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Absolute standardization of carbon-14 by the CIEMAT/NIST method with empirical determination of the Birks parameter

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HIGHLIGHTS

- CIEMAT/NIST method validated for absolute Carbon-14 standardization in LSC.
- Universal calibration curve established using tritium for Carbon-14 efficiency.
- Optimized Birks parameter (kB) achieved a deviation below 2.1% from certified values.
- Method eliminates need for nuclide-specific calibration standards in LSC.
- First national-level application of CIEMAT/NIST for Carbon-14 in toluene cocktails.

ABSTRACT

This study presents the implementation and validation of the CIEMAT/NIST efficiency tracing method for the absolute standardization of Carbon-14 using an ultra-low-level Quantulus 1220 liquid scintillation counter, toluene-based cocktails, and the EFFY-9 code. Due to the absence of a dedicated profile for classical toluene cocktails in the software library, Ultima Gold was used as a substitute. To achieve this, a universal curve was constructed using a series of tritiated standards as a tracer, correlating the instrumental quench index with the model's free parameter. Subsequently, the activity of two certified Carbon-14 standards was computed across a range of Birks parameter (kB) values from 0.004 to 0.014 cm.MeV^{-1}. The results exhibited excellent agreement with certified values, with relative deviations consistently remaining below 2.1%. Detailed analysis indicated that the minimum bias corresponds to kB=0.004 cm.MeV^{-1}. This finding confirms that, in this specific configuration, kB serves as an effective parameter, compensating for the residual mismatch between the actual properties of toluene and the surrogate computational profile. This research emphasizes the necessity of experimentally determining the Birks parameter for each specific laboratory setup to ensure maximum accuracy.

KEYWORDS

Liquid Scintillation Counting
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1 Introduction

Since its introduction by Collier (Kallman, 1950) and Reynolds (Reynolds et al., 1950) in the early 1950s, liquid scintillation counting (LSC) has been recognized as one of the most accurate techniques for the measurement of radionuclides, particularly beta emitters. The method is based on the conversion of the kinetic energy of charged particles into optical photons within a liquid scintillation cocktail, which are then detected. In a typical configuration, the sample dissolved in the cocktail is placed between two photomultiplier tubes (PMTs). By applying a coincidence requirement, pulses from thermal noise are filtered out, allowing only photon signals from radioactive events to be recorded. Early applications, such as carbon14 tracing in biochemical studies (Passmann et al., 1956), or lowlevel tritium measurement using pulseshape discrimination techniques (Horrocks and Studier, 1964), rapidly demonstrated the potential of LSC. However, the main challenge in transforming LSC from a relative counting technique into an absolute standardization method (Gibson and Gale, 1968) was determining how to derive the true activity of a sample from its raw photon counts. The core of this challenge lies in the phenomenon of quenching,

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where part of the deposited energy or generated photons is lost before reaching the detector, thus reducing counting efficiency. Quenching may arise from chemical impurities (chemical quenching) or sample coloration (color quenching), both of which weaken the light intensity and shift the recorded energy spectrum toward lower energies. In the 1960s, J. B. Birks (Birks, 1964) proposed a semiempirical formalism demonstrating that the scintillation response depends nonlinearly on the ionization density of the particle. This effect, known as ionization quenching, is characterized by the Birks parameter (kB) (Horrocks, 1974; LAnnunziata, 2020).

In the late 1970s, researchers at the Spanish Centre for Energy, Environment and Technology (CIEMAT) built upon this theoretical basis to develop a computationaltheoretical model capable of predicting the relationship between counting efficiency and the degree of quenching (Garca Torao, 2023). This model, which later became known as the 'free parameter model' (Grau Malonda, 1999) relies on two key quantities: the Birks parameter (kB), which characterizes the physico-optical properties of the cocktail, and the 'free parameter,' which represents the overall optical-electronic gain of the system and is defined as the mean energy required to produce at least one photoelectron in the PMTs. While this model allowed for the calculation of counting efficiency as a function of the free parameter and the Birks parameter, turning it into a practical method required a clear link between theoretical quantities and measurable laboratory variables. This connection was established through a collaboration between CIEMAT and the U.S. National Institute of Standards and Technology (NIST). The key concept involved using a tracer with a well-known beta spectrum (typically tritium) to map the theoretical space onto the experimental one. The CIEMAT/NIST method consists of four main steps (LAnnunziata, 2020):

