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## Superconducting thermal neutron detectors

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**Abstract.** A neutron detection concept is presented that is based on superconductive niobium nitride (NbN) strips coated by a boron (B) layer. The working principle is well described by a hot spot mechanism: upon the occurrence of the nuclear reactions  $n + {}^{10}\text{B} \rightarrow \alpha + {}^7\text{Li} + 2.8 \text{ MeV}$ , the energy released by the secondary particles into the strip induces a superconducting-normal state transition. The latter is recognized as a voltage signal which is the evidence of the incident neutron. The above described detection principle has been experimentally assessed and verified by irradiating the samples with a pulsed neutron beam at the ISIS spallation neutron source (UK). It is found that the boron coated superconducting strips, kept at a temperature  $T$  below 11K and current-biased below the critical current  $I_C$ , are driven into the normal state upon thermal neutron irradiation. Measurements on the counting rate of the device are presented and the basic physical features of the detector are discussed and compared to those of a borated Nb superconducting strip.

### 1. Introduction

The capability of superconducting materials to act as radiation detectors for charged particle (minimum and/or minimum ionizing) as well as x and gamma rays is well established in the literature [1-3].

The main mechanism is explained in terms of the so-called “hot-spot” model (see figure 1) [4]: the ionizing radiation releases its energy in the bulk giving rise to a local temperature enhancement. The heat then propagates over the material. In the case of a charged particle, where ionization occurs along the particle track the hot spot is in a simplified model cylindrical and spread over an area provided by the relation [5]:

$$S = \frac{dE}{dx} \frac{1}{\Delta h} \quad (1)$$



With:

$\frac{dE}{dx}$  : energy release per unit length into the material

$\Delta h$  : enthalpy difference per unit volume for the superconducting transition

In this model, the transport (or bias) current  $I_B$  circulating into the strip featuring a resistivity  $\rho$ , is forced to pass through the reduced superconducting region, left by the definite hot spot (normal) region. When the density of transport current  $J_B$  exceeds the critical density current,  $J_C$ , the whole strip undergoes a transition from the superconducting to normal region that gives rise to the onset of an ohmic current and thus to a potential drop:

$$V = 2\rho J_C \left( \frac{dE}{dx} \frac{1}{\pi\Delta h} \right) \quad (2)$$

tagging the presence of the traversing particle.

Figure 1 illustrates schematically the mechanism of the hot spot.

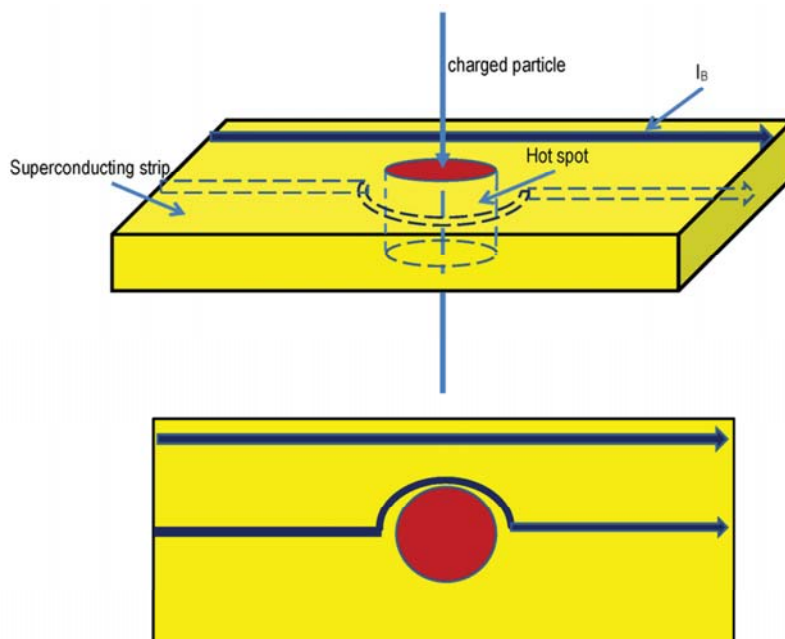


Figure 1: Schematic mechanism for the hot spot generation upon particle energy release

The tests performed on superconducting radiation detectors and presented in different experimental papers (see Refs. [1-3] for example) have shown that, depending on the material and at the proper thermodynamic conditions voltage pulses related to charged particles (minimum and/or non-minimum

ionizing) up to 50-60 mV. Recently, a Nb superconducting strip coated with boron was tested for neutron detection at the ISIS spallation neutron source [6].

