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ABSTRACT

The mass–energy–information equivalence principle proposed in 2019 and the information content of the observable matter in the universe estimated in 2021 represent two important conjectures, called the *information conjectures*. Combining information theory and physical principles of thermodynamics, these theoretical proposals made specific predictions about the mass of information as well as the most probable information content per elementary particle. Here, we propose an experimental protocol that allows for empirical verification of the information conjectures by confirming the predicted information content of elementary particles. The experiment involves a matter–antimatter annihilation process. When an electron–positron annihilates, in addition to the two 511 keV gamma photons resulting from the conversion of their rest masses into energy, we predict that two additional low energy photons should be detected, resulting from their information content erasure. At room temperature, a positron–electron annihilation should produce two ~50 μm wavelength infrared photons due to the information erasure. This experiment could, therefore, confirm both information conjectures and the existence of information as the fifth state of matter in the universe.

I. INTRODUCTION

Since IBM's development of the first magnetic hard disk drive (RAMAC) in 1956, digital information storage technologies have radically transformed our modern society. In binary code, digital information is stored as logical 1s and 0s, known as bits. Bits of information can be stored in any material capable of displaying two distinctive and switchable physical states (magnetic, electric, optical, and resistive) by allocating a logical 0 or 1 to each physical state. Digital information became so entrenched in all aspects of our society that the recent growth in information production appears to be unstoppable. Each day on Earth we generate 500×10^6 tweets, 294×10^9 emails, 4×10^6 gigabytes of Facebook data, 65×10^9 WhatsApp messages, and 720 000 h of new content added daily on YouTube.[1] In 2018, the total amount of data created, captured, copied, and consumed in the world was 33 zettabytes (ZB) or the equivalent of 264×10^{21} bits,[2] where 1 ZB is 8×10^{21} bits. This grew to 59 ZB in 2020 and is predicted to reach a 175 ZB by 2025.[1] The incredible amount of digital data being created annually at planetary scale triggered a recent study, in which it has been estimated that at the current digital information production growth rate, ~350 years from now we will create more digital bits than all atoms on Earth.[3] This theoretically predicted phenomenon was termed the information catastrophe.[3]

An interesting exercise is then to estimate the fundamental limit of digital data storage as dictated by the physical realities of our universe and its governing laws. In other words, restricting the estimate to material forms of data storage, the smallest size of a digital bit would have to be the smallest bit of matter that is stable and can exist on its own. It has been concluded that the smallest theoretical size of digital bits would have to be the elementary particles, as they are the smallest known building blocks of matter in the universe. Of course, this is a theoretical limit assuming that, at some distant future, data storage technologies will be developed to allow write/read of digital data to/from elementary particles. Nevertheless, this is very instructive as the recent estimate gave an upper limit of

~6 × 10^{80} bits to the amount of digital data that could be stored in the whole universe.[4] The study was based on Shannon's information theory, assuming the most effective compression mechanism, which yielded a value of 1.288 bits of information stored per electron (e^-), proton (p^+), and neutron (n^0). When quarks were taken into account, the maximum amount of information that could be stored per elementary particle became 1.509 bits.[4] Hence, the estimate of the information content of the observable universe could be interpreted as the maximum amount of information that could be stored digitally if the universe was a giant data storage device. However, the author of the study argued that this is not just a theoretical upper limit of information storage capacity, but, in fact, the elementary particles already store information about themselves. It has been proposed that this information could be seen as a particle DNA, or a matter DNA, and it physically represents the distinguishable degrees of freedom of each particle or pure quantum states.

In 1961, Landauer first proposed the idea that a digital information bit is physical and it has a well-defined energy associated with it.[5,6] This is known as the Landauer principle and it was recently confirmed experimentally.[7–10] In a different study, using Shannon's information theory and thermodynamic considerations, the Landauer principle has been extended to the Mass–Energy–Information (M/E/I) equivalence principle.[11] The M/E/I principle states that information is a form of matter, it is physical, and it can be identified by a specific mass per bit while it stores information or by an energy dissipation following the irreversible information erasure operation, as dictated by the Landauer principle.[5,6] The M/E/I principle has been formulated while strictly discussing digital states of information. However, because Shannon's information theory is applicable to all forms of information systems and it is not restricted only to digital states, the author extrapolated the applicability of the M/E/I principle to all forms of information, proposing that information is the fifth state of matter.[11,12] These ideas, regarded as the information conjectures, are truly transformational because, without violating any laws of physics, they offer possible explanations to a number of unsolved problems in physics, as well as complementing and expanding our understanding of all branches of physics and the universe and its governing laws. Hence, testing experimentally these information conjectures is of extreme importance.

