candidate known as a weakly-interacting massive particle (WIMP).

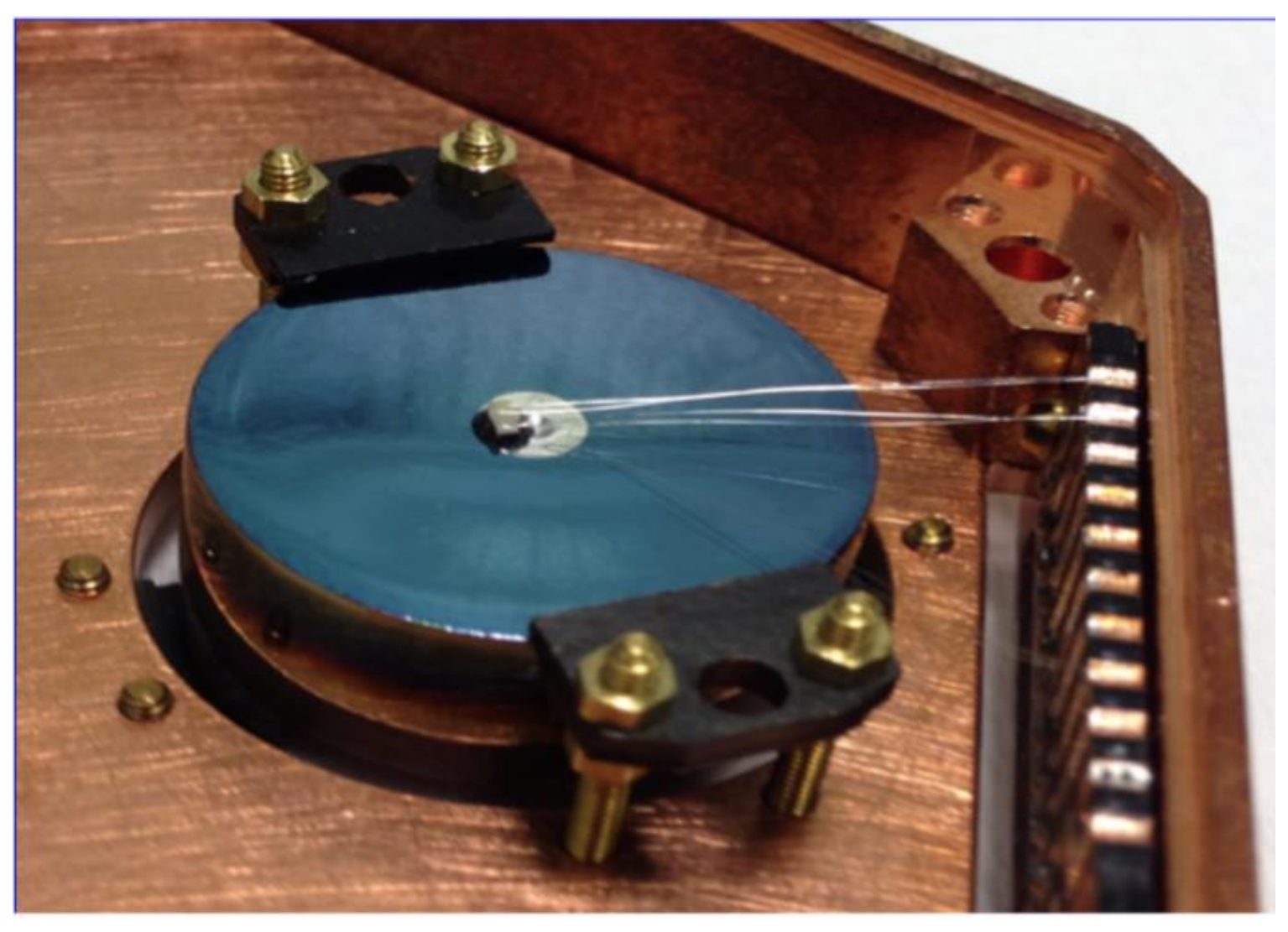
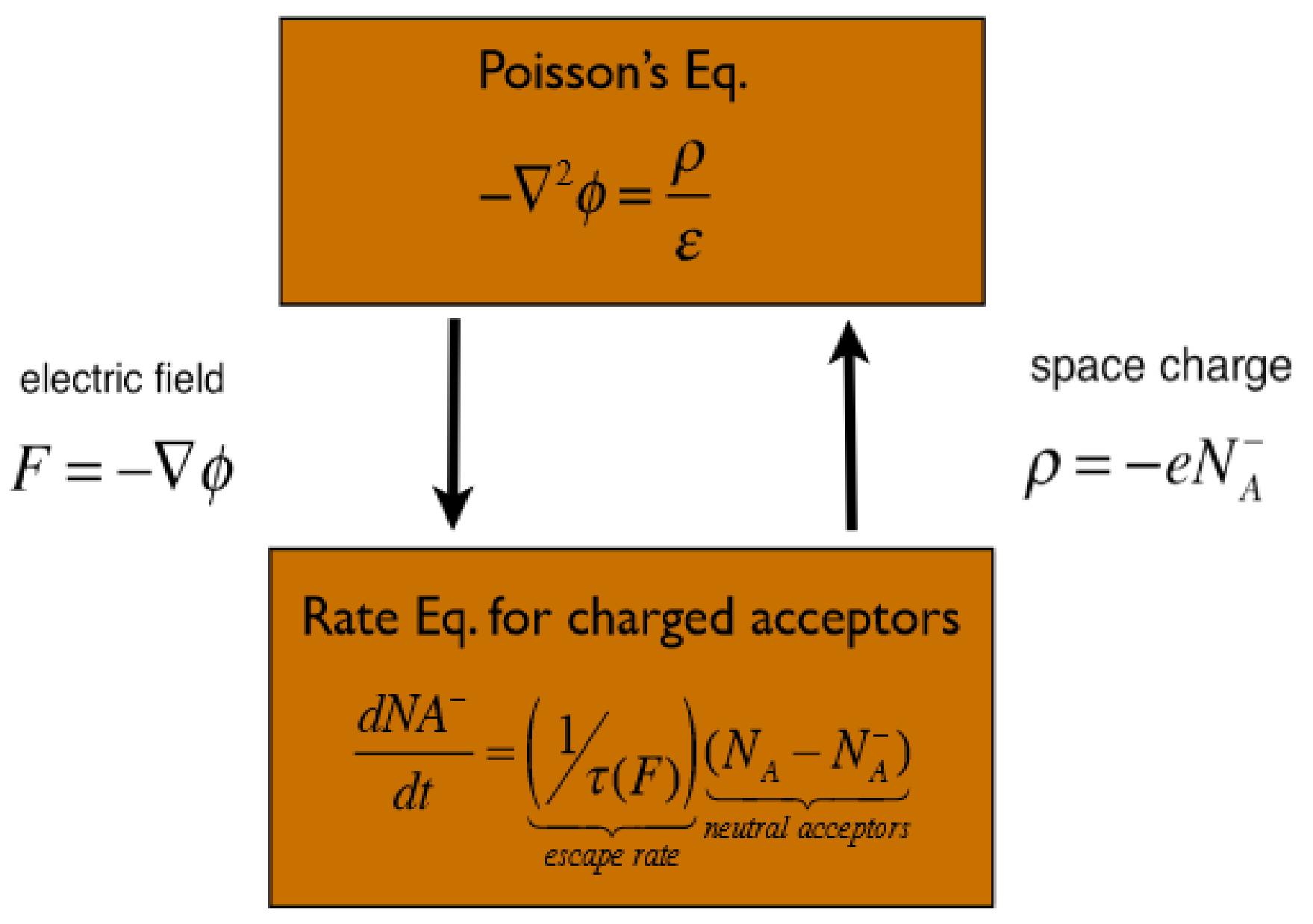


