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MEASUREMENT OF THE NARROW COMPONENT OF THE ANNIHILATION RADIATION PEAK

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1 INTRODUCTION

The establishment of a reliable chain connecting γ-ray lines with reference standards as well as the obtention of a consistent system connecting them to the fundamental constants has a longstanding history. It has been the object of tremendous efforts in the passed and still remains with many open questions (see for example Ref.[1,2] and references quoted there). We refer to these review papers for more details and present in work an attempt to measure with improved techniques the electron mass using the annihilation radiation peak with a ^{22}Na source.

The only monochromatic radiation whose energy is completely determined by the fundamental physics constants is the radiation emitted in annihilation of the parapositronium at rest, i. e. of a system consisting of a positron and an electron with the opposite spins orientations. In the center of mass reference frame the two annihilation quanta are emitted in opposite directions.

The binding energy of the parapositronium in the ground state may be estimated to a good accuracy in the lowest approximation of the quantum electrodynamics. Then the energy of each of the two emitted quanta (if $m_{e^-} \equiv m_{e^+}$) is:

$$h\nu^{\pm} = m_e c^2 - m_e e^4/8h^2 = m_e c^2(1 - \alpha^2/8) \quad (1)$$

$$\cong m_e c^2 - 3.4eV, \quad (2)$$

here α is the fine structure constant. Relations (1) and (2) can be used for two purposes: either for energy calibration of gamma-quanta, using the fundamental constants, or to determine the electron (positron) rest mass by measuring the position of the annihilation peak using a well established energy scale for gamma-quanta.

2 EXPERIMENTAL CONDITIONS

Based on the assumption that the centroid of a symmetric gamma line leads to correct relative energy measurements, several experiments have been carried out to measure $h\nu^{\pm}(\lambda^{\pm})$ - energy or wavelength of the annihilation radiation. The results, corrected for subsequent changes in the values of fundamental constants following Ref.3 are listed in Table 1.

Since the experimental error of the measured value of $h\nu^{\pm}$ is much worse than the one obtained from adjustment based on the fundamental constants (Table 2), *the problem of* measuring $h\nu^{\pm}$ with high accuracy (and, consequently, $m_e c^2$) has not arisen up to now. On the contrary, there was a problem of using the $h\nu$ value deduced from the fundamental constants for the determination of the gamma-quantum energy standards. Actually, this way would be justified from the metrological point of view, if it were not for one significant fact: when positrons interact with matter under normal conditions, the annihilation peak broadens and gets a complicated shape of several components, the center of gravity of this peak depending on the annihilation conditions.

The most obvious way of overcoming these difficulties was shown in Ref. [12]. The authors [12] made use of the fact that the angular distribution of annihilation gamma-quanta with respect to each another is unequal for annihilation in water and in ice. When water freezes, the annihilation component arising from the gamma-quanta which are emitted in almost exactly opposite directions (the narrow component) is strengthened. This phenomenon was discovered and thoroughly studied during investigations of angular correlations [13-15]. Using the experimental lay-out of Knowles [2] and the idea of existence of the narrow peak of the annihilation line in the water-ice system, Murray et al. [12] carried out an experiment to measure the energy of the 411.8 keV gamma-transitions from the decay of ^{198}Hg . The point was to measure the small difference in energies of the photoelectrons knocked out from the K-shell by the narrow component $h\nu^{\pm}$ and from the L_3-subshell by the $\gamma 411.8 - {}^{198}$Hg in the uranium atom. These authors found

$$\Delta E = (h\nu^{\pm} - \epsilon_k(U)) - (\gamma 411.8 - \epsilon_{L_3}(U)) = 0.766 \pm 0.006 keV \qquad (3)$$

where ϵ_k(U) and ϵ_{L_3}(U) are the binding energies of the electron in the K and L_3 shells of uranium. Then, using the values of $\epsilon_K(U)$ and $\epsilon_{L_3}(U)$ from Bearden's Tables [16] with their own $h\nu^{\pm}$, they obtained for the energy of this transition:

$$411.794 \pm 0.006 keV. \qquad (4)$$

Table 1. Experimental values of $h\nu^{\pm}$ (measurement with the crystal diffraction method*)