In this contribution, the characterization of NbN superconducting strips coated with thin film of boron is presented. These devices were tested at the ISIS spallation neutron source and a brief overview of results are discussed. Eventually a comparison between NbN and Nb strips is highlighted in terms of counting rate. NbN offers, when compared to Nb, the advantage of a higher transition temperature (about 16K, opposed to the 9K of Nb) and a superior mechanical hardness. Future perspectives are briefly outlined in the concluding section.

## 2. Device characterization

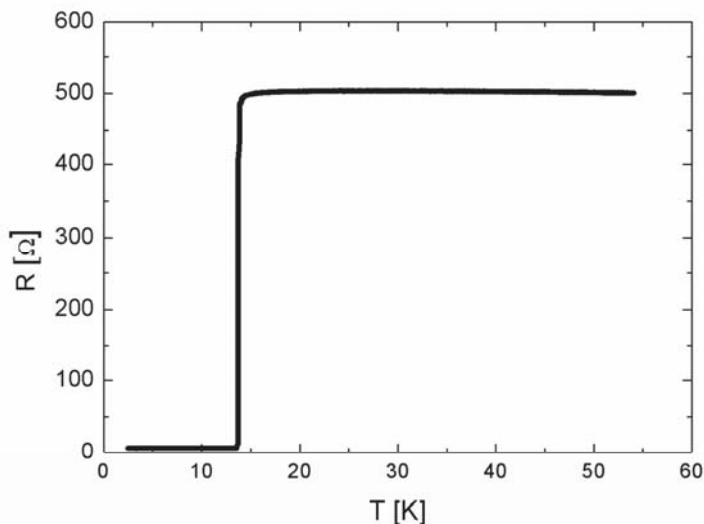
In this section the electrical characterization of the NbN strip and the boron coating procedure and analysis are briefly described.

### 2.1. Superconducting strips

Niobium Nitride (NbN) was grown on a 2 inches silicon wafer with a 1  $\mu\text{m}$   $\text{SiO}_2$  layer on the top. The geometrical patterns of the strips were defined by a lift-off lithographic technique: a “negative” pattern of resist was first impressed on the substrate and subsequently the superconductive film was deposited by reactive magnetron sputtering in DC mode. The removal of the residual resist left only the patterned strips on the sample. During the sputtering process we had a gas mixture composition of 9:1  $\text{Ar}/\text{N}_2$  flux and the total pressure in the deposition chamber was  $10^{-1}$  Pa. In these conditions a 150 nm (thickness measured by an ex-situ profilometer) NbN film thickness was obtained. The liftoff process could be employed just due to the fact that the substrate was not heated during deposition and its temperature could reasonably be kept below 370K during deposition.

The properties and the quality of the NbN films were checked also characterized by XRD and XPS spectroscopy according to a procedure described in [7] in order to verify their properties.

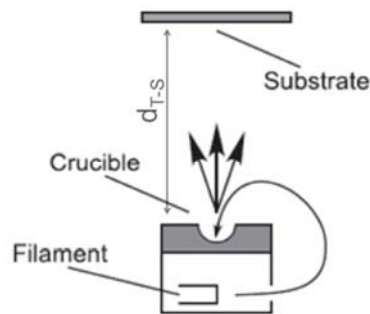
In figure 2, a typical R(T) curve measured on a NbN strip by means of a 4-probe setup is shown.



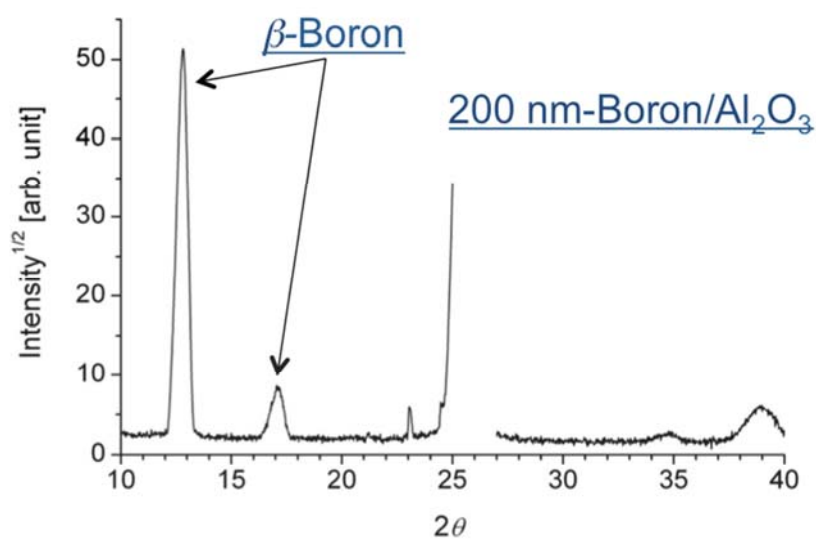
**Figure 2:** Trend of a NbN thin film resistance as a function of the bath temperature