Figure 2. A PPC Ge detector in its copper housing [1].



Poisson's Eq.

$$-\nabla^2\phi = \frac{\rho}{\varepsilon}$$

electric field

$$F = -\nabla\phi$$

space charge

$$\rho = -eN_A^-$$

Rate Eq. for charged acceptors

$$\frac{dNA^-}{dt} = \underbrace{\left(1/\tau(F)\right)}_{escape\ rate}\underbrace{(N_A - N_A^-)}_{neutral\ acceptors}$$

Figure 3. Coupled physics equations using the AC/DC and Coefficient Form PDE modules. *N*N_A represents the total acceptor density. N_A^- represents the ionized acceptor density.

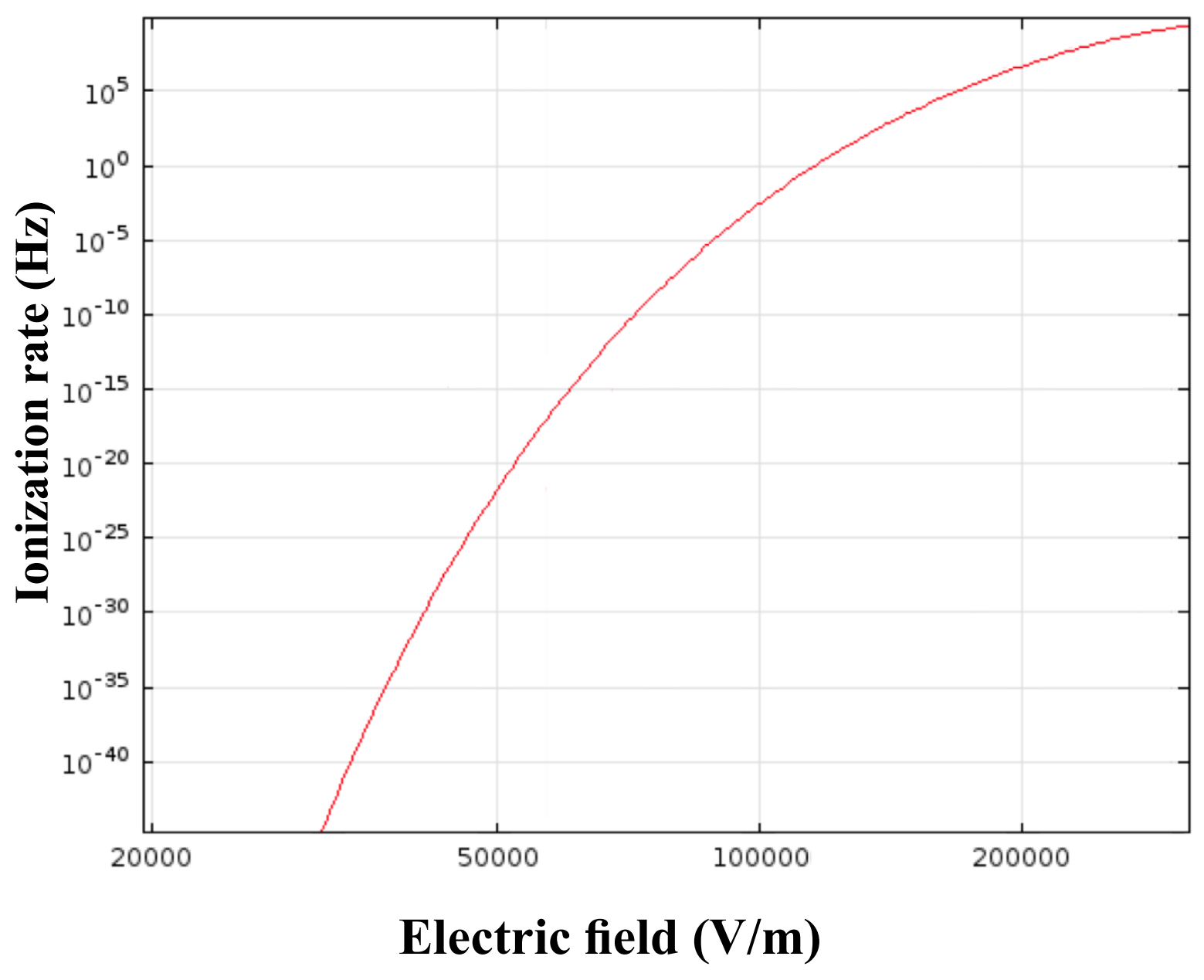


Figure 4. The auto-ionization rate (Hz) of hydrogenic acceptors in germanium as a function of the electric field (V/m).

