INFLUENCE OF GAMMA RADIATION ON JOSEPHSON JUNCTION

by

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Quantum mechanics consideration, supported by a concrete example, yielded standard sources of direct voltage measured by frequency (which is the most accurate measurable physical quantity) and extremely sensitive instrument for measuring magnetic induction SQUID (which is an acronym based on the term Superconducting Quantum Interference Device). The possibility of these measurements is based on the Josephson junction. In this paper, the influence of gamma radiation on the measurement uncertainty Type A, of a commercial Josephson compound, is investigated. The conclusion is that both dynamic gamma radiation and the dose of gamma radiation, under the conditions of the experiment, have a negligible effect on the measurement uncertainty of the Josephson junction. Based on the obtained result, it was concluded that in the primary metrological conditions, the measurement uncertainty type A of the Josephson junction is negligible, *i. e.*, that the secondary cosmic radiation does not affect the standard of the DC voltage source.

Key words: Josephson junction, gamma radiation, measurement uncertainty Type A

INTRODUCTION

Josephson B. D. showed that when a superconductor is intersected by a narrow insulator barrier, the thickness of which is less than the actual length of the Cooper pair, a superconducting current will still flow through the barrier. Part of the superconductor with a thin barrier acted as a kind of electronic component, the so-called Josephson element which has a complex U-I characteristic. It is shown that in one place of the U-I characteristics of the tunnel connection, there is at the same time a DC voltage U, and also an alternating voltage component with frequency f [1, 2].

The DC voltage and frequency are related by expression [3, 4]

$$U = \frac{h}{2e} f \tag{1}$$

where the coefficient of proportionality $h/2e$ between voltage and frequency is determined by the values of two fundamental constants. This means that this coefficient is also a natural constant. Equation (1) can be compared to Faraday's law of induction

$$U \quad \frac{\mathrm{d}\phi}{\mathrm{d}t} \quad \frac{\phi}{t} \quad \phi f \tag{2}$$

Comparing eqs. (1) and (2), it is concluded that the term $h/2e$ has the dimension of magnetic flux and that it represents the elementary quantum of magnetic flux. The numerical value of this quantum is [5-8]

$$\phi_0 = 2.067833636 \times 10^{-15}\, Wb \tag{3}$$

In principle, the quantum of magnetic flux is given by the equation $f = h/q$ where q is the charge. In superconductors, the carriers of charge are Cooper pairs $q = 2e$ [9, 10].

Based on the SQUID theory, the Josephson compounds were first realized, with which the correctness of the theoretical work was experimentally confirmed. The term of the Josephson effect and the term of a radio-frequency magnetometer are connected with the Josephson junction. The Josephson junction magnetometer is the most accurate magnetometer [11, 12].

U-I FORMS OF JOSEPHSON JUNCTION CHARACTERISTICS

There are a number of techniques for the Josephson junction production like evaporation, chemical corrosion and ion photolithography. Some of these types of Josephson junction consist of a thin

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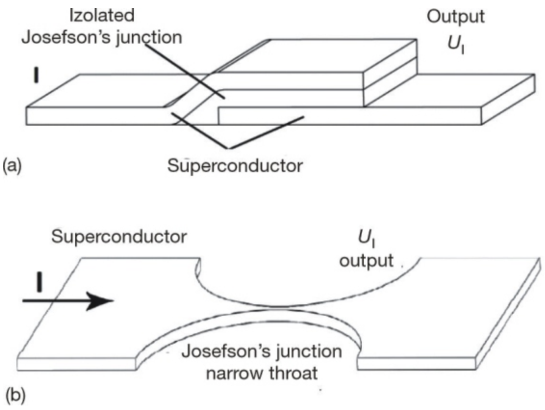

Figure 1. (a) Josephson junction obtained by inserting a layer of insulator (or conductor) between two superconductor and (b) the connection made by narrowing the superconductor

layer of insulator inserted between two superconductors. One example of such a junction is shown in fig. 1(a). Niobium alloyed with elements such as gold, indium and others, is used as a superconducting material. The insulating layer can be silicon oxide about ten nanometers thick. Instead of an insulator, it is possible to use a layer of some usual conductors or semiconductors, that do not reach the superconducting state. In some microscopic constructions, the Josephson junction is achieved without inserting another material through the narrowing of the superconductor, fig. 1(b). The conduction of current through the junction is based on the tunnel effect, which is why the Josephson junction is also called the tunnel element [13-17].

The invention of high temperature superconducting materials has enabled their successful application in the manufacture of Josephson junction. Ceramic Josephson junctions give less repeatability of results than Josephson junctions based on metal alloys.

The DC voltage-current characteristic of the Josephson junction has the hysteresis shape shown in fig. 2.

If the current increases from zero to the value shown by Point A, the junction behaves as an ideal superconductor, *i. e.*, the voltage on it is equal to zero. At Point A, the voltage rises sharply, passing to Point B. With a further increase in current, the characteristic has a smaller slope up to the critical current I_c when the junction loses its superconducting properties. With a further increase in current $I > I_c$, the characteristic has a constant slope, *i. e.*, the voltage increases linearly with the current, according to Ohm's law. With a gradual decrease in current, the voltage moves through the upper part of the characteristic. Starting from Point *D* and moving to 0, there is a steep part of the characteristic on which the junction acts as a voltage-frequency converter used in Josephson's standard voltage sources.

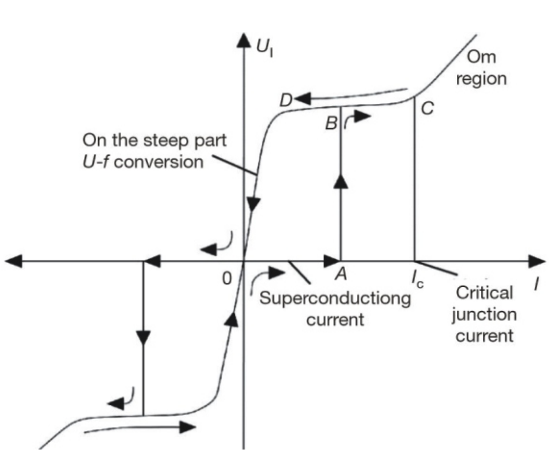

Figure 2. The U-I Josephson junction characteristic

When the current changes direction, a symmetrical characteristic is obtained in the region of negative voltages where the co-ordinate origin represents the point of symmetry [18-24].

The current-voltage characteristic is used in two ways:
- in the case of a SQUID-based magnetometer, the junction is used in the range starting from Point *B* and further in the ohmic region and
- for standard voltage sources, the junction operates in the steep part of the characteristic between Points *D* and 0.

PRACTICAL APPLICATION OF SQUID

The SQUID is intended for measurements of weak magnetic fields, several orders of magnitude smaller than the usual fields originating from geomagnetism, or from the operation of telecommunication or electromagnetic devices [25-27]. A prerequisite for measuring very weak fields is that the interfering fields, the so-called magnetic noise, be reduced as much as possible. This is mostly achieved in dedicated rooms that are protected from external fields with several sheets of high permeability. However, such rooms exist only in larger metrological institutes [28, 29]. Theoretically, ideal protection from external magnetic fields would be achieved in a room whose walls consist of a superconducting material. However, due to technological difficulties, this method of protection is not used in practice.

When measuring induction, the principle of transformer for flux transfer from the measuring point to SQUID, is applied. Transformer windings are superconducting which allows the primary and secondary to be spaced apart, unlike transformers with resistant conductors where the windings must be close. For SQUID, it is desirable to be away from the measuring point because it is surrounded by wires for power supply and transmission of the output signal which, together with parts of the cooling system, partially disturb the field to be measured. At the measuring point, there is only the primary winding of the flux trans-

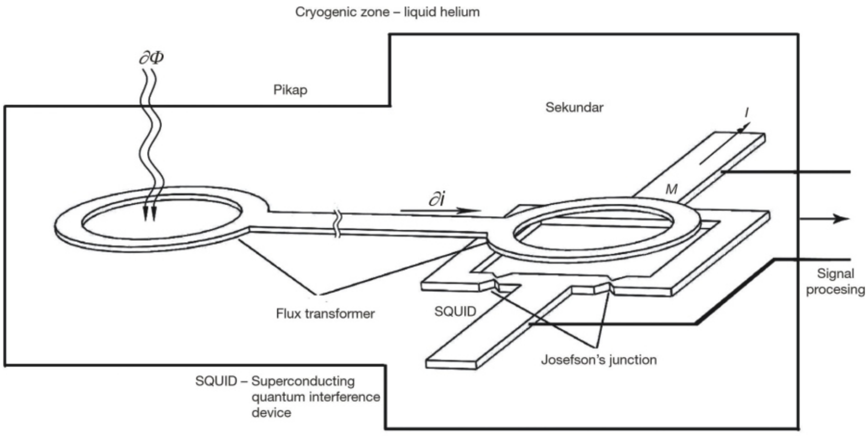

Figure 3. Measurement of magnetic induction using SQUID with signal transmission by flux transformers

former called the tentacle, fig. 3. The primary is connected to the secondary winding which is close to the SQUID and is inductively coupled to it [30-32].