1. Experimental calibration of the tracer efficiency (e.g., tritium) as a function of the instrumental quench parameter.
2. Calculation of the theoretical efficiencies for both tritium and the target nuclide (e.g., carbon14) as functions of the free parameter at a given kB value.
3. Construction of a universal curve by combining experimental and theoretical data to map the free parameter directly to the instrumental quench parameter.
4. Determination of the target nuclide counting efficiency using the universal curve and the measured quench level of the sample.

By tracing the quenching behavior of the target nuclide through the universal curve, this approach eliminated the need for nuclide-specific calibration standards, representing a significant advancement in absolute radionuclide standardization using liquid scintillation counting. The choice of tritium as the tracer is driven by three key advantages: its exceptional sensitivity to quenching due to its low beta energy (18.6 keV), its pure beta spectrum, which enhances the reliability of theoretical calculations, and the availability of primary long-lived standards.

Over the past decades, various computational codes have been developed within the CIEMAT/NIST framework for calculating counting efficiency. A comprehensive overview of these developments is provided in Ref. (LAnnunziata, 2020).

The CIEMAT/NIST method has since become a global reference standard in radiation metrology. It has been validated for a wide range of radionuclides from simple pure beta emitters to more complex decay schemes. Numerous intercomparisons with absolute methods such as Triple to Double Coincidence Ratio (TDCR) (implementable on 3PMTs LSC systems) and $4\pi\beta - \gamma$ coincidence counting have confirmed its accuracy and robustness (Broda et al., 2007; Coll, 2009; Kossert et al., 2015; LAnnunziata, 2020). The primary objective of this study is the practical implementation and parametric optimization of the CIEMAT/NIST theoretical model, marking its first application at the national level for the absolute standardization of Carbon-14 in toluene-based cocktails. Since toluene is a classical solvent and most modern computational codes focus on contemporary safety-oriented cocktails, adapting and validating the model for this specific configuration was the main challenge of this research. To address this, an experimental counting efficiency curve was first established using tritium standards as a tracer. Subsequently, theoretical efficiencies for both tritium and Carbon-14 were computed using the EFFY-9 code (Garca Torao, 2023). By constructing a universal calibration curve and performing a sensitivity analysis of the Birks parameter (kB), the activity of Carbon-14 standards was determined and compared to certified values. The results show that, through experimental optimization of kB, a relative deviation of less than 2.1% from certified values can be achieved, confirming both the validity of the system's performance and the robustness of the implemented methodology.

2 Theoretical Basis of the CIEMAT/NIST Model

The computational CIEMAT/NIST model is built upon a detailed simulation of the coupled physical and statistical processes involved in LSC. Its ultimate purpose is to compute the total counting efficiency as a function of a single free parameter that encapsulates all ionization-quenching effects. The methodology can be described in four principal steps:

Step 1 : *From particle energy to scintillation light (detector response function)*

The interaction of beta particles with the scintillator is strongly nonlinear. This nonlinearity, known as ionization quenching is described by Birks' law (Birks, 1964), which relates the light-production rate per unit path length ($\mathrm{d}L/\mathrm{d}x$) to the local ionization density ($\mathrm{d}E/\mathrm{d}x$) according

to Eq. (1):

$$\frac{\mathrm{d}L}{\mathrm{d}x} = \frac{A.\frac{\mathrm{d}E}{\mathrm{d}x}}{1 + kB.\frac{\mathrm{d}E}{\mathrm{d}x}} \quad (1)$$