We assume that space charge arises in this system due to the auto-ionization (or "field emission") of hydrogenic acceptors subject to high applied electric fields. At millikelvin temperatures, the thermionic emission (Fig. 5a) of charge carriers from localized impurities can generally be neglected. Considering relatively large field strengths in this detector (~1000 V/cm), we also neglect the presence of any stable D-/A+ states. We further assume the substrate to be p-type, thereby dominated by a concentration of acceptors acting as Bohr-like, hydrogenic impurities. In this case, auto-ionization in an external electric field is dominated by quantum mechanical tunneling. Therefore, a bound hole escapes a neutral acceptor from its ground state directly to the continuum (Fig. 5b). Field-dependent ionization rates were calculated by K.M. Sundqvist (Fig. 4) [2], based on the WKB approximation [3] and implemented using a 3D spatial integral over a neutral acceptor with an assumed isotropic effective mass. We do not model the transport of escaping holes, but instead use our interpolated ionization rates within COMSOL to model a variable density of space charge self-consistently with the electric field. This was performed using the Coefficient Form PDE module to model the population of charged acceptors, while the AC/DC module computed Poisson's equation including space charge (Fig. 3). We implemented a logarithmic version of the PDE for the population of charged acceptors, thereby reducing the unphysical effects of large derivatives in our numerical solutions [4]. A 2D axial symmetry was used to model our PPC germanium detector. This included a voltage-constant, biased electrode at the point-contact and the entire reverse face held at ground. We find that the space charge created in this detector, even at extremely pure acceptor concentrations of only $5\text{x}10^{10}$ cm^{-3}, still affects the internal electric field (Figs. 7,8).

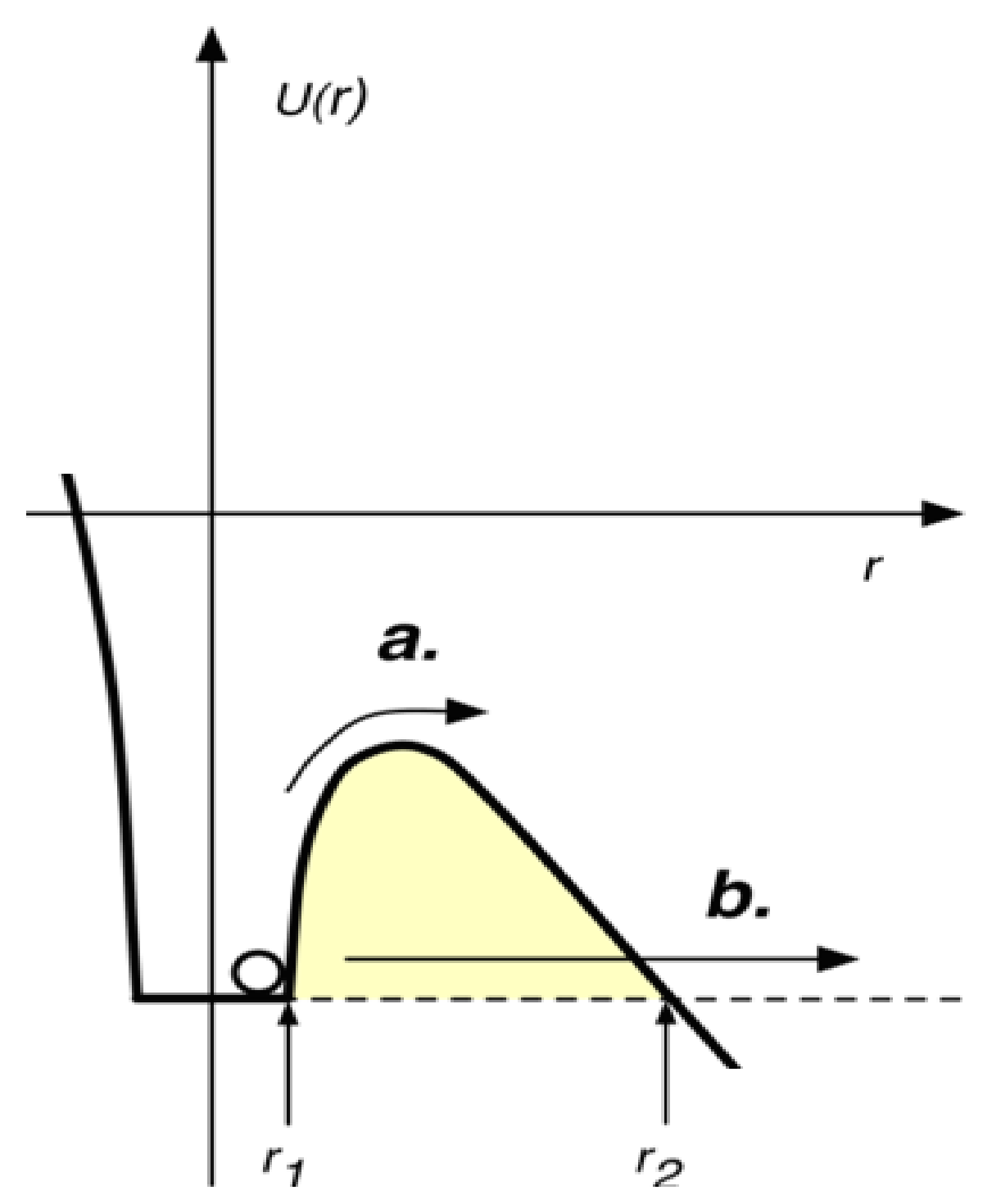


Figure 5. The auto-ionization of a bound carrier from a hydrogenic impurity [2]. Process ***a.*** illustrates classical emission and is exceedingly small at millikelvin temperatures. Process ***b.*** shows the dominant auto-ionization mechanism at low temperature, which is through quantum mechanical tunneling.