The first proposed experiment to test the M/E/I equivalence principle involved the measurement of the mass change in 1 Tb data storage device before and after the digital information is completely erased.[11] At room temperature, the calculated mass change for this experiment is in the order of ~10^{-25} kg, making the measurement unachievable with our current technologies.

The recent prediction of the information mass content per elementary particle allows us to extend this experimental idea beyond digital data storage to a simple material body of mass m. Because the mass of information is temperature dependent,[11] in this experiment, one could simply confirm the information conjectures by observing the effect of the temperature change on the information mass content of elementary particles contained within a physical body of a known mass. Let us consider a random mono-atomic solid of mass m made up of identical atoms of atomic mass weight A, each atom containing N_{e-} electrons, N_{p+} protons, and N_{n0} neutrons. If each elementary particle contains I bits of information, then a mass m would contain N_b bits of information,

$$N_b = I \cdot \frac{mN_A}{A}\left(\mathrm{N}_{e^-} + 3\left(\mathrm{N}_{p^+} + \mathrm{N}_{n_0}\right)\right), \tag{1}$$

where $\mathrm{N_A}$ is Avogadro's number, $\mathrm{N_A} = 6.022 \times 10^{23}\ \mathrm{mol^{-1}}$, and the factor of 3 accounts for the fact that each proton and each neutron are made up of three quarks.

According to the M/E/I principle,[11] for a temperature change ΔT, the general expression of the information mass change Δm^{inf} of a body of mass m is

$$\Delta m^{\mathrm{inf}} = I \cdot \frac{mN_A k_b \Delta T \ln(2)}{Ac^2}\left(\mathrm{N}_{e^-} + 3\left(\mathrm{N}_{p^+} + \mathrm{N}_{n_0}\right)\right), \tag{2}$$

where $\mathrm{k_b} = 1.380\,64 \times 10^{-23}$ J/K is the Boltzmann constant and c is the speed of light.

Relation (2) predicts a temperature dependence of the information mass change.

Hence, one could design an experiment to measure the mass change inflicted by a temperature change to the body mass m. Since the physical mass of the material under test does not change with the temperature (assuming solid materials are thermally and chemically stable), the detected mass change can only be related to the information mass change, providing a direct confirmation of the proposed information conjectures.

Let us assume a metallic body of $m = 1$ kg copper (Cu), with each Cu atom containing $N_{e-} = 29$ electrons, $N_{p+} = 29$ protons, and $N_{n0} = 34.5$ neutrons. The fractional value of N_{n0} accounts for the existence of the two Cu isotopes containing 34 neutrons (70%) and 36 neutrons (30%), respectively. This proportion of isotopes gives a relative atomic mass number $A = 63.55$ g. If each subatomic elementary particle contains $I = 1.509$ bits of information as predicted previously,[4] then using (1) we obtain the total number of bits of information stored in a kg of Cu as $N_b = 29.8 \times 10^{26}$ bits.

For a temperature change $\Delta T = 100$ K of the Cu sample (cooling or heating), using (2) we obtain an absolute value of information mass change of $\Delta m^{inf} = 3.33 \times 10^{-11}$ kg. This value significantly improves the required measurement resolution relative to the initial proposed experiment ($\Delta m^{inf} \sim 10^{-25}$ kg), but an accurate measurement of ~10^{-11} kg is still extremely challenging.

Therefore, in this paper, we combine the estimates of the information content per elementary particle, with the M/E/I equivalence principle, to formulate a new experimental protocol suitable to test the information conjectures.

II. PROPOSED EXPERIMENTAL PROTOCOL

In order to test experimentally the information conjectures described in the introduction, let us first consider an elementary particle. For convenience, we will consider an electron. We also assume that the electron stores I_{e^-} bits of information in itself about itself. According to M/E/I, the electron's rest mass is the sum of its physical mass and the information mass,

$$m_{e^-} = m_{e^-}{}^{phys} + m_{e^-}{}^{\mathrm{inf}}. \tag{3}$$

Although here we are examining an electron, this conjecture applies to any elementary particle that is stable and has a non-zero rest mass. The mass of a bit at temperature T is given by[11,13–16]

$$m_{bit} = \frac{k_b T \ln(2)}{c^2}. \tag{4}$$

Hence, the mass of the electron becomes

$$m_{e^-} = m_{e^-}^{phys} + \frac{I_{e^-} k_b T \ln(2)}{c^2}. \tag{5}$$

A quick numerical estimate indicates that the information mass of the electron is extremely small so that

$$\frac{m_{e^-}}{m_{e^-}{}^{\inf}} = \frac{9.11 \times 10^{-31}}{I_{e^-} \cdot 3.19 \times 10^{-38}} \approx \frac{2.85}{I_{e^-}} \times 10^7. \tag{6}$$

Taking $I_{e^-} = 1.288$ bits, it results that the rest mass of the electron is ~22 × 10^6 times larger than its information mass, indicating that, indeed, the mass of the electron is well approximated by its physical rest mass, while its information mass is negligible. Again, this makes the experimental testing impossible via direct mass change measurements.

Here, we propose an experiment, which involves the measurement of the information mass indirectly, via an information erasure process. According to the M/E/I and Landauer principles, the information mass must be dissipated as energy upon erasure.

A. How can one erase the information contained within an electron?

In order to completely erase the information within any elementary particle, one needs to remove the particle from existence. This can be achieved via a matter–antimatter annihilation reaction. Luckily, in the case of an electron, there is a routinely accessible process known as electron–positron annihilation, where the positron (e^+) is the antiparticle of the electron (e^-), and a collision between an electron and a positron can lead to their mutual annihilation. In the annihilation process, the rest mass energies and the kinetic energies of the electron and positron are converted into radiation.

Depending on the total spin of the positron–electron pair, the annihilation process can take place via two possible pathways for the emitted radiation. When the total spin is one, the annihilation produces three gamma photons. When the positron–electron pair has a total spin of zero, the annihilation process produces two gamma photons.

This latter process is an ideal candidate to study the information content of the input particles by examining what may arise from the erasure of the information upon their annihilation. The total energy of the colliding electron–positron pair is

$$E_{tot} = E_{e^-} + K_{e^-} + E_{e^+} + K_{e^+}, \tag{7}$$

where $E_{e^-} = m_{e^-} c^2$ and $E_{e^+} = m_{e^+} c^2$ are the rest mass energies of the electron and positron, respectively. $K_{e^-} = m_{e^-} v_{e^-}{}^2/2$ and $K_{e^+} = m_{e^+} v_{e^+}{}^2/2$ are the kinetic energies of the colliding particles moving with velocities v_{e^-} and v_{e^+}, respectively. Since c ≫ v_{e^-} and v_{e^+}, the kinetic energies are negligible. Performing the experiment with a beam of slow positrons and static electrons in the target can easily meet this condition. The electron–positron pair must conserve the total energy, the momentum, and the angular momentum after the annihilation process. The energy conservation ensures that two 511 keV gamma photons are produced from the conversion of their rest mass energies. The angular momentum conservation is automatically fulfilled in the two-photon annihilation process, where one spin is up and the other spin is down. The momentum conservation imposes the condition that these two gamma photons travel in the directions 180° to each other. Reaction (8) and Fig. 1(a) show the standard electron–positron annihilation process that produces two gamma photons,

$$m_{e^-} c^2 + m_{e^+} c^2 = \gamma + \gamma. \tag{8}$$

However, relation (7) does not include any information energy that might be contained in the particles themselves. Accounting for

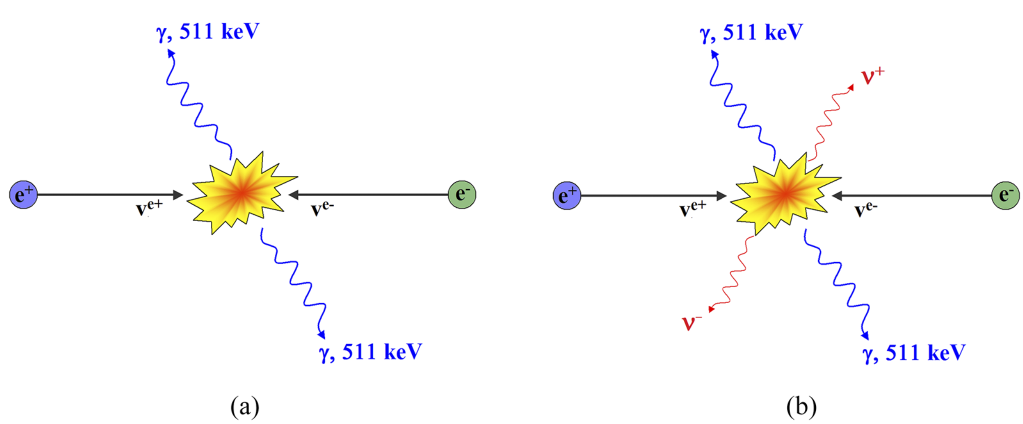

FIG. 1. Diagrammatic representation of the positron–electron annihilation process. (a) Standard positron–electron annihilation process that produces two 511 keV gamma photons only and (b) positron–electron annihilation process that produces two 511 keV gamma photons and two additional low energy photons from information erasure.

the information content and neglecting the kinetic energies, the total energy is

$$E_{tot} = m_{e^-}c^2 + m_{e^+}c^2 + I_{e^-}k_bT\ln(2) + I_{e^+}k_bT\ln(2), \quad (9)$$

where $T_{e^-} = T_{e^+} = T$ because the positrons will reach thermal equilibrium with the metallic sheet containing the target electrons, so each particle will have the same temperature at the time of collision. I_{e^-} and I_{e^+} are the amount of information bits stored by the electron and the positron, respectively.

The rest masses of the electron and positron as well as their information contents must be equal to each other. The energy conservation ensures again that two gamma photons of about 511 keV are produced. However, if particles store information, upon annihilation (i.e., erasure), the information content must also be conserved by producing two information energy photons ν^+ and ν^-.

The momentum conservation imposes the condition that these two additional photons also travel in the opposite direction to each other. Reaction (10) and Fig. 1(b) show the electron–positron annihilation process that includes the information erasure,

$$m_{e^-}c^2 + m_{e^+}c^2 + I_{e^-}k_bT\ln(2) + I_{e^+}k_bT\ln(2) = \gamma + \gamma + \nu^+ + \nu^-. \quad (10)$$

III. THEORETICAL PREDICTIONS

The successful detection of the information energy photons ν^+ and ν^- will confirm both information conjectures: (i) the mass–energy–information equivalence principle and (ii) the bit information content of elementary particles implying the existence of information as the fifth state of matter.

The information energy photons have very specific characteristics that allow their identification with a high degree of confidence. First, they should emerge simultaneously with the 511 keV gamma photons. This means that synchronized detection of the gamma and the information energy photons would offer a strong indication of their origin.

Second, the information energy photons have very specific wavelengths, which are not only proportional to the amount of information bits stored by the electron and the positron but also proportional to their temperature.

Recently, the information content per elementary particle has been estimated to be 1.509 bits.[4] Although the estimation accounted only for stable elementary particles excluding anti-particles, we can assume that the information content of the positron is equal to that of the electron, so $I_{e^-} = I_{e^+} = I = 1.509$ bits, and upon erasure, the resulting photons also have the same energies/frequencies $\nu^+ = \nu^- = \nu$.

According to the M/E/I equivalence principle, the wavelength of the information energy photons is

$$\lambda = \frac{hc}{Ik_bT\ln(2)}, \quad (11)$$

where h = 6.62×10^{-34} m^2 kg/s is Planck's constant. Figure 2 shows the predicted wavelength of the information energy photons as a function of the temperature, which extends from the mid-infrared (MIR) to far-infrared (FIR) spectral regions. Since the information content of 1.509 bits is a theoretical prediction not confirmed yet,

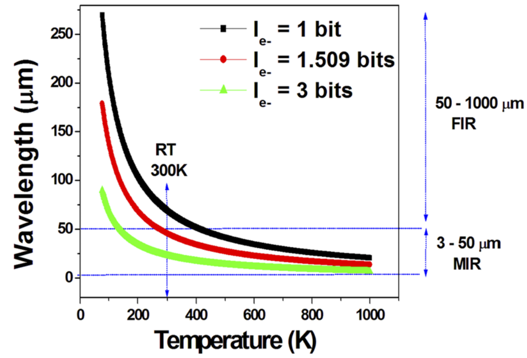

FIG. 2. Predicted wavelength of the information energy photons as a function of the T for three possible information contents per elementary particle.

it is instructive to extend the possible range of the bit information content per particle.