Here, A is the absolute scintillation yield in the absence of quenching. Integrating Eq. (1) along the full particle track yields the scintillation-equivalent energy $L(E)$ for a beta particle with initial energy E. For computational convenience, $L(E)$ as expressed in Eq. (2) is the product of the initial particle energy and an ionization-quenching function $Q(E)$:

$$L(E) = E.Q(E) \quad (2)$$

where $Q(E)$ is obtained by integrating Birks' law according to Eq. (3):

$$Q(E) = \frac{1}{E}\int_0^E \frac{\mathrm{d}E}{1 + kB.\frac{\mathrm{d}E}{\mathrm{d}x}} \quad (3)$$

In these expressions, kB is Birks' parameter, a purely empirical parameter dependent on the chemical composition and molecular properties of the scintillation cocktail. Accurate calculation of $Q(E)$ is challenged by three main factors: determining the optimal value of kB, uncertainties in electron stopping powers below $\sim$ 1 keV, and the lack of detailed atomic composition data for commercial liquid scintillators.

Step 2: *From scintillation light to photoelectrons (production statistics)*

The generated scintillation energy $L(E)$ must be transported to the PMTs and converted into an electrical signal. All loss mechanisms along this path, including chemical quenching, color quenching, PMT quantum efficiency, and geometrical light-collection efficiency, are consolidated into a single free parameter λ (Grau Malonda and Garca Torao, 1982; Grau Malonda, 1999), defined physically as the mean scintillation energy required to produce one photoelectron at the photocathode of a PMT.

Thus, the mean number of photoelectrons $m(E)$ produced by a particle with energy E is shown by Eq. (4):

$$m(E) = \frac{L(E)}{\lambda} = \frac{E.Q(E)}{\lambda} \quad (4)$$

Since photoelectron emission is a stochastic process, the actual number of photoelectrons in each event follows a Poisson distribution with mean $m(E)$.

Step 3: *From photoelectrons to coincident counts (detection statistics)*

In a liquid scintillation counter equipped with two PMTs, a pulse is recorded only if both PMTs detect at least one photoelectron within the coincidence window. Assuming symmetric light sharing, each PMT receives on average $m(E)/2$.

According to Poisson statistics, the probability that a PMT receives zero photoelectrons is $\exp[-m(E)/2]$, and therefore the probability of detecting at least one is $1-\exp[-m(E)/2]$. Since the two PMTs operate independently, the coincidence-detection probability P_{12} can be expressed by Eq. (5):

$$P_{12} = \left[1 - \exp(-\frac{m}{2})\right]^2 = \left[1 - \exp(-\frac{E.Q(E)}{2\lambda})\right]^2 \quad (5)$$

Step 4: *From detection probability to total counting efficiency (decay physics)*

The total counting efficiency for a radionuclide is the spectrum-weighted average of the coincidence probability over its beta-emission energy distribution. Substituting Eq. (5) into the spectral integral yields the final expression as Eq. (6) for a two-PMT system (Garca Torao, 2023; LAnnunziata, 2020):

$$\begin{aligned}\varepsilon(\lambda) &= \int_0^{E_{max}} N(e).P_{12}\mathrm{d}E \\ &= \int_0^{E_{max}} N(e).\left[1 - \exp(-\frac{E.Q(E)}{2\lambda})\right]^2 \mathrm{d}E\end{aligned} \quad (6)$$

The accuracy of the model critically depends on the precision of the theoretical beta spectrum $N(E)$, which must incorporate all relevant nuclear and atomic corrections, including the Fermi function, shape factors, finite-size effects, screening, and exchange effects. Such spectra are typically generated using evaluated nuclear data combined with advanced computational beta-spectrum codes.