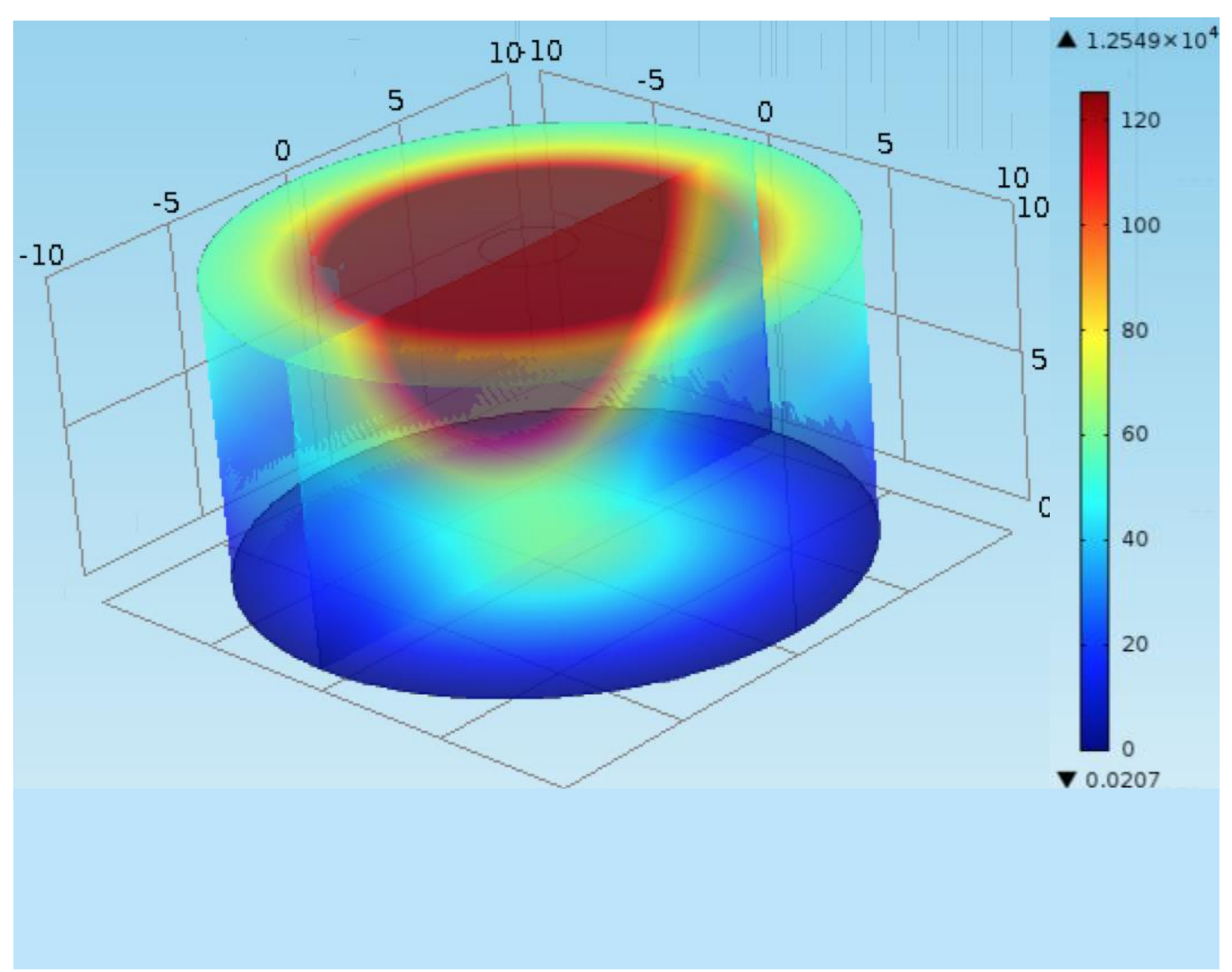


Figure 6. 3D electric field (V/cm) inside the PPC detector, Vb=+400 V.

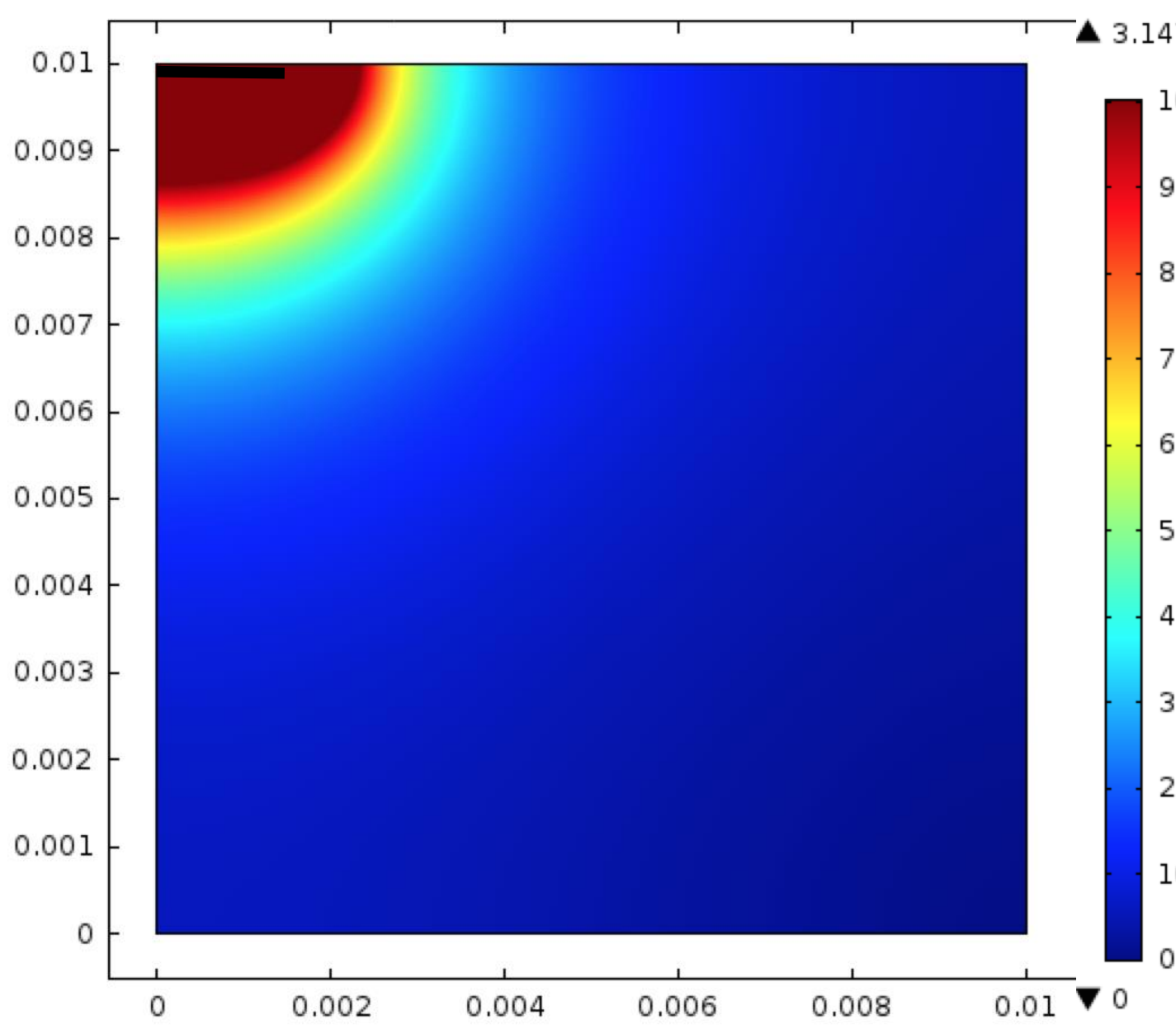


Figure 7. Electric field (V/cm);
With no space charge.
Vb= -400 V
Max E-field = 1700 V/cm

The effect of the polarity of bias on the electric field is also noteworthy (Figs. 8,9):