Hence, in Fig. 2, we also show the predicted values for two additional information contents of 1 and 3 bits per particle, respectively. The data show that, for 1.509 bits of information content, the expected information energy photon wavelength ranges from 3 to 180 μm, depending on the temperature of the experiment. At room temperature, information energy photons of ~50 μm wavelength are predicted to emerge. This value changes proportionally to the bit information content, so from 1 to 3 bits per elementary particle, the wavelength at room temperature ranges broadly from 25 to 75 μm. Knowing these predicted values is very important for the experimental design and the choice of IR detectors.

IV. PROPOSED EXPERIMENTAL DESIGN

The experiment should be designed to ensure that not only the two 511 keV gamma photons are detected but also the additional two IR photons, ν^+ and ν^-. The detection of the IR photons presents some additional challenges because they are easily attenuated within the sample.

For our experiment, we propose to use positrons generated by a ^{22}Na radioactive source. Figure 3 shows the decay scheme of ^{22}Na. This isotope is very convenient because of its relatively low cost, long half-life of 2.6 years, and high positron yield. Positrons emitted via

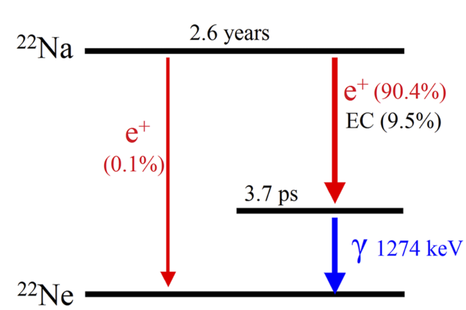

FIG. 3. Decay scheme for ^{22}Na. EC = electron capture, e^+ = positron, and γ = gamma photon.

nuclear radioactive decay of ^{22}Na sources have an energy distribution range from 0 to 545 keV, and 90.4% of the time they decay according to the following reaction:

$$^{22}_{11}\mathrm{Na} \rightarrow {}^{22}_{10}\mathrm{Ne} + e^{+} + \nu + \gamma, \quad (12)$$

where e^+ is the positron, ν is a neutrino, and γ is a 1274 keV gamma photon.

Unfortunately, the γ-decay reaction of ^{22}Na generates high-energy positrons (also known as fast positrons), and they have a large penetration range into the sample material. Therefore, the sample material must be thick enough to absorb the positrons, but thin enough to ensure that it does not attenuate the 511 keV gamma rays that are created in the electron–positron annihilation within the sample. Most importantly, we need to ensure that the two IR photons ν^+ and ν^- produced at the erasure of the information content are also not fully attenuated within the sample material. In order to fulfill these requirements, one option is to use a metallic thin layer target material bombarded with low energy positrons (also known as slow positrons). Slow positrons have a higher probability of electron annihilation, as they diffuse through the target material. When fast/high-energy positrons enter a material, they lose energy by interacting with the material, slowing down to thermal energies. This thermalization process takes only a few picoseconds, while the positron mean lifetime in metals ranges from 100 to 450 ps.[17] Fast-to-slow positron moderation is easy to accomplish using a moderation step made of a suitable material that has a negative work-function for positrons.[18,19]

Fast positrons penetrate the moderation step where some will emerge on the other side as fast positrons but with reduced energies, some will annihilate inside the moderator, and some will thermalize and diffuse to reappear at the surface of the moderation step where they are spontaneously emitted as mono-energetic slow positrons of kinetic energy close to the work function of the moderation material (a few eV). The fast-to-slow positron conversion efficiency is typically $\sim 10^{-4}$,[20] and one of the best moderation materials is the tungsten single-crystal.[21–24]

We propose to cover the ^{22}Na source with a thin (1–2 μm) single-crystal tungsten foil in (100) orientation,[22] which has a negative work-function of around 3 eV.