1952	$(\lambda^{\pm})^*$	$h\nu^{\pm} = 511.0 \pm 0.7$	keV	[4]
1952		$h\nu^{\pm} = 510.974 \pm 0.041$	keV	[5]
1962	$(\lambda^{\pm})^*$	$h\nu^{\pm} = 511.010 \pm 0.016$	keV	[6]
1971	$(\lambda^{\pm})^*$	$h\nu^{\pm} = 511.006 \pm 0.017$	keV	[7]
1979		$h\nu^{\pm} = 510.990 \pm 0.005$	keV	[8]
Mean valua		$h\nu^{\pm} = 510.993 \pm 0.005$	keV	

For a long time this work seemed to be satisfactory and the value (4) was widely used in experimental physics as a main standard for the gamma-ray energies [17]. However, with the development of the optical X-ray method combined with the crystal diffraction spectroscopy, Kessler et al.[3] could determine a more accurate absolute value of the wave length, λ, of the γ411.8 keV (^{198}Hg) transition [15] leading to the energy

$$411.8044 \pm 0.0011 keV \tag{5}$$

It was shown later by Deslattes et al.[1] with there new measurements of the K and L_3 binding energy difference in uranium atom, that this discrepancy is removed and that the value (5) was taken as a γ-standard energy up to now. It is curious that, despite the metrological significance of such experiments, there has been little progress during the last decade to improve measurement conditions with the Murray's lay-out or simply repeat such experiment using new techniques.

3 EXPERIMENTAL PROCEDURE

In view of all this we have tried to carry out an experiment according to Murray's lay-out and measure the energy of the "narrow component" of the annihilation peak using a semiconductor detector (SCD) spectrometer.

Notice that the resolution of such a spectrometer is worse than that of Ref.[12] (FWHN of magnetic spectrometer $\sim$ 360 eV, while FWHM of SCD $\sim$ 1 keV), but the former spectrometer allows multichannel detection, which can be significant in studying effects where the line shape plays the main role. Moreover, modern spectrometric equipment and techniques [18] allows a higher accuracy of gamma energy measurements in the $\sim$ 500 keV region than the magnetic electron spectroscopy; this accuracy becomes comparable with the errors of the energy standards (i. e. of the order of one or several electron-volts).

Gamma spectra were registered by means of a 200 $mm^2 \times 5mm$ Ge(Li)-detector whose energy resolution (FWHM) in the region 511 keV (^{106}Ru transition) was 0.95 keV.

For a more thorough analysis of the annihilation line shape the investigated energy range 476-570 keV covered 1200 channels. The energy calibration of the spectrometer was carried out by γ-radiations of the following nuclei

^{7} Be $E_\gamma = 477.6064 \pm 0.0026 keV$ [19]
^{106} Ru $E_\gamma = 511.8562 \pm 0.0022 keV$ [19]
^{207} Bi $E_\gamma = 569.702 \pm 0.002 keV$ [20]

The annihilator was doubly distilled water of conductivity $10^{-6} Ohm^{-1} cm^{-1}$ contained in a cylindrical stainless steel tank (20 mm diameter, 30 mm height). To avoid system-

Table 2. Values of $h\nu^{\pm}$ deduced from the fundamental constants (we shall discuss below the analysis of the data with the last 1986 constants)

1965	$h\nu^{\pm} = 511.003$	± 0.020	keV	[9]
1969	$h\nu^{\pm} = 511.0007$	± 0.0016	keV	[10]
1973	$h\nu^{\pm} = 511.0000$	± 0.0014	keV	[11]

