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MONTE CARLO SIMULATION OF A DIGITAL COINCIDENCE SYSTEM APPLIED TO ^{60}Co STANDARDIZATION

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ABSTRACT

The Laboratório de Metrologia Nuclear (LMN) at the Instituto de Pesquisas Energéticas e Nucleares (IPEN) is developing a Digital Coincidence System (DCS), including the design of the proper acquisition electronics and analysis software. A brief discussion about the measurement methodology and the electronics operation is presented. This work is focused on the results of the designed software (the Monte Carlo simulation of ^{60}Co decay data and the Coincidence Data Analysis), which are in good agreement with the experimental data.

1. INTRODUCTION

The $4\pi\beta-\gamma$ coincidence absolute activity counting method is widely used in Nuclear Metrology, for radionuclide standardization. The Laboratório de Metrologia Nuclear (LMN) of Instituto de Pesquisas Energéticas e Nucleares (IPEN) is equipped with three systems of this type, two of then consist of proportional gas counters (beta channel) and NaI(Tl) scintillation detectors (gamma channel). In one of these systems, the $4\pi\beta$ detector can operate up to 1.0 MPa gas pressure. The third coincidence system uses a plastic scintillation detector in place of the $4\pi\beta$ proportional counter. A conventional associated electronics incorporates a Time to Amplitude Converter (TAC) and a Multi Channel Analyzer (MCA) for registering beta, gamma and coincidence events. The radionuclide sample activity determination is accomplished by the Efficiency Linear Extrapolation technique [1].

In order to improve these $4\pi\beta-\gamma$ coincidence systems, LMN is developing a Digital Coincidence System (DCS), including the design of the proper electronics for data acquisition and recording, as well as special software, for hardware control and data analysis. The DCS design is based on a recent methodology, known as Digital Coincidence Counting or Software Coincidence Counting [2,3]. Differently of the referenced systems, DCS digitizes only the pulse amplitude (height), instead of the entire pulse shape. With this approach, very lower sample rates can be used.

The radioactive sample activity is determined in two steps:
- Data Acquisition: the nuclear pulses (beta, gamma etc.) are digitized and recorded on disk;
- Analysis: the beta, gamma and coincidence counting are determined from recorded data.

Some system parameters (such as delays and time fluctuations) can be set into the analysis program, providing a software adjusting capability. Thus, any system changing can be matched by the proper parameter setting, in the Analysis step.

When the Efficiency Linear Extrapolation method is used, normally, many measurements are required, setting different beta detector efficiencies. In some cases, the efficiency setting is reached by changing the beta detection threshold level. With the proposed system, the extrapolation curve can be obtained from a single measurement, by software emulation (v. item 3.2). In addition, different extrapolation curves can be obtained, for different gamma energy ranges. Conventional modules (discriminators, TAC and MCA) are not needed.

2. DIGITAL COINCIDENCE SYSTEM (DCS)

DCS consists of: Nuclear Detection Electronics (NDE), Data Acquisition Electronics (DAE) and Personal Computer (PC). The block diagram of DCS electronics is shown in Fig. 1:

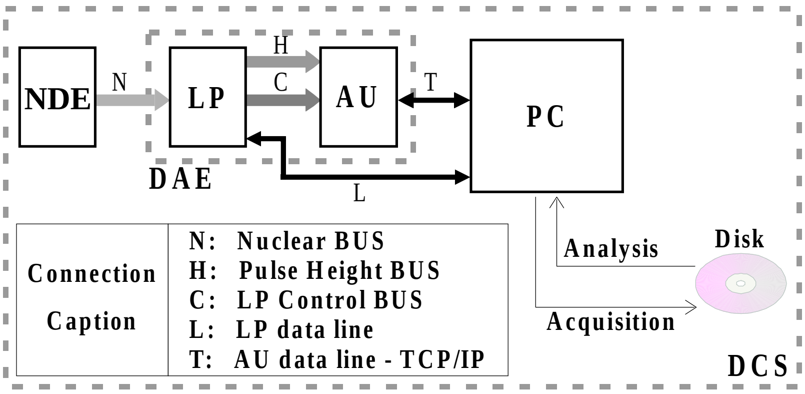

Figure 1. Digital Coincidence System Block diagram.

NDE is composed of radiation detectors and includes biasing, pulse shaping and amplification. A detector output (detection channel) is a BUS line of the Nuclear BUS (N).

DAE is composed by the Local Processor (LP) and the Analog Unit (AU):

- LP, under development at LMN, is based on microprocessor techniques. The main time module and the Channel modules (1 per detector) will constitute the LP section:
  - Time Base Unit (TBU), for the DAE real time counting, including:
    - 2MHz Oscillator (OSC), the DAE time mark (0.5μs);
    - real time, 5 Bytes, free running counter, or Chronometer (CHR).
  - Channel modules, for the pulse height and instant registering, including:
    - Peak Detection (PD), for the logic DAE controlling (the LP Control BUS: C);
    - Sample & Hold (S&H), for pulse height sampling (the Pulse Height BUS: H);
    - Live Time Counter (LTC), 5 Bytes, binary counter, with clock inhibit control.
- AU, a commercial module [4] provides:
  - 16 independent analog inputs (at 20k samples per second maximum rate);
  - 12 bits Analog to Digital Converter (ADC);
  - data buffering and transferring, via TCP/IP (line T in Fig. 1).

PC, Personal Computer (IBM compatible), running under Windows or LINUX OS, executes the final data saving (into CDF, item 2.2) and the coincidence analysis (CDA, item 3.2).

2.1. DCS Operation Overview

All the NDE signal cables, from up to 16 detectors, are connected to their respective Channel modules. LMN conventional systems are composed by 3 detectors, 1 for the beta Channel, and 2 for the gamma Channel. Each Channel is associated to an AU input (here, also called Channel, and software identified by hexadecimal digits from 0 to F, the Channel Id numbers). Virtually, more then one NA could be connected, simultaneously, to DAE.

At DCS starting, all the LP time counters are reset to zero. The measurement parameters (such as description, total time, etc.) can be set in the acquisition user interface (at PC). At Start Command, time counting begins. Arriving pulses trigger the PD circuitry, leading to:
- the pulse heights sampling (S&H); height DC levels available at Pulse Height BUS (H);
- the H levels binary converting, by the AU (ADC), into a 2 Bytes field;
- the copying of CHR (5 Bytes) to the proper pulse instant field (LP memory locations);
- the LTC gating, for the live time computing.

Pulse data blocks are sent from DAE (via L and, T) to the PC. During a pulse processing interval, a new incoming pulse is neglected and the respective LTC counting is inhibited (to be again enabled at the end of the process). At the end of acquisition, the LTC contents correspond to the Channel live times, necessary to the actual Channel pulse rates calculation.

2.2. Coincidence Data Files

As described, software coincidence counting is performed in two steps:
- Registering of all the pulse data (heights and respective occurrence instants);
- Data analