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SUPERCONDUCTIVE TUNNEL STRUCTURES AS RADIATION DETECTORS*

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Abstract

A brief review is given on various aspects of the potential of superconducting tunnel junctions as detectors for atomic and nuclear radiations. On the basis of recent results main advantages and drawbacks are indicated providing a preliminary comparison with the presently used semiconductor detectors. The basic ideas underlying the physics of the interaction of nuclear particles and other radiations with superconducting junctions are outlined.

Introduction

Investigations concerning the interaction of radiation with superconductors dates back to several decades ago (see for instance ref. 1). Even though of great importance, we shall not discuss here the interesting works performed using superconducting films nor the more recent ones on complex superconducting structures. Rather we confine ourselves to the attempts and developments of detectors based on superconducting tunnel junctions. In this context Wood and White (2) obtained preliminary significant results concerning the possible use of such junctions operating in the quasiparticle tunneling regime as charged particle spectrometers of high energy resolution. More recently the new possibilities offered by the development of the junction fabrication technology and the better knowledge of the basic mechanisms of nonequilibrium superconductivity allow a cautious optimism towards such detectors.

A different application of superconducting tunnel junctions lies in the possibility of using the fast switching of a Josephson junction between the zero and the

finite voltage state. As it is well known in the frame of digital information devices the switching occurs as a consequence of a depression of the Josephson current by a suitable applied magnetic field whereas in this case the "trigger" is provided by the radiation impinging the junction.

Both these possibilities of application of superconducting junctions appear very stimulating although a number of problems remains to be solved.

High Energy Resolution Spectroscopy

Whatever will be the kind of detector (ionization chamber, semiconductor devices) the signal output charge produced by the interaction of the ionizing radiation is intrinsically subject to random fluctuations. In a semiconductor ionizing collisions will produce a number of electron-hole pairs; similarly in superconductor a number of quasiparticles will be created by a pair breaking mechanism. Thus, roughly speaking, we can say that the variance in the number N of charge "carriers" produced by the ionizing radiation is given within simple Poisson statistics by $\Delta N = \sqrt{N}$ where E is the energy released by the incident radiation and ϵ is the average energy necessary to create each pair of "carriers". Actually the fluctuation of N is $\Delta N = \sqrt{FN}$ where F is the Fano factor which accounts for the incorrect statistical hypothesis on the events. To simplify we can make the conservative assumption $F = 1$. We see that for a given energy loss E the energy resolution improves (ratio $\Delta N/N$ decreases) for lower values of ϵ . This very well known argument suggests that since ϵ is related to the energy gap a superconductor should provide a much better resolution (typically $\Delta_{\text{sem}} \sim 1 \text{ eV}$ and $\Delta_{\text{sup}} \sim 10^{-3} \text{ eV}$).

As stated in the introduction the knowledge of the various aspects of nonequilibrium superconductivity (3) provides a fundamental tool in the understanding of the interaction of high energy radiation with a superconductor. Various aspects of such an interaction, the diffusion of the released energy, the rôle of length scales etc. are outlined in a recent paper (4) (see also references reported therein). Once the "free carriers" are created the charge must be collected and this is realized by means of the quasiparticle tunneling through the barrier deviding the two superconducting electrodes. A suitable voltage bias within the gap region, $V < \Delta/e$, is applied to the junction whereas the Josephson zero-voltage current is suppressed by an applied magnetic field (the Josephson current is present due to the required high transparency barrier). The

excess quasiparticles produced by the incident radiation gives rise to a current pulse signal. The competition between tunneling rate, recombination rate, losses etc. will influence the characteristic time dependence of the signal.

Recent experiments (5,6,7) employing α particles have shown the right pulse amplitude spectrum and gave values of ϵ down to ≤ 20 meV. Such a value compared with those of usual semiconductors appears to be rather encouraging. Data are roughly indicated in Table 1.

The main difficulties for such devices are the intrinsic low geometrical efficiency and the necessity of developing a proper low noise electronics.

Table 1

Material	ϵ	Temp.
Silicon	3.81 eV	77K
Germanium	2.96 eV	77K
Superconductors	20×10^{-3} eV	0.3 - 1.2K

preliminary results of ϵ values (see ref. 6,7,8) for superconducting junctions compared with those of semiconductors.

Fast discrimination

A second possibility of application of a superconductive junction as a radiation detector is when a "discriminator-like" or "on-off" operation is required regardless of the energy of the radiation (8). In this case the basic mechanism should be the following. The junction is polarized at a current value I_p just below the critical one I_c (maximum Josephson current). The interaction of the radiation with the junction will produce a breaking of Cooper pairs leading thereby to a reduction of the supercurrent to a value $I_r < I_p$. As a consequence the switching from the zero to a finite voltage state will occur whenever energy above a certain threshold is released into the junction (discrimination).

A qualitative view of the situation can be appreciated by resorting to the usual description of the Josephson junction by the brownian particle in a one dimensional washboard shaped periodic potential. As it is well known, in the zero noise case, depending on the values of junction parameters, there exist a re-

gion of current values where two stable solutions are possible. These are the locked state (i.e. the particle is trapped in a potential well) and the running state (i.e. the particle is running down the potential with a non zero mean velocity) which correspond to zero and the finite voltage state of the junction. From this consideration it also follows that the polarization current value I_p "just below" I_c is set by the noise which can simulate the effect of the ionizing radiation.

Experiments on the switching induced by α particles have been carried out a few years ago (9) giving interesting though preliminary results.

A main drawback in this context appears to be the severe limitations to be imposed on the size of the junction and consequently on the geometrical efficiency of the device. One possibility to overcome such a problem would be the use of suitable large arrays of junctions. Moreover the associated ultrafast electronics required also appears as a hard task. A further drawback is the sensitivity of the Josephson current to magnetic fields.

Conclusions

On the basis of the available preliminary results and in spite of the problems outlined above, we believe that the study of possible new radiation detectors employing superconducting junctions deserves great attention. The possibility of realizing high energy resolution spectroscopy as well as that of ultrafast detection represent very stimulating perspectives. In both cases the intrinsic properties of these superconducting devices such as the low value of the energy ϵ and the high switching speed represent a paramount advantage over conventional detection systems.

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