Alternatively, a polycrystalline thin film tungsten moderator[23] could be coated directly onto the ^{22}Na positron source via a suitable thin film deposition process. The low energy positrons leaving the moderator will annihilate in the metallic target material. The range of the positrons in the target dictates the choice of the metal. For example, 545 keV positrons penetrating an Al target have a mean lifetime of 166 ps and a range of 0.954 mm, while for an Au target, the mean lifetime is 118 ps and the range is 0.194 mm,[25] which is almost five times shorter range than that of Al. To ensure a high probability of positron–electron annihilation, we propose to use a metallic Al thin film as the target material. The thickness of the Al thin film must be in the range of a few nm so the thermalized positrons can undergo a surface annihilation in the Al material and a large fraction of the resulting photons (gamma and IR) can reach the detectors.

Figure 4 shows a schematic diagram of the proposed experiment (thickness of the layers not at scale).

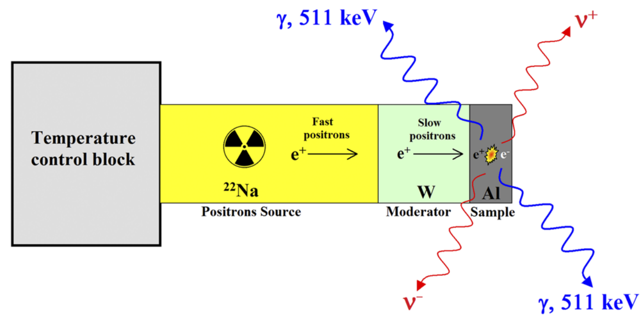

FIG. 4. Schematic diagram of the proposed positron–electron annihilation experiment for detection of the information content in matter.

It is important that the W moderator and the Al thin film sample completely encapsulate the ^{22}Na source. The experimental design requires one end of the ^{22}Na source to be in contact with a temperature controller, while the other surface is used for the positron beam.

Gamma and IR detectors are placed in the close proximity of the Al thin film. The temperature controller (cooling and heating) is required because the theory predicts that the IR photons detected at information erasure display a linear temperature scaling of their energy. Assuming the successful detection of the IR information energy photons, the ability to vary the temperature of the sample will act as a double confirmation of the experiment by detecting the wavelength change in the IR photons with the temperature. This experimental geometry is the easiest path to controlling the temperature of the emitter (positrons) and sample (electrons), simultaneously. However, if the infrared photons are totally absorbed in the Al sample, then a different, more complex experimental geometry could be designed, in which the Al film and the W moderator are detached from the source.

V. CONCLUSIONS

Two information conjectures have been recently proposed: (a) the mass–energy–information equivalence principle,[11] stating that information transcends into mass or energy depending on its physical state and (b) the existence of an intrinsic information underpinning the fundamental characteristics of elementary particles in the universe, implying that stable, non-zero rest mass elementary particles store a fixed and quantifiable value of information about themselves.[4] The two conjectures also imply that the information is a form of matter, called the fifth state of matter or the fifth element.

These conjectures have been limited only to theoretical frameworks, but the acceptance of their validity can only come from a solid experimental confirmation.

In this article, we propose an experimental protocol designed to confirm these information conjectures by validating the existence of the information content of elementary particles and by detecting its exact value. The proposed protocol makes the assumption that the information content is conserved during particle–antiparticle annihilation via the production of two IR photons. Using the predicted value of 1.509 bits of information per elementary particle at room temperature, we expect a positron–electron annihilation to produce two IR photons of ~50 μm wavelength due to information erasure, which should be detected simultaneously with the two 511 keV gamma photons emerging due to the energy conversion of the rest masses of the annihilating particles.

The experiment is highly achievable using current technologies and it provides a few control tools to ensure that the detection is indeed due to information erasure. The main control tool is the fact that the wavelength of the information energy IR photons must shift with the temperature of the sample. By performing the experiments at different temperatures, the detection of the wavelength shift of the IR photons would be an ultimate confirmation of this hypothesis.

It is important to recognize that we make a strong assumption that the transfer of the information mass content of the annihilating particles takes place via conversion into IR photons. However, other mechanisms of conversion are possible, including the gamma photons becoming carriers of this excess information energy. Hence, even if the information conjectures are correct, the proposed experiment is, therefore, not totally guaranteed to succeed. However, the implications of a successful experiment are so transformational that we hope this article will stimulate research groups actively working on positron–electron annihilation spectroscopy to attempt this experiment.

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AUTHOR DECLARATIONS

Conflict of Interest

The author has no conflicts of interest to disclose.

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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