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SUPERCONDUCTING Nb-Nb_xO_y-Pb TUNNEL JUNCTIONS FOR PROPORTIONAL COUNTING. PRELIMINARY RESULTS(*)

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ABSTRACT

Preliminary experimental results are reported on the development of a proportional detector based on a superconductive tunnel junction. High resolution is expected due to the low value of the energy ε_0 required per elementary charge collected and to the uniform response which can be obtained with suitable junction geometry.

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1. - INTRODUCTION

The spectrum of the total "visible" energy released in low Q weak decays of nuclei (β-decay or electron capture) could, in principle, yield new determinations of the limits of the (anti)neutrino mass. This kind of total absorption experiment does not require critical theoretical corrections to take into account the variety of final states of the emitting system and the effect of the molecular bonds as required for other kinds of experiments such as measurements of end point β-spectrum shape(1,2). One of the major drawback of total absorption experiments is due to the unsatisfactory energy resolution of the best calorimetric detectors now available, semiconductor detectors, that is limited to hundreds of eV in the range of interest.

To improve the previous results(3), as the one obtained with a very careful and sophisticated calorimetric experiment of Tritium β-decay in a Si(Li) detector by Simpson, a dramatic reduction is needed of the line width of the total absorption spectrometer.

The breaking of Cooper pairs in a superconductor that involves an energy gap of a few meV seems to be an excellent candidate as elementary process for a new detector, especially for low energy total absorption spectrometry where the excitation energy of atomic and molecular structures have to be also measured. A large number of quasiparticles will be produced of a small energy loss in the superconductor, hopefully with efficiency quite independent by higher level deexcitation mechanism, and a large charge signal can be produced collecting the fraction of the quasiparticles tunneling to a second superconductor through a thin (about 10 Å) non conducting (oxide) layer.

Detection based on superconductive tunneling was already independently proposed for nuclear radiation(4, 5). Positive experimental results were reported firstly by Woods and White(6, 7). They showed the ability of a Sn-Sn_xO_y-Sn sandwich at 1.2 K to detect α-particles. In their experiment, as in the more recent one by Kurakado and Mazaki(8, 9), a quite continuous pulse height distribution was observed. Such a spectrum cannot be explained on the basis of the energy loss distribution nor in terms of electronic noise and indicates a very unfavorable response function of the detector to a given energy loss.

In the present experiment we have investigated the behavior of the Nb-Nb_xO_y-Pb junctions, irradiated with α-particles, in the attempt to clarify the basic phenomena involved in the process of pulse formation. Pulse shapes and pulse distribution in different conditions and geometries were investigated. We have observed that the pulse height distributions and the decay time of current pulses are affected by the size of the junction and by the collimation of the α-particles beam hitting the junction. These effects can be interpreted as due to diffusion of quasiparticles (charge carriers) produced by the ionizing particles in the superconductors.

Following this conclusion we realized junctions with proper geometry to drastically reduce the effect of diffusion phenomena. With these junctions we observed a peak in the pulse height distribution, whose width is consistent with that expected in terms of energy loss spread and electronic noise. The intrinsic line width of the detector was not measurable with the present set up, that was not optimized for the purpose. The energy spent by the α-particles per electronic charge collected is about 70 meV for junctions with thin oxid layer.

2. - JUNCTION PREPARATION AND CHARACTERISTICS

The junction employed in the present experiments were Nb-Nb_xO_y-Pb tunneling structures. The niobium base electrode was deposited in a diffusion vacuum system by rf sputtering in Argon atmosphere (3×10^{-3} mm Hg) onto 7059 corning glass substrate at an ultimate pressure of 10^{-8} mm Hg. Deposition rate of 5 Å/s was obtained for a "peak-to-peak" voltage of 2.1 kV and 5 cm of electrodes spacing. The sputtering of Nb layers was obtained by a conventional high resolution (1-2 μm) photolithografic process. The necessary sputter-cleaning step was performed in the same vacuum system. Oxide barrier growth was realized by thermal oxidation in air at room temperature. Oxide composition analyzed by Auger spectroscopy results to be of both niobium oxide (Nb_2O_5) and lead oxide formed by free oxygen adsorbed on the oxide surface which can react with the Pb for top layer. The lead film was deposited in a vacuum diffusion pump from molibdenum heaters in the 10^{-7} mm Hg pressure range (deposition rate of 100 Å/s).

In most measurements we used a cross junction geometry with strips width-ranging from 0.1 to 1.2 mm. To avoid possible diffusion of quasiparticles along the arms of the junction structure a new geometry "island" type was adopted such as reported in Fig. 1. The dimensions were 1×1 mm^2, film thickness values were ranging within 0.25 μm and 0.30 μm, and within 2.00 μm and 3.50 μm for Nb and Pb respectively.

The voltage-current characteristic of the junctions shows the presence of the zero voltage Josephson current(10) as a consequence of the high-transparency (low tunneling resistance) required for our purpose. It is important to stress that, although in the experiments only quasiparticle tunneling enters in the detection process, the occurrence of Josephson current allows a careful check of the junction barrier uniformity via measurement of maximum zero voltage current vs. applied magnetic field.

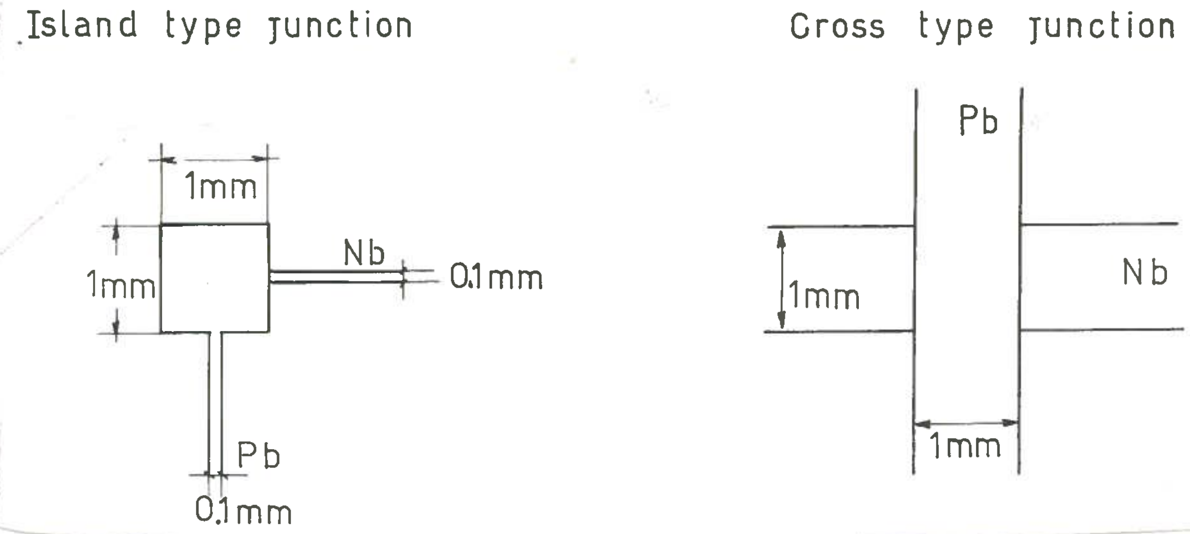

FIG. 1 -Layout of the B set junctions.

Indeed barrier thickness fluctuations can contribute to an undesirable spread in the energy resolution performances of the detector.

As far as the choice of superconductor materials is concerned, let observe that niobium based junctions guarantee properties of high stability against mechanical and thermal stress. Moreover both lead and niobium satisfy requirements of relatively high temperature (largely above 4.2 K) which allows the possibility of performing experiments at temperatures which guarantee good stability and reduced junction thermal noise. The high density of these materials represents a further advantage of radiation absorption.