3 Methods and Materials

All measurements were performed using a PerkinElmer Wallac Quantulus 1220, a low-level liquid scintillation spectrometer. This instrument, equipped with two PMTs, is specifically designed for high-sensitivity, low-level background measurements. The counting window was configured to ensure the complete registration of all pulses originating from the beta decay spectrum. The system employs an external Eu-152 standard source to determine the Spectral quench parameter (SQP(E)). This quantitative index reflects the displacement observed in the external standards Compton spectrum and provides a precise metric for evaluating the quench level in each sample. A classical set of quenched tritium standards, model NES-203 (Lot: S203010-17, DuPont), was used as the tracer. This set consists of ten 20-mL glass vials, each containing 15 mL of a toluene-based scintillation cocktail (5 g.L^{-1} PPO and 250 mg.L^{-1} POPOP) with identical tritium activity. Varying quench levels were generated by adding progressively increasing amounts of nitromethane. Tritium was chosen because the low-energy, pure beta spectrum exhibits high sensitivity to quenching phenomena and is traceable to the NIST standard (SRM 4947C). The decay-corrected activity of this set at the time of measurement was calculated to be 34,180.75 DPM per vial, with an expanded uncertainty ($k = 2$) of 1.95%.

For model validation, a Carbon-14 standard set, model NES-202 (Lot: S202006-15, DuPont), was utilized. This selection ensured compliance with the model's key prerequisite, namely the constancy of the Birks parameter (kB), because the tracer and target sets are chemically identical and were prepared in the same scintillation matrix (toluene/PPO/POPOP with nitro methane as the

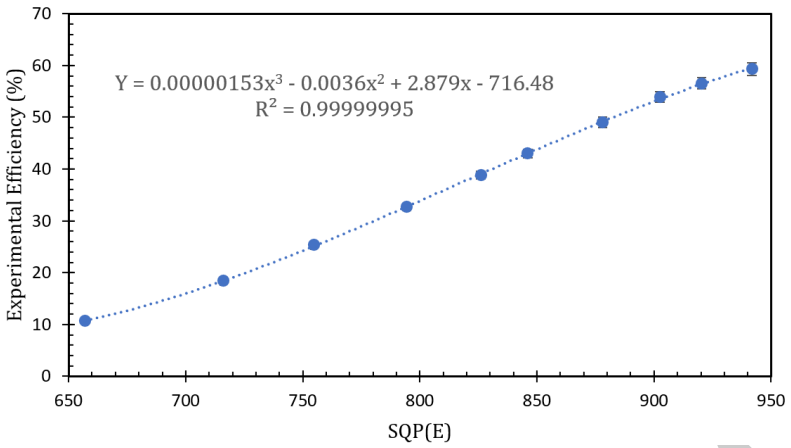

Figure 1: Experimental counting efficiency plot for quenched tritium standards versus the instrumental quench parameter (SQP(E)). The 3rd-order polynomial fit shows outstanding agreement with the experimental data.

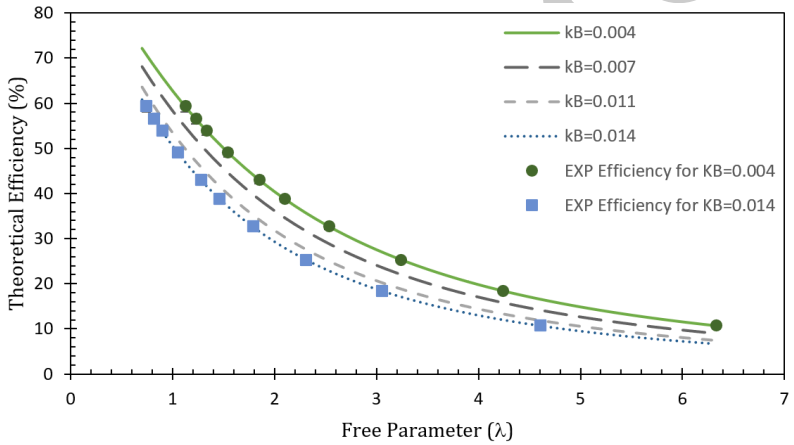

Figure 2: Theoretical tritium counting efficiency curves as a function of the model's free parameter for various Birks parameter (kB). Solid points represent experimental efficiency values for kB=0.004 and 0.014.

quencher). The decay-corrected activity of these samples was determined to be 99,583.90 DPM ($k = 2, 1.98\%$) based on a half-life of 5730 years. The counting time for all samples was set to 60 minutes to reduce the statistical counting uncertainty to below 1%.