## 2.2. Boron deposition

B coating was obtained by means of electron beam evaporation technique with a multi-crucible Thermionics 3 kW electron beam system with 4 kV of electron acceleration voltage and 750 mA of maximum current. As source for evaporation Alfa Aesar crystalline natural B pieces, 10 – 30 mm in size and purity 99.5 at% were used. Film growth rate was monitored by a quartz crystal controller and fixed at 0.2–0.3 nm/s by tuning the electron beam current,  $I_b$ . The distance between evaporation source and sample holder was  $d_{T-S} = 12.5$  cm. Boron film thickness was 450 nm equivalent to a 90 nm thick film of  $^{10}\text{B}$  considering the natural  $^{10}\text{B}$  isotope abundance. A sketch of the deposition set-up is shown in Figure 3. NbN strips were protected by a stainless steel mask in order to allow film growth on a defined circular area 1 mm in diameter. In Figure 4, the x-ray diffraction  $\theta$ - $2\theta$  pattern is plotted for a typical Boron film deposited on  $\text{Al}_2\text{O}_3$  substrate. As can be seen, peaks related to the  $\beta$ -Boron phase are observed, in addition to other weak reflections indicating the presence of minor films contaminations such as Boron oxides and carbides. A more quantitative analysis carried out by XPS spectroscopy techniques has revealed that the sample contains only B, O and C [8]. The total Boron content can be as high as 80 at.%.



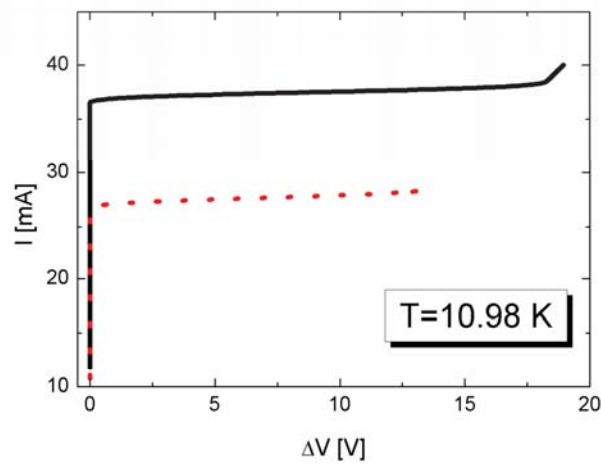
**Figure 3:** Schematic layout of the e-beam deposition system used for NbN boron coating.



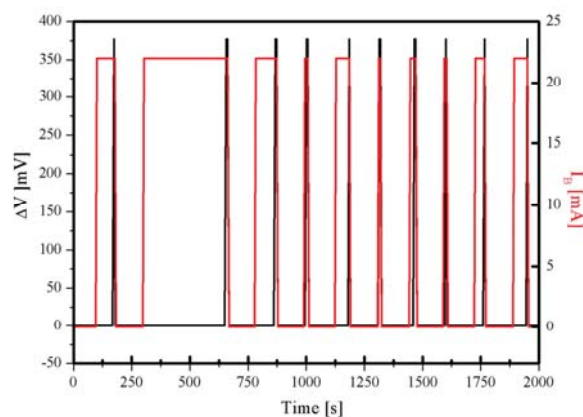
**Figure 4:** X-ray diffraction pattern from a test boron film deposited onto a  $\text{Al}_2\text{O}_3$  substrate

### 3. Tests on beam

The NbN strip with 450 nm boron deposition was tested at the INES diffractometer [9] at the ISIS spallation neutron source [10]. The instrument is equipped with B4C mechanical jaws that are used to tail the thermal neutron beam. Figure 5 shows the  $I/V$  characteristic of the NbN strip in two different cases: i) without neutron irradiation (jaws closed) and ii) during irradiation (jaws open). In the former case the transition to the normal state occurs when  $I_B$  exceeds  $I_C$  ( $\sim 32$  mA as noted in figure 5). During neutron irradiation the transition occurs at a lower value of  $I_B$  ( $\sim 27$  mA). During detector test, the jaws were opened simultaneously to  $I_B$  supply. This is explained in terms of the hot spot model: indeed, the hot spot reduces the effective volume of the superconducting region of the strip. Thus a lower  $I_B$  can provide a  $J_B > J_C$ .