3. - EXPERIMENTAL SET-UP

The experimental set-up is sketched in Fig. 2. Both source and junctions were maintained in the cavity of the cryostat in high vacuum conditions. For background determination the cavity was filled with liquid Helium to prevent the α-particles from reaching the detector. In fact a mechanical shutter, initially used for this purpose, was found to influence junction temperature.

The temperature of the sample maintained in tight thermal contact with the bath was measured by a calibrated resistor thermometer and by pressure monitoring. When necessary a feedback temperature control system was provided. Normally the measurements were taken at the temperature of about 1.4 K.

Current pulses from the superconductive sandwich were detected through a stepping up transformer and a low noise wide band preamplifier realized with a suitable integrated circuit (SL561B, Plessey Semiconductors). The preamplifier has a flat

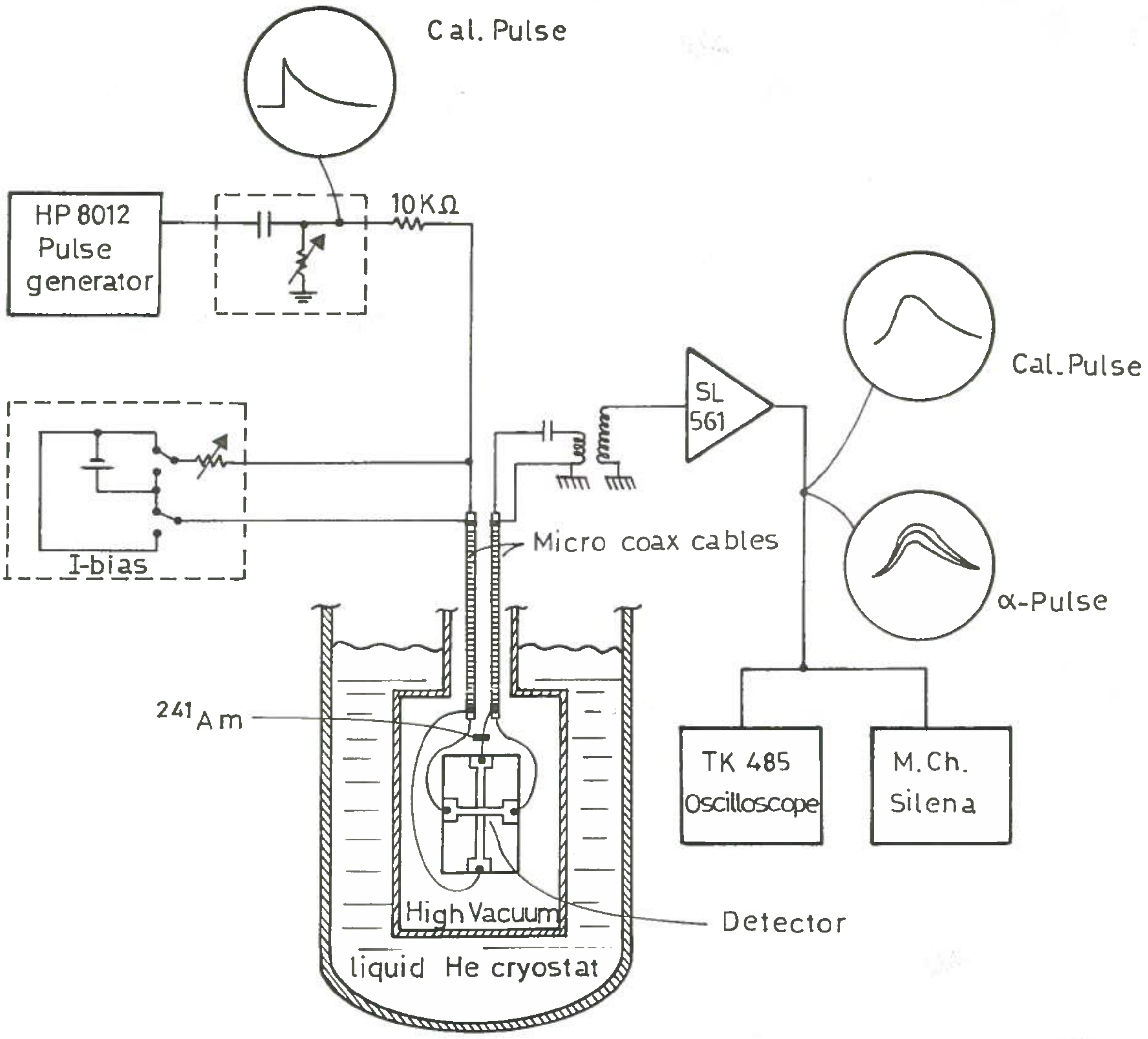

FIG. 2 - Sketch of the experimental set-up.

gain of 500 between 10 KHz and 3.5 MHz with a noise of the order of 2 μV RMS for low source impedances. Transformer and preamplifier, battery powered, were kept at room temperature. The junction was connected to the preamplifier through an unterminated microcoax cable of 60 cm length. This kind of electronic chain, not optimized for impedance matching to the detector, was well suited for the experiment as it was possible to adapt parameters during a single transfer and allowed us to roughly measure the pulse shapes. The transfer function of the whole system was experimentally determined by injecting current step pulses on the junction in operating conditions. The overall rise time resulted to be around 80 ns.

The shape of output pulses produced by α-particles in the junction was well reproduced by calibration current pulses with exponential decay.

Pulse height amplitude spectra were recorded by a multichannel analyzer (Silena 7934). Pulse shapes were observed with a Tektronix 485 wideband (350 MHz) oscilloscope. Volt-amperometric behaviors of the junctions were checked during the runs with standard technique.

4. - EXPERIMENTAL RESULTS AND DISCUSSIONS

In the present experiments two series of junctions (A, B) were investigated. The main results are summarized in Table I. The various samples differ for barrier transparency, size and geometrical configuration.

TABLE I

Parameters \ Junctions sets	A	B (island)	B (cross)	Units
Pb thickness	3. 5	2. 0	2. 0	μm
Pb width	0. 1	1. 0	1. 0	mm
Nb thickness	0. 29	0. 39	0. 39	μm
Nb width	0. 1	1. 0	1. 0	mm
R_{nn}	20	1-2	1-2	mΩ
α energy loss	0. 9	3. 8	3. 8	MeV
ε_o	70	180-250	180-250	MeV
Relative FWHM of the α-spectrum	37	22	31	%

Preliminary measurements were performed on cross type 0.5×1.2 mm^2 junctions. We firstly observed a quite continuous pulse height distribution. Pulse due to the α-particles hitting the junction at normal incidence were regular in shape.

An exponential calibration current pulse with 250 ns decay time, injected into the junction in operating conditions, produced at the output of the electronic chain pulses with almost the same shape. We observed that, by inserting a collimator with a hole of 0.4 mm of diameter, the lower part of the spectrum was suppressed and the pulse height distribution showed a broad peak. We interpreted these results as due to edge effects probably connected with diffusion phenomena.

To obtain more quantitative information further measurements were performed on two types of junctions. The former were 100×100 μm^2 cross geometry junctions with very low resistance per unit area (2 $\mu\Omega$·cm^2). The latter were of 1×1 mm^2 both of "cross" and "island" (see Fig. 1) geometry with relatively higher resistance per unit area (10-20 $\mu\Omega$·cm^2). Higher resistance values were chosen to keep detector impedance high enough in order to avoid reduction of the signal transfer to the amplifier system. Moreover for this set of junctions, to obtain a signal well above noise level, the α-particles were impinging the detector at almost grazing incidence to loose their full energy into the lead layer.