Theoretical counting efficiencies were computed using the EFFY-9 code (Garca Torao, 2023)), developed at CIEMAT's Metrology of Radionuclides Laboratory. This code implements a physical model based on electron stopping power and Birks' law for ionization quenching. In this version of the program, beta spectra are calculated following the standard beta-decay formalism, including the Fermi function, finite nuclear size correction, transition shape factors, outer radiative corrections, atomic screening, and, when applicable, atomic exchange corrections. Due to the absence of a dedicated library profile for the classical Toluene solvent in EFFY-9, the modern Ultima Gold profile was selected as a surrogate. This choice was based on the similarity in their aromatic structure and effective Z/A ratio, which is a key parameter governing beta particle interactions. To ensure accuracy and reproducibility, a data-driven computational framework based on fitting and linear interpolation was implemented using the Python programming language, utilizing the NumPy library for numerical computations and Pandas for data management.

Measurement uncertainty was evaluated according to the GUM framework (IEC et al., 1995). Sources of uncertainty, including statistical counting components, calibration source activity certificates, modeling parameters, and systematic sample preparation errors, were identified and incorporated into the uncertainty budget. Finally, results are reported as expanded uncertainty with a coverage factor of $k = 2$ (95% confidence level).

4 Results and Discussion

4.1 System Calibration with Tritium Tracer and Universal Curve Extractionn

In the initial phase, the experimental counting efficiency (ε_{EXP}) for the quenched tritium standards was measured as a function of the instrument's quench-indicating parameter, SQP(E). The standards covered a wide range of quench levels, from 657 for the most highly quenched sample to 942 for the least quenched sample. As illustrated in Fig. 1, a continuous and smooth relationship is observed between the experimental efficiency and SQP(E), which is

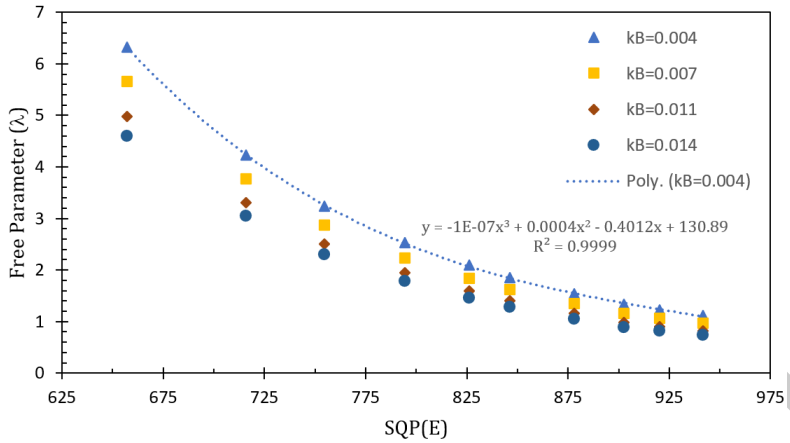

Figure 3: Universal curves establish the critical link between the model's free parameter and the measurable instrumental quench index. A 3rd-order polynomial fit provides the best and most stable model for constructing this bridge.

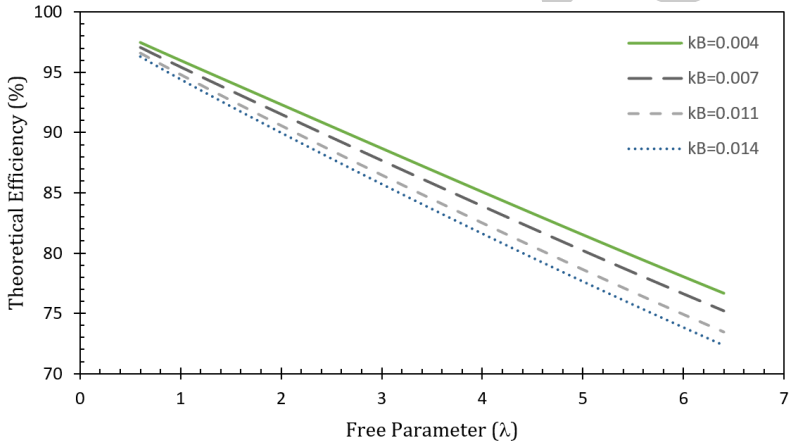

Figure 4: Theoretical counting efficiency curves for Carbon-14 as a function of the models free parameter, calculated for various Birks parameter (kB).

well described by a third-order polynomial regression.