If the primary has N windings of the area mean value A, by changing the induction δB it's changed primary flux $\delta\ \ _p = NA\ \ B_p$. This creates a change of the current δi in the circuit, according to the eq.

$$(L_1 \quad L_2)\delta i \quad \phi_p \tag{4}$$

where L_1 and L_2 are the inductors of the primary and secondary. If the inductive coupling coefficient of the secondary and the SQUID is M, the flux change in the superconducting ring of the SQUID is

$$\partial \phi_s \quad \partial iM \quad \frac{MNA}{L_1 \quad L_2} \partial B \tag{5}$$

From eq. (5), it follows that the change of the incident flux is proportional to the change of induction, at the place where the measurement is performed.

The application of SQUID to record magnetic signals of the human brain is done by multichannel measurement of the change in magnetic induction on the surface of the head, that provides a visual representation of brain activity in real time (magnetoencephalography). Changes in the magnetic field are the result of a change in the current inside the brain that is also recorded by a number of electrodes arranged on the surface of the head.

A plastic helmet is placed on the patient's head, under the surface of which there is a matrix of several tens of primary windings of superconducting transformers. The windings and SQUID are in a cryostat part cooled by liquid helium. Each primary winding is connected to a secondary that is inductively coupled to the SQUID. The visual representation is based on a computer program in which the brain is modeled by a conducting sphere in which circular currents are formed. Regardless of the simplicity of the model, the system provides, every millisecond, the useful visual information about brain activities during real psychic processes. Thermal insulation of the head is realized by a thin vacuum gap. A prerequisite for successful recording of magnetoencephalogram is a low level of other magnetic fields, which is achieved by magnetic protection of the laboratory.

MEASUREMENT UNCERTAINTY TYPE A

Measurement uncertainty type A is determined exclusively by the method of statistical processing of results [33-35]. It follows that the measurement uncertainty Type A exists only if it is a measurement that has been repeated several times. The result of repeated measurements is represented by a sample $x_1, x_2, ..., x_i, ... x_n$. If the elements of the sample are equal, *i. e*., if the repeated experiments are performed in the same way and with the same measuring equipment, the measurement result is obtained as the mean value

$$x_s \quad \frac{1}{n} \quad x_i \tag{6}$$

Since the mean value represents a random variable whose standard deviation is given by the eq.

$$S_{x_s} \quad \frac{1}{n}\sqrt{nS^2} \quad \frac{s}{\sqrt{n}} \tag{7}$$

which is $\sqrt{n}$ times smaller than the standard elementary sample. By definition, the measurement uncertainty type A is equal to the standard deviation of the mean value

$$M_A \quad S_{x_s} \quad \sqrt{\frac{{}_1^n(x_i \quad x_s)^2}{n(n \quad 1)}} \tag{8}$$

The mean value of the measurement, for a sufficiently large number of samples, satisfies the conditions of the Central limit theorem, which means that is joined by the Gaussian distribution (or Student's distribution if a smaller number of samples are involved) [36-41].

EXPERIMENT

The experiment was performed on an experimental animal with a human-like head shape (which means that it was not necessary to make any adjustments to the professional instrument used). During the measurement, the experimental animal was placed in a shallower level of coma and protected from ionizing radiation. The room in which the measurement was

performed was in the dark and the possibility of any event that could affect the sedated experimental animal was excluded. As a result of the measurement, the intensity of brain activity at five points of the brain was taken and translated into a numerical value. The pause between two consecutive measurements was 3 minutes. Three series of measurements were performed:
- without any effect on SQUID,
- with the effect of gamma radiation on SQUID, and
- after receiving a dose of gamma radiation on SQUID.

As a source of gamma radiation Co-60 was used which has two close lines in the spectrum of gamma radiation with values of 1.17 MeV and 1.33 MeV. Coincident with gamma radiation, the Co-60 emits a beta particle that could not penetrate SQUID, so it can be ignored for analysis of the results. The kerma in the air was measured by reference with an ionization chamber and an electrometer verified by the primary standard. Both during dynamic measurement and during dose administration to SQUID, gamma radiation was collimated and directed to the center point of the SQUID axis. The doses given to SQUID were [Gy]: 20, 30, 40, 50, 60, 70, 80, 100, 200 and 1000 [42, 43].

The experimentally obtained results were processed in the following way:
- doubtful results were rejected using the Chauvenet's criterion,
- the results were tested by the *U*-test for belonging to a single statistical distribution,
- the affiliation of statistical samples to the Gaussian distribution was tested by the χ^2-test, and
- the measurement uncertainty type A was determined [44].

All the measurements were repeated 50 times, which enabled the conclusion of the test to be credible (according to the Student's distribution) [45].

RESULTS AND DISCUSSION

Figure 4 shows a diagram of the dependence of the measurement uncertainty Type A on the ordinal number of measurements (taken chronologically). The parameter of the results shown in fig. 4, related to applicability (or the non-application of gamma radiation during the experiment).