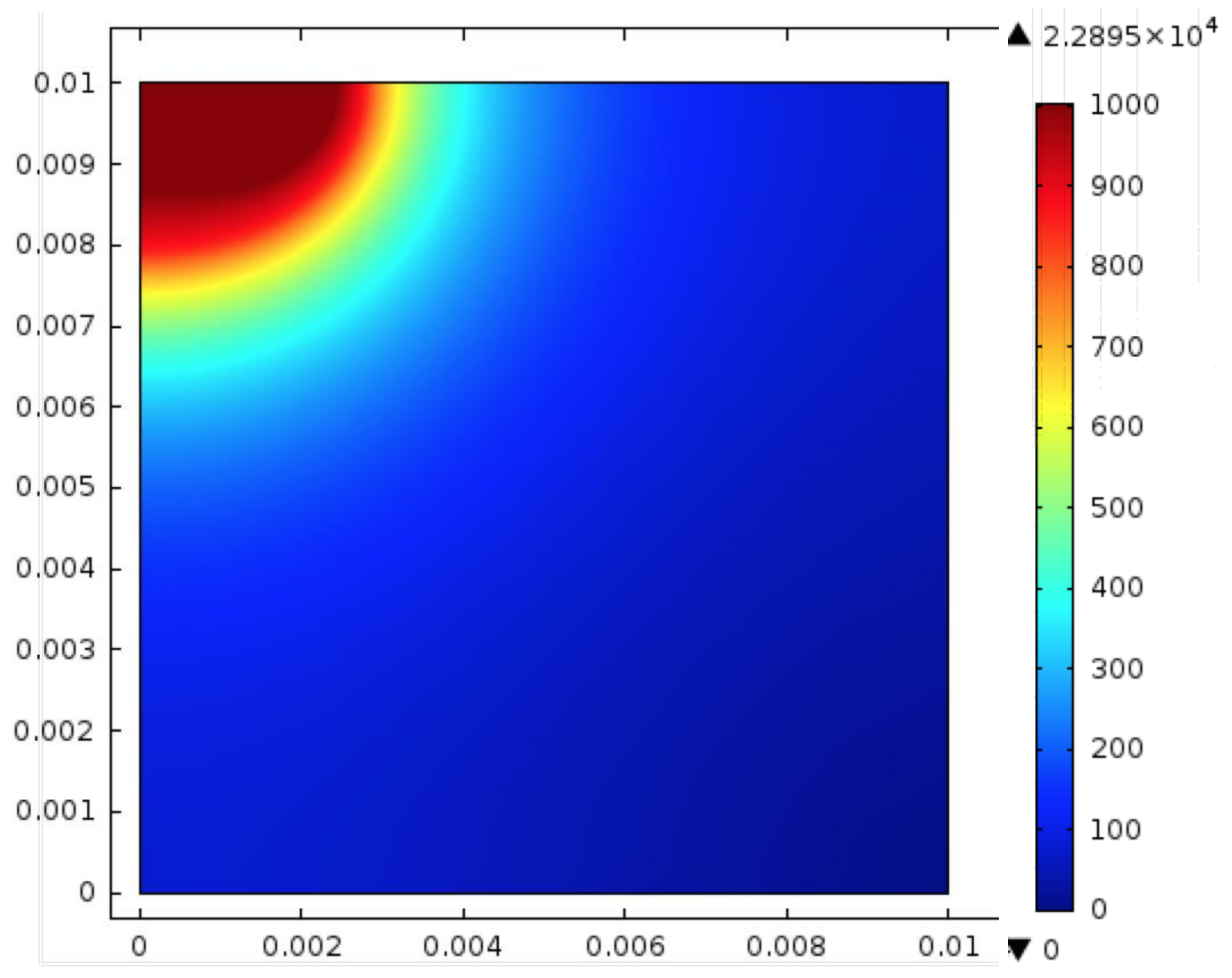


Figure 8. Electric field (V/cm);
with space charge.
Vb= -400 V, NA=$5\text{x}10^{10}$ cm^{-3}
Max E-field = 1200 V/cm