Subsequently, utilizing the EFFY 9 computational code, the theoretical counting efficiency of tritium (ε_{Th}) was calculated as a function of the free parameter (λ) for various Birks parameters (kB) values ranging from 0.004 to 0.014 cm.MeV^{-1}. The final range for the free parameter λ was selected based on the experimental efficiency range of tritium (10% to 60%). The results of these calculations, presented in Fig. 2, reveal a family of theoretical efficiency curves for different kB values.

After determining the experimental tritium efficiency versus instrumental quench and calculating the theoretical efficiencies as a function of the free parameter λ for different kB values, the next step was to correlate the two datasets. For each SQP(E) value, the corresponding experimental efficiency was first extracted from the polynomial fit. This value was then compared against the theoretical tritium curves, and using linear interpolation on the theoretical outputs, the corresponding λ value for that specific SQP(E) was numerically determined. Repeating this process for all quench points produced a set of universal curves of λ_{kB} versus SQP(E), as shown in Fig. 3.

These curves, forming the cornerstone of the CIEMAT/NIST method in this study, provide a nuclide-independent mapping from the measurable quench index SQP(E) to the models free parameter λ. As observed in Fig. 3, in low-quench regions, the lines corresponding to different kB values nearly overlap; however, as quenching increases, the divergence between them grows, indicating an increased sensitivity of the λ−SQP(E) relationship to the kB value.

4.2 Model Validation and Empirical Determination of the Birks parameter (kB)

To validate the model, the results were applied to determine the activity of two Carbon-14 standard samples. First, the theoretical counting efficiency of C-14 was calculated as a function of the free parameter (λ) for all kB values (Fig. 4). Subsequently, for any given SQP(E) of a C-14 sample at an assumed kB, the corresponding λ was extracted via linear interpolation from the universal function. Using this λ, the quench-equivalent theoretical counting efficiency for C-14 was computed. The output of this two-stage process is a family of operational calibration curves, each predicting C-14 counting efficiency directly from SQP(E) for a specific kB, as displayed in Fig.

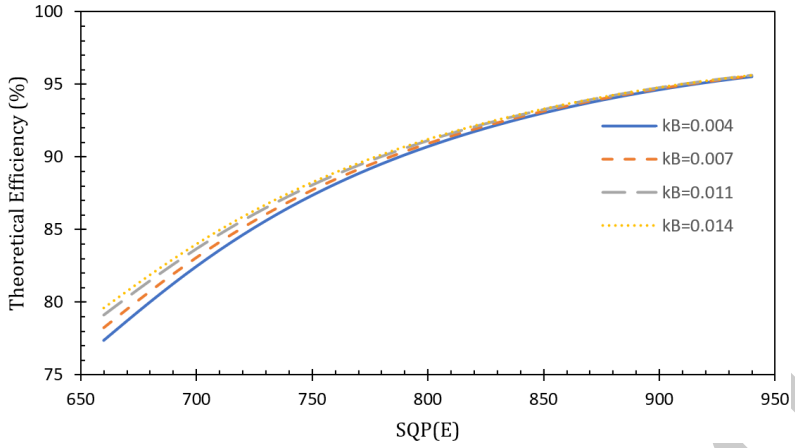

Figure 5: Final calibration curves for Carbon-14, predicting counting efficiency directly based on the measurable parameter SQP(E) in the range of 660 to 940.

Table 1: Comparison of calculated and nominal activities of Carbon-14 standard samples for various Birks parameter (kB).