The main features of the pulses due to the α-particles were basically the same of those obtained in preliminary measurements. The pulse heights distributions were recorded on the multichannel analyzer. In all case a peak was clearly identified in higher region of the spectrum.

The smallest relative width of the peak was obtained corresponding to a sample of island geometry and was consistent with what expected by the combined effect of spread in the energy of the α-particles and electronic noise. The largest value was obtained for junctions of cross geometry with dimensions of $100 \times 100\ \mu m^2$.

In Fig. 3 are reported the spectra observed for the junctions of cross (a) and island (b) geometry. Data are summarized in Table I.

To evaluate the energy spent per collected electronic charge ε_0 we have followed the following procedure. A calibration current pulse was injected into the junction in working conditions. The decay time constant of the pulses was adjusted for the best matching of the shape of the pulses produced by α-particles. The amplitude of the current pulses was set to produce a peak, at the same position of the pulses produced by α-particles. The width of the peak gives a measure of the electronic noise of the system.

5. - DATA ANALYSIS

We compare the experimental results obtained for the different junctions according to the following assumptions.

a) The number of quasiparticles $N(0)$ produced by the ionizing particle that losses in the junction the energy E is given by

$$N(0) = kE/2\Delta$$

where k is a parameter whose value ranges between 0 and 1. In this way it is taken into account that the actual energy to excite the quasiparticles is larger than the energy gap 2Δ.

b) The tunneling probability W_T is given by$^{(6)}$

$$W_T = 1/(e^2 N_m \lambda A R_{nn})$$

where e is the electronic charge, N_m is the electron density per cm^3 and per eV, λ is the lead layer thickness, A is the junction area and R_{nn} is the junction tunneling resistance in the normal state.

c) A diffusion process, characterized by a coefficient D, produces a spread of quasiparticles out of the tunnel region.

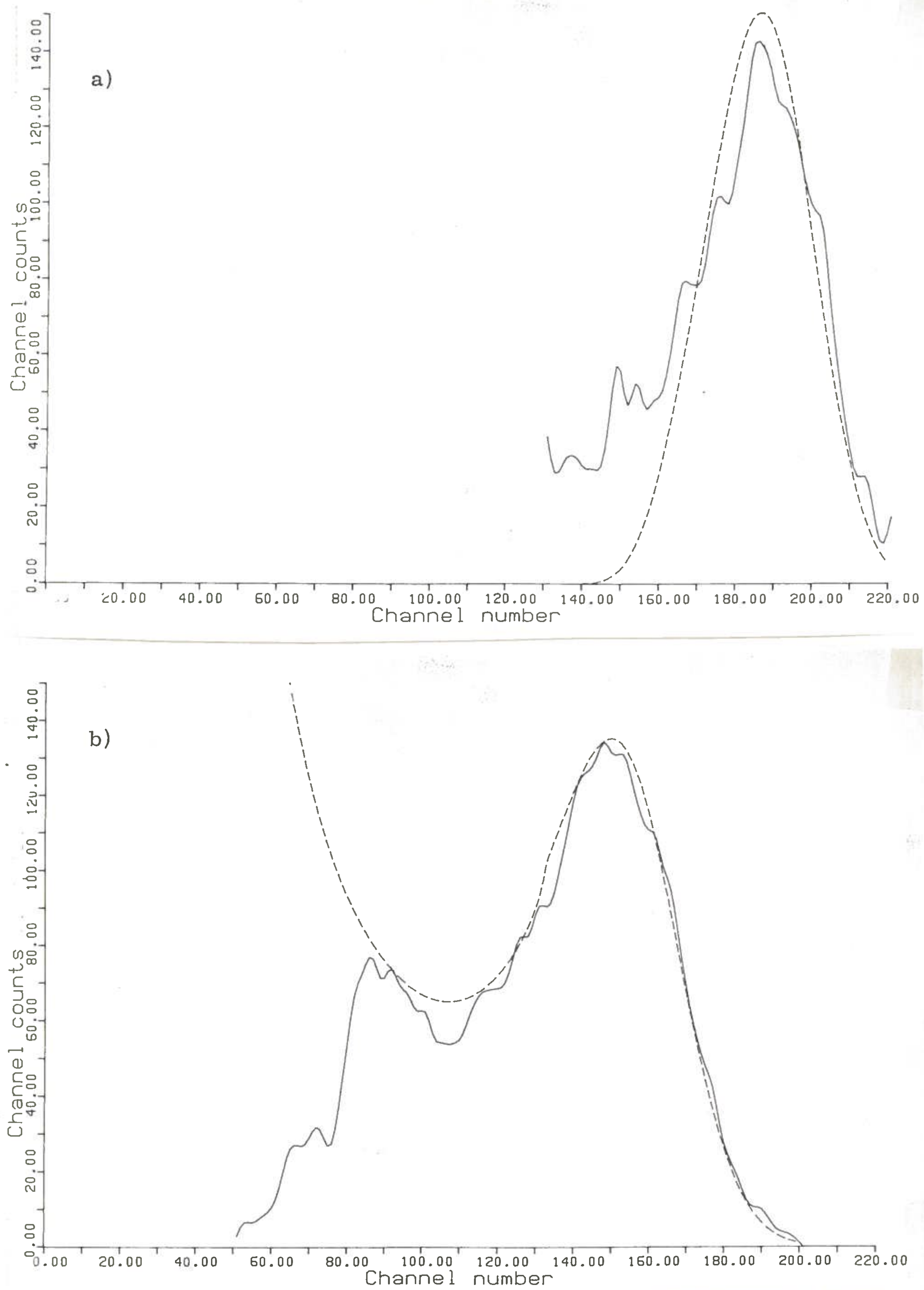

FIG. 3 - a) Full line: pulse amplitude spectrum of an "island type" junction. Dashed line: computed pulse spectrum from α-particles energy distribution and electronic noise. b) Full line: pulse amplitude spectrum of a "cross type" junction. Dashed line: computed pulse spectrum from α-particles energy distribution, electronic noise and diffusion effect.

Let us assume that for **island** junctions geometry the diffusion of quasiparticles out of the barrier region can be neglected. In this case the current pulse is given by

$$i(t) = eW_T N(0)\, e^{-t/\tau}$$

where $1/\tau = W_T + W_R$, where W_R indicates an "effective" recombination probability.

From the experimental values of ε_0 we can evaluate k and obtain results ranging between 0.4 and 0.8 mainly due to the indetermination of the normal resistance R_{nn}. This high value of k supports the assumptions of negligeable diffusion phenomena assumed for the island junction geometry. The value of ε_0 for the smaller junction size of cross geometry is somewhat higher than that expected by the expression of W_T. Assuming that such a decrease of the collection efficiency is entirely due to diffusion phenomena along the superconducting electrode strip we computed an effective diffusion length $l = \sqrt{D\tau}$ which results to be of the order of $100\,\mu m$(11). Using these data we can account for the different shape of the various spectra and evaluate the FWHM in the various cases with good agreement. Following the above consideration we expect that island type junctions with oxide thickness, and then W_T, equal to that of A type sample, will have an ε_0 value of about 20 meV.

Incidentally we observe that a similar procedure seems to apply also to the results of ref. (7) giving a value of l in substantial agreement with our results.

Far from being conclusive the present investigation indicates that it is possible realizing proportional detectors with a value ε_0 of two order of magnitude smaller than that obtainable by the best semiconductor detectors. Island type geometry can guarantee uniform response avoiding effects of charge carriers diffusion. The sensitive area is of the order of 1 x 1 mm^2 and a sensitive thickness of several micrometers.

Special electronics has to be developed in connection with junctions of higher transparency in order to extract efficiently the signal from the low impedance detector without spoiling the potential ultimate resolution.

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