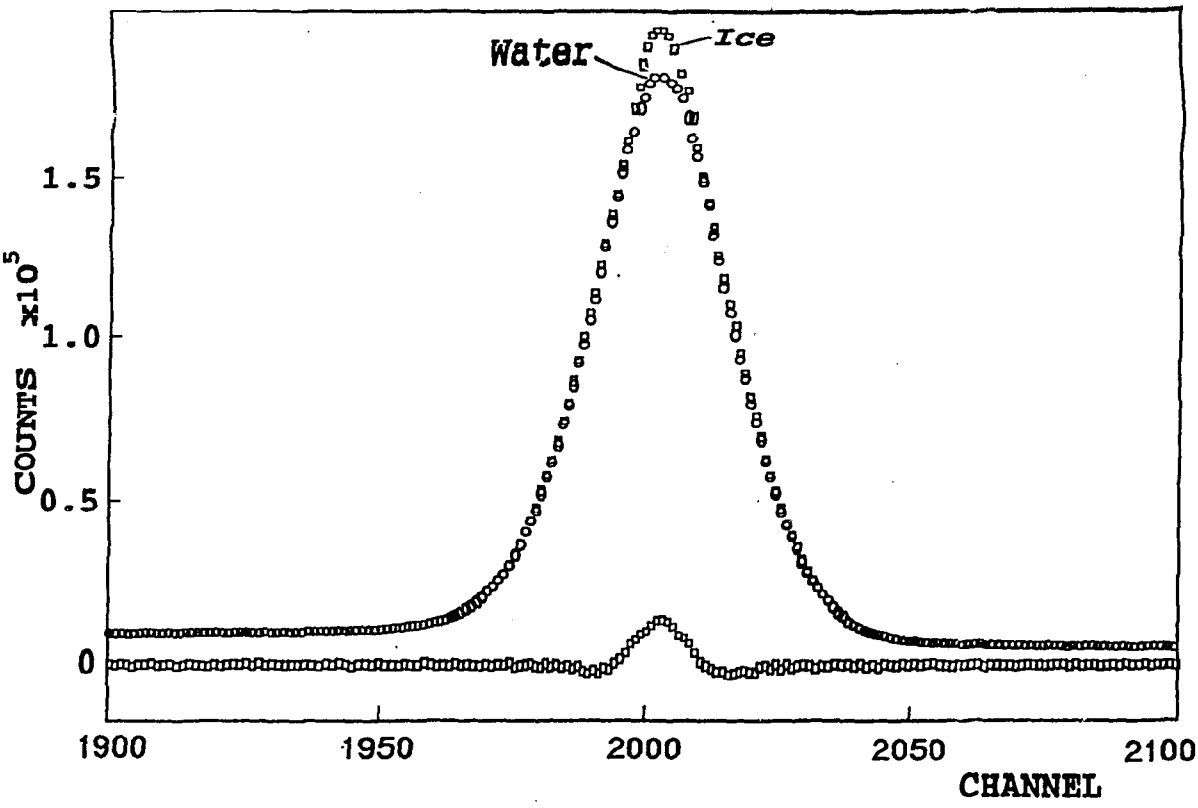

Fig. 1. Annihilation gamma-spectra registered by a Ge(Li)-detector in the case when Na was dissolved in water and in ice respectively. The curve shown at the bottom of the figure corresponds to the "water-ice" difference as described in the text.

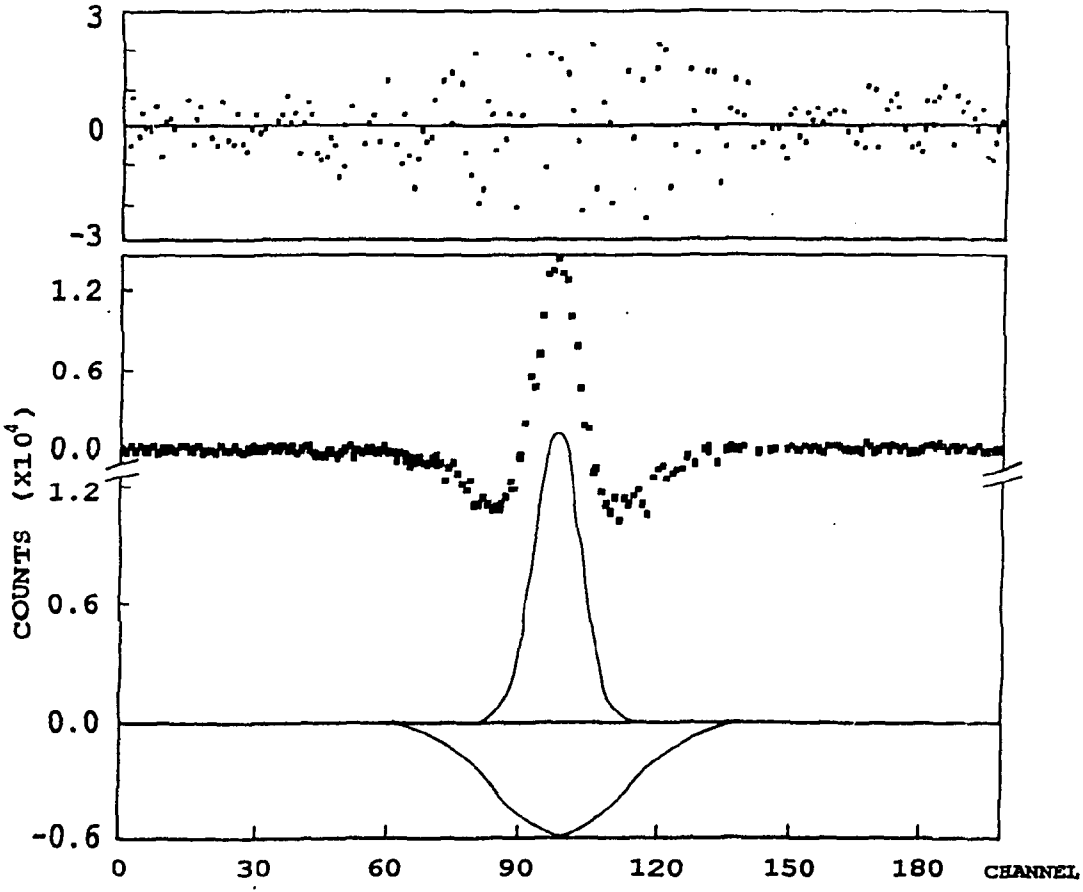

Fig. 2. The "water-ice" difference spectrum is given in the middle of the figure. Below one gives the fitting Gaussian curves of the narrow (positive amplitude) and the broad (negative amplitude) components. At the top is shown the quality of the fitting procedure.

atic errors arising from the physical extent of the water-ice source, calibration sources were evenly distributed over the surface of similar cylinder. The annihilator temperature could vary from $+20°C$ to $-160°C$ (by cooling the tank with liquid nitrogen) and it was controlled by a thermocouple.

The source of positrons was ^{22}Na in the form of NaCl with an activity of about 0.2 μCi. At first, repeating Murray's experimental conditions [12], we used a quasi-point source obtained by evaporation and placed between two thin Teflon films. This set-up was placed in the middle of the tank separating the whole container into two half cylinders. It was impossible, however, to isolate the narrow component of the annihilation radiation reliably in the water-ice difference spectrum under these conditions.

Direct solution of ^{22}Na in the annihilator water was much more effective. The annihilation spectrum in water together with the "side" reference sources ^{7}Be and ^{207}Bi was registered for 10 hours at 20°C , so that 3×10^6 counts were accumulated in the annihilation spectrum. After the fast freezing to $-160°C$ the spectrum was registered again for the same time. After the thawing of the annihilator the cycle was repeated.

The shift of the subsequent spectra in water and in ice due to the long-term instability of electronics did not exceed 1 channel. So, in order to plot a water-ice difference spectrum, we had to shift the "water" spectrum using the procedure of the Lagrange 5-point interpolation. Typical annihilation lines for the "water-ice" system and the corresponding difference spectrum are shown in Fig. 1. The narrow component of the annihilation peak is distinguishable from the weak negative symmetric background which remains from the wide component (note that because of the equal measuring time it is the total number of counts in the full water and ice annihilation peaks which are equal).

4 RESULTS AND DISCUSSION

To analyze the water-ice difference spectrum obtained the narrow and wide components were approximated by a symmetric Gaussian function with positive and negative amplitude, respectively. Result of this analysis is shown in Fig. 2. The energy width of the narrow component at half-maximum was ~ 0.95 keV, which coincides with the intrinsic resolution of the spectrometer.

Our results are in agreement with the result of fitting the total annihilation peak in the "water-ice" system of Refs. [21,22].

The narrow component energy was determined by means of calibration with of the "side" reference spectra which were registered simultaneously with the "ice" annihilation spectrum. In each series a non-linearity correction was introduced; the correction was found by measurements with three reference spectra. The results are given in Table 3.

Thus, the result coming out from the analysis of the narrow components is

$$h\nu = 510.9996 \pm 0.0034 keV. \tag{6}$$

Note that the new energy standard value of γ411.8 keV (^{198}Hg) (5), and as well as the Uranium $K_{\alpha 1}$ X-ray energy was measured by Kessler et al. [23]

$$E(U\,K_{\alpha 1}) = 98.4322 \pm 0.0003 keV \tag{7}$$

Table 3. The results of eight series of measurements of the narrow component energy obtained in different electronic set-ups.

Series No	Electronic set-up	Energy value obtained	Error
		in electron-volts	
1	a)	510 997.0	5.2
2	a)	511 002.2	8.7
3	b)	510 987.1	10.3
4	b)	510 999.8	6.3
5	b)	511 000.3	6.8
6	c)	511 003.2	5.4
7	c)	511 004.2	6.2
8	c)	510 999.6	4.5
Mean value:		510 999.6	2.1
Systematic errors:			
– reference spectrum error			1.9
– spectrometer calibration procedure error (non-linearity, shift)			1.9

and our group [24]

$$E(U K_{\alpha 1}) = 98.4316 \pm 0.0008 keV \tag{8}$$

allow to obtain from the Murray's et al. results [12]

$$h\nu = 511.002 \pm 0.007 keV. \tag{9}$$

The new value is seen to be in good agreement with our result (6).

5 ELECTRON MASS

The basic principles of the quantum field theory require invariance against combined CPT-transformation. The simplest check of the CPT-invariance validity is the equality of masses and life times of particles and their antiparticles. Taking into account the fact that the energy equivalent of the annihilating mass measured in Ref. [12] and in this paper is actually a half-sum of the electron and positron masses and using $m_e c^2$ [11], one can obtains

$$m_{e+} - m_{e-}/m_{e-} = (2.7 \pm 8.3)10^{-6} \tag{10}$$

Similar mass estimations were made for other particles- antiparticles as well [25].

On the other hand, keeping in mind that comparison [25] of anomalous magnetic moments

$$g_{e-} - g_{e+}/g_{e-} = (2.2 \pm 6.4)10^{-11} \tag{11}$$

ensures the most accurate check of CPT-invariance for the electron and the positron, one can consider our result as a new experimental estimation of the electron mass following from (6) and (2)

$$m_e c^2 = 511.0030 \pm 0.0034 keV. \tag{12}$$

6 ADDITIONAL REMARKS

An analysis of our result (6) allows a conclusion that further refining of $m_e c^2$ requires more accurate gamma-quantum energy standards or another more accurate energy measurement technique.

Interesting prospects will open up if one could observe the narrow component of the annihilation radiation by means of the crystal-diffraction gamma-spectrometry. Actually, if the wavelength (λ) of the quanta emitted in the annihilation of the parapositronium at rest could be measured in absolute units, we would have a new model-independent method of determining such a fundamental quantity as the fine structure constant [26].

$$\alpha = \left\{ \frac{2\lambda R_{oo}}{1 + \frac{\lambda R_{oo}}{4}} \right\}^{1/2} \tag{13}$$

(this expression follows from (1) after substitution $h/m_e c = 1/2(\alpha^2/R_{oo})$, where R_{oo} is Rydberg constant).

The high resolving power achieved in two-crystal spectrometers [27] is quite enough for an attempt to find and thoroughly study the narrow component of the annihilation peak using a frozen source of positrons.

Finally, it should be mentioned that last rechecking of the fundamental constants in 1986 [2] resulted in noticeable changes in some values accompanied with a significant reduction in their errors. For instance, these changes led to the following value of the $E_\gamma 411.8 keV(^{198}\mathrm{Hg})$ energy, when recalculating it from the experimental value of $\lambda_{411.8}$ [15], one obtain

$$411.8012 \pm 0.0002 keV, \tag{14}$$

which results in changes in gamma-quantum energies measured with this standard.

That is why we give below the results of this paper recalculated taking into account the (14) energy standard.

For $h\nu$ measured by SCD (6) we obtain

$$h\nu = 510.9950 \pm 0.0027 keV, \tag{15}$$

and for $h\nu$ obtained from Murray's data [12] one gets

$$h\nu = 510.998 \pm 0.006 keV. \tag{16}$$

From the adjustment values of the fundamental constants [2] it follows that

$$h\nu(\mathrm{theor}) = 510.9956 \pm 0.0002 keV. \tag{17}$$

7 CONCLUSION

In this work we have presented a new measurement of the electron mass using the narrow component of the annihilation peak. These measurement led to an improvement in the accuracy by a factor of 2.

Moreover careful measurement of the difference of binding energies in the K and L_3 shells in uranium atom allowed us to reach an accuracy of 0.8 eV for this difference. Taking into account the fundamental constants of 1986, we could establish a new energy standard value for E_γ 411.8 keV in ^{198}Hg decay, using the result of the Kessler's et al. experiment [3]. The reanalysis of the Murray's data with the new standards leads to a good agreement with our data.

If we want to get an accuracy comparable to the "theoretical" ones (adjustment from the fundamental constant, i.e. 0.2 eV) we should gain an order of magnitude in the precision. It is clear, from the sources of errors which are shown in Table 3, that this could be achieved only by use of crystal diffraction methods.

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