SQP(E)	Count Rate (CPM)	kB	Calculated Efficiency (%)	Calculated Activity (DPM)	Relative Error (%)
935 ± 4	93,474.12 ± 93.48	0.004	95.40	97,984.22 ± 1,998.88	1.61
		0.007	95.44	97,936.30 ± 1,988.11	1.65
		0.009	95.46	97,915.08 ± 1,987.68	1.68
		0.011	95.48	97,900.28 ± 1,987.38	1.69
		0.014	95.50	97,878.84 ± 1,986.94	1.71
879 ± 4	91,705.08 ± 91.70	0.004	93.88	97,553.08 ± 1,999.84	2.04
		0.007	93.78	97,465.86 ± 1,998.05	2.13
		0.009	93.71	97,422.64 ± 1,987.42	2.17
		0.011	93.67	97,389.94 ± 1,986.75	2.20
		0.014	93.61	97,348.11 ± 1,985.90	2.25

5. These curves represent the final tool for standardizing unknown C-14 samples without the need for a nuclide-specific standard. The transferability of this method is based on a key assumption of the CIEMAT/NIST model, namely that a single Birks parameter kB applies to both the tracer (Tritium) and the target nuclide (Carbon-14) for the experimental configuration under study. This condition is fulfilled here through the use of chemically identical scintillation cocktails. Furthermore, while variations in vial material or sample volume affect optical photon transport, the CIEMAT/NIST methodology remains robust as these physical effects are effectively absorbed into the experimental tritium quench calibration curve for each specific setup.

To determine the optimal experimental Birks parameter (kB), two Carbon-14 standard samples with identical decay-corrected activities but different quench levels (SQP(E) of 879 and 935) were counted. Utilizing the final calibration curves (Fig. 5), the activity of each sample was calculated based on its experimental count rate across a computational range of kB (0.004 to 0.014 cm.MeV^{-1}). The results are presented in Table 1. Analysis indicates that the relative error (bias) between the calculated activity and the certified standard value ($99,583.90 \pm 1,971.76$ DPM) remains below 2.3% for all kB values. Given the standard's expanded uncertainty (1.98%), this level of accuracy demonstrates the models highly satisfactory performance in efficiency prediction. Examination of the relative error behavior across the computational range reveals that as kB decreases, the relative error for both samples continuously decline, reaching a minimum at kB=0.004 cm.MeV^{-1}. This optimal value is significantly lower than values reported in the literature for Toluene (kB ≈0.007 (Horrocks and Studier, 1964)) and Ultima Gold (kB ≈0.012 (Colle et al., 2008)). This behavior is mainly attributed to the use of Ultima Gold in the EFFY software as a surrogate for Toluene, with additional systemdependent factors potentially contributing. Although Toluene and Ultima Gold differ in density and hydrogen-to-carbon ratio, causing variations in electron stopping power calculations, this systematic shift affects both the tritium standard and the carbon-14 sample equally. As a result, the kB parameter optimization effectively compensates for these differences. By adjusting the kB value, the mathematical model tunes the efficiency curve to match the experimental Tritium data. In this context, the parameter kB transcends its intrinsic physical definition and transforms into an "Effective Parameter" that absorbs the mismatch between the computational model and the actual sample. This effective parameter integrates the system's overall response, including the true ionization quenching of toluene, deviations caused by the surrogate cocktail profile, the optical response of the Quantulus 1220, and minor effects such as vial optical characteristics. Ultimately, the results suggest that for maximum accuracy, the empirical determination of kB for each specific configuration (counting system, cocktail, and software) is essential, offering a significant advantage over

Table 2: Uncertainty Budget for the determination of Carbon-14 standard activity (SQP(E)=879).

Uncertainty Component	Value (x_i)	Standard Uncertainty $u(x_i)$	Type	Sensitivity Coefficient (c_i)	Uncertainty Contribution $u_i(y)$	Relative Share (%)
Tracer Standard Activity	34100 DPM	332.48 DPM	B	2.87	955.08	91.1
Fitting & Mapping Model	0.940	0.003	B	-104,65	293.85	8.6
Net Count Rate	91705.08 CPM	45.85 CPM	A	1.068	48.98	0.2
Quench Parameter SQP(E)	878.99	1.85	B	7.40	13.69	<0.1
Combined Standard Uncertainty (u_c)	-	-	-	-	991.21 DPM	-
Expanded Uncertainty ($k = 2$)	-	-	-	-	1998.42 DPM (2.04%)	-
Final Calculated Activity	-	-	-	-	97,961.90 ± 2,001.41 DPM	-

sole reliance on theoretical or literature-reported values.