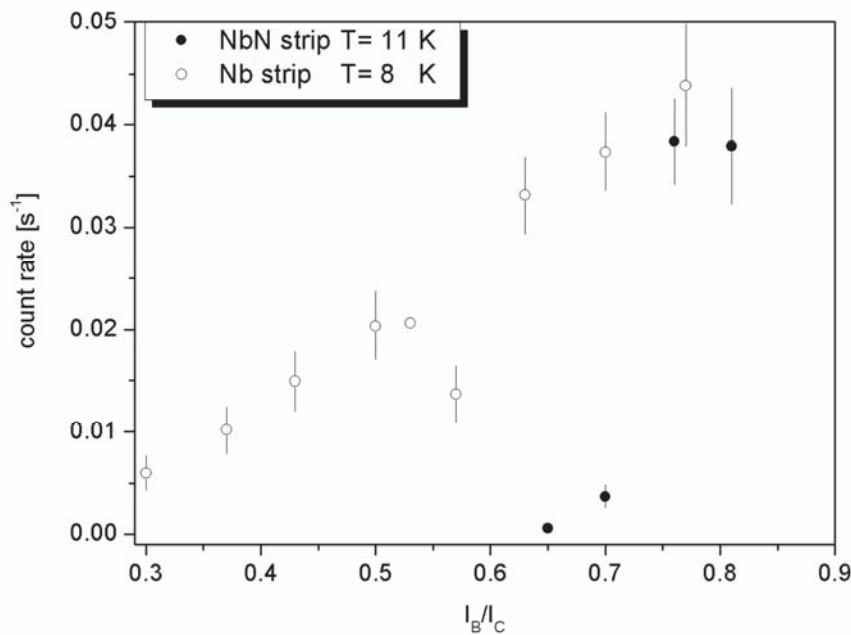


**Figure 5:**  $I/V$  characteristic of the NbN strip without (continuous black line) and with (dashed red line) neutron irradiation



**Figure 6:**  $V-t$  measurement for a NbN strip detector with 450 nm deposition of natural boron, in the continuous operation mode. The red line (scale on the right) illustrates the on-off bias current which switches simultaneously to the open-close jaws status. The black line (scale on the left) is the measured voltage strip across the strip.

The count rate has been extracted from the experimental data by counting the number of leading edges of the voltage time traces (see Figure 6). This value was then corrected taking into account the detector dead time using a non-paralyzable counter model [11]. In the case here discussed, dead time was fixed at 120 s, suggested (although a little bit overestimated) by the time needed to allow the strip to bring back to the superconducting state after the hot spot transient. Considering the particular geometry and the finite thickness, the escape probability cannot be taken as unity (i.e. particles emitted at wide angles are stopped in boron or are out the active volume of the detector). The estimate was obtained following Ref. [9], where the detailed calculation for a somewhat similar geometry was carried out. This approach provided a calculated efficiency of about 0.1% and 0.5% at the thermal peak (25 meV), for the NbN and Nb strips, respectively. The count rate increases as the  $I_B$  is raised [2,6] and figure 7 shows the comparison between the count rates measured for the Nb and NbN strips at T=11 and 8 K, respectively.



**Figure 7:** Comparison between the NbN (full dots) and Nb (empty dots, from Ref. [6]) SCNDs.

In the case of the NbN detector (full dots in Figure 7) the behavior in the range 0.65-0.8 seems not linear. This trend was already evidenced in Refs. [2,3] and explained as a sort of “threshold” where for a given material and geometry, the transition to normal state, in absence of irradiation, occurs beyond a certain value of  $I_B$ . Thus upon irradiation the trend is conserved although the threshold value might differ (lower) due to the effect of the hot spot.

#### 4. Conclusions

In this paper, we presented a detection device relying on the use of NbN superconducting strips coated with natural boron, thus making the material sensitive to thermal neutrons. The secondary alpha and lithium particles emerging from the  $n$ - $^{10}\text{B}$  nuclear reactions release energy in the bulk of the strip,

owing to a transition of the overall strip to the normal state whose mechanism is well described within the framework of the hot spot model.

The detector was characterized on beam at the ISIS spallation neutron source using the INES beam line. The count rate, in the best case, is in the order of  $0.04 \text{ s}^{-1}$ , corresponding to an efficiency of  $10^{-3}$ .

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