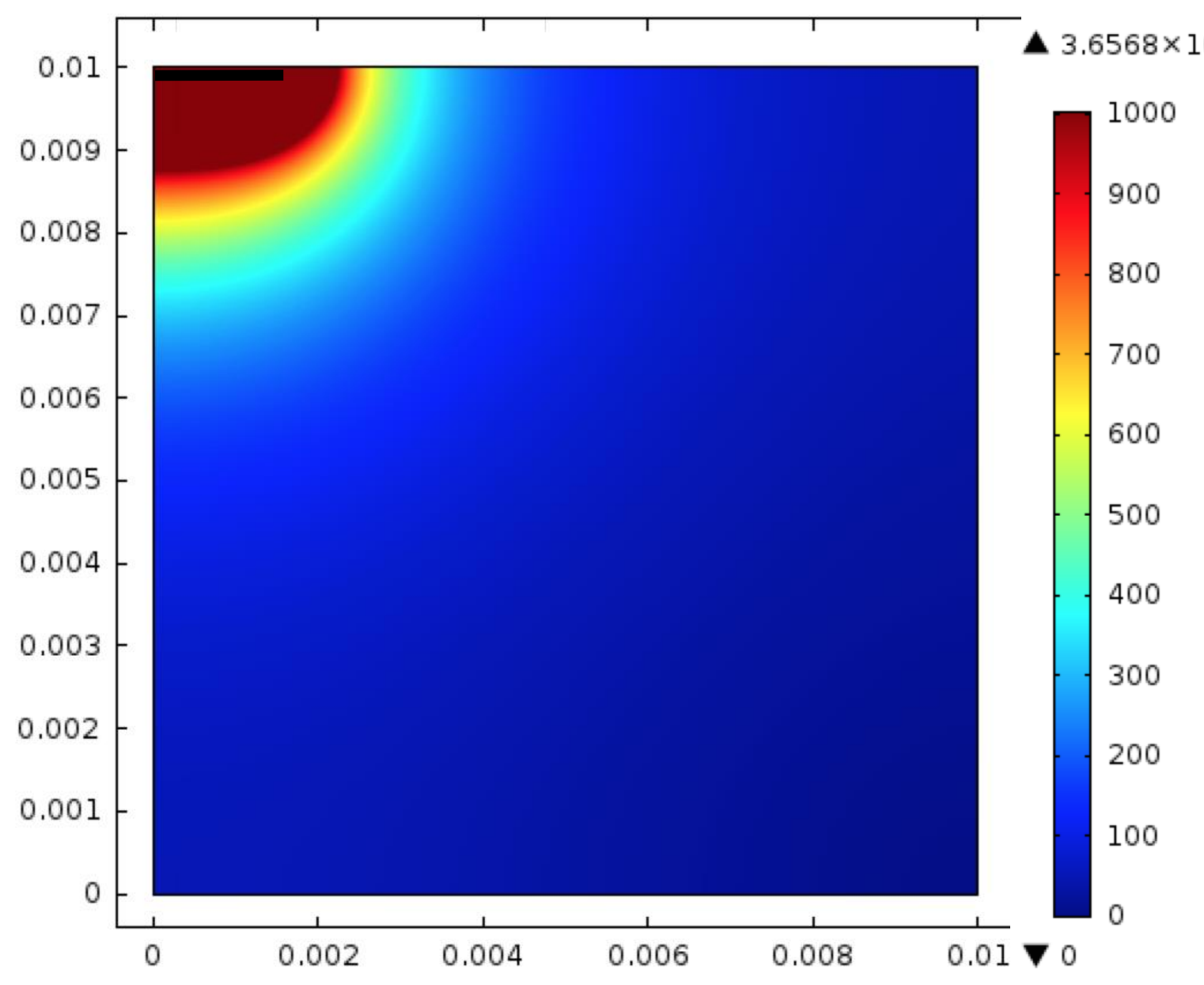


Figure 9. Electric field (V/cm);
with space charge.
Vb = +400 V, NA=$5\text{x}10^{10}$ cm^{-3}
Max E-field = 1900 V/cm

These results lead us to believe that, perhaps with an intentional, regional introduction of the correct impurity type and concentration, we may be able to mitigate unwanted voltage breakdown effects due to high fields near the contact electrodes.

References:

[1] N. Mirabolfathi, et al., *Neganov–Luke Phonon Amplification in P-type Point Contact Detectors*, Journal of Low Temperature Physics, 176, 209, 2014.

[2] K.M. Sundqvist, *Carrier Transport and Related Effects in Detectors of the Cyrogenic Dark Matter Search*, PhD Thesis, University of California, Berkeley, ProQuest/UMI, 2012.

[3] D. Bohm, *Quantum Theory*, Prentice-Hall, Upper Saddle River, NJ, 1951.

[4] COMSOL Knowledge Base 952, *Avoiding negative concentrations*, http://www.comsol.com/support/knowledgebase/952/.

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