Based on the results shown in fig. 4(a), it can be concluded that the direct (dynamic) effect of gamma radiation on the measurement uncertainty Type A of SQUID exists, but at a level within 1-2%. It can also be concluded that the absorbed dose of gamma radiation in SQUID affects its measurement uncertainty Type A, but not significantly, fig. 4(b). The effect of the absorbed dose on the measurement uncertainty Type A of SQUID increases to 4% with very large dose differences (which can be considered negligible). Since neither direct gamma radiation nor the absorbed dose of gamma radiation can disturb the Cooper pair system,

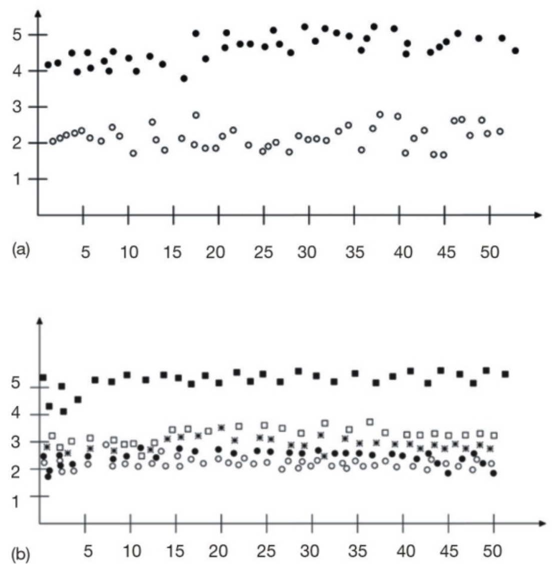

Figure 4. (a) Measurement uncertainty Type A of SQUID (ordinate) depending on the chronology of measurements (abscissa): ○ without radiation, • with dynamic gamma radiation of 100 Gy and (b) measurement uncertainty type A of SQUID (ordinate) depending on the chronology of measurements after receiving a radiation dose: • without radiation, ○ 20 Gy, * 50 Gy, □ 100 Gy, ■ 1000 Gy

the only explanation for the observed effect is through the electronic component.

Miniaturization of electronic components, as a basic technological process that has enabled the dynamic development of many branches of technology, is conditioned by their resistance to the formation of ion pairs in electronic circuits. The small cross-section of the layers of multilayer integrated circuits causes one formed ion-electron pair to drastically increase the current density in them. As the essential laws of electrical engineering (Maxwell's equations) relate to the current density (and not to the current), the noise generated in this way can affect the measurement uncertainty Type A of SQUID.

CONCLUSION

Since theoretically the Josephson junction is the most accurate magnetometer (for several orders of magnitude it surpasses all other types of magnetic field gauges in terms of accuracy) and since the Josephson junction is a standard source of direct current, the influence of radiation on it is extremely important. Since it is impossible to avoid the effect of secondary radiation, it is necessary to know whether it has any effect on such a sensitive instrument as the standard of a DC voltage source. In other words, it is necessary to know whether the Josephson junction is stable under natural conditions, *i. e.*, whether gamma radiation affects the expression of its measurement uncertainty Type A. Tests by indirect measurements have shown that there is a small influence of gamma radiation on the measurement uncertainty Type A, in appropriate medical devices. However, based on the quantitatively obtained results, it can be stated with certainty that, under maximally controlled conditions, it is possible to eliminate any influence of radiation on the measurement uncertainty of the Josephson junction.

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AUTHORS' CONTRIBUTIONS

S. D. Djekić gave the idea for the experiment which was carried out by S. D. Djekić and S. B. Djekić. The other authors, U. R. Ramadani and D. P. Nikezić, analyzed the results and participated in preparation of the final version of the manuscript under supervision and guidelines of N. M. Kartalović.

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УТИЦАЈ ГАМА ЗРАЧЕЊА НА ЏОЗЕФСОНОВ СПОЈ

Квантно механичким разматрањем које је подржано конкретним примером добијени су: еталонски извори једносмерног напона који се мере помоћу фреквенције (што је најтачније мерљива физичка величина) и екстремно осетљив инструмент за мерење магнетне индукције SQUID (што представља акроним базиран на изразу Superconducting Quantum Interference Device). Могућност ових мерења заснива се на Џозефсоновом споју. У овом раду је на комерцијалном Џозефсоновом споју испитиван утицај гама зрачења на мерну несигурност типа А Џозефсоновог споја. Закључак је да и динамичко гама зрачење и доза гама зрачења, у условима експеримента, занемарљиво утичу на мерну несигурност Џозефсоновог споја. На основу добијеног резултата закључено је да је у примарним метролошким условима мерна несигурност типа А Џозефсоновог споја занемарљива тј. да секундарно космичко зрачење не утиче на еталон извора једносмерног напона.

Кључне речи: Џозефсонов спој, гама зрачење, мерна несигурност типа А