To quantitatively assess the contribution of each error source to the final uncertainty, a comprehensive uncertainty budget based on the GUM guide (IEC et al., 1995) was prepared for the higher-quench sample (SQP(E)=879) at kB=0.004 cm.MeV^{-1}. The results are detailed in Table 2.

Analysis of the uncertainty budget reveals several key points. The dominant contribution to the combined uncertainty, exceeding 91%, arises from the uncertainty associated with the certified Tritium tracer standard. This behavior is fully expected in efficiency-tracing approaches and indicates that the overall accuracy of the method is primarily governed by the quality of the primary calibration standard. In contrast, the statistical counting uncertainty, owing to the extended counting time (60 minutes), contributes negligibly ($< 0.2\%$), supporting the adequacy of the adopted measurement protocol. Finally, the calculated expanded uncertainty of 2.05% is in close agreement with the certified uncertainty of the Carbon-14 standard (1.98%), thereby confirming the internal consistency and metrological reliability of the measurement and analysis procedure.

5 Conclusions

This investigation provides a rigorous implementation and validation of the CIEMAT/NIST efficiency-tracing method for the absolute standardization of Carbon-14 in classical toluene-based scintillation cocktails. By combining high-precision experimental measurements with advanced computational modeling using the EFFY-9 code, this study shows that accurate and metrologically traceable activity determination is possible even without a dedicated solvent profile in the computational framework. Through the construction of a robust experimental quenchefficiency relationship for tritium and the generation of theoretical efficiency curves over a wide range of Birks parameter, a set of universal calibration functions was established, enabling a direct and nuclide-independent mapping between the instrumental quench parameter and the models free parameter. Application of these universal functions to Carbon-14 standards yielded activities exhibiting relative deviations consistently below 2.1% across all evaluated kB values, thereby confirming the internal consistency and predictive capability of the implemented methodology.

A key outcome of this work is the empirical identification of $kB = 0.004$ cm.MeV^{-1} as the optimal effective Birks parameter for the specific configuration employed (toluene scintillator, Quantulus 1220 counter, Ultima Gold surrogate model). The systematic reduction in bias at lower kB values reflects the role of the Birks parameter as an effective compensatory quantity, absorbing discrepancies arising from differences between the true physical properties of toluene and those encoded in the surrogate computational profile. This observation reinforces a central principle in liquid scintillation metrology: the Birks parameter, in practical applications, operates as an effective system parameter incorporating ionization quenching, optical transport behavior, detector response characteristics, and modelmedium mismatches. The uncertainty budget constructed in accordance with the GUM guidelines further substantiates the validity of the approach. The dominant contribution, exceeding 91%, originates from the activity uncertainty of the tritium primary standard, while statistical and instrumental components contribute negligibly due to the long counting times and stable system performance. The resulting expanded uncertainty of 2.05% ($k = 2$) is fully consistent with the certified uncertainty of the Carbon-14 standard, thereby confirming the metrological reliability of the adopted method.

Overall, this study reveals that:

1. The CIEMAT/NIST method is fully applicable to traditional aromatic solvents, such as toluene, when accompanied by empirical optimization of the quenching parameter.

2. The EFFY-9 computational model, despite relying on a surrogate solvent profile, is capable of producing highly accurate efficiency predictions under an appropriately determined effective kB.

3. Experimentally derived kB values provide a superior basis for accurate standardization compared to literature-derived constants, particularly for nonstandard cocktails or legacy counting systems.

These findings provide a validated, operational framework for the standardization of beta-emitting radionuclides in classical scintillation matrices and can serve as a foundation for future extensions involving additional radionuclides, cross-validation via TDCR and $4\pi\beta-\gamma$ coinci-

dence methods, and the development of dedicated physical profiles for legacy scintillation solvents.

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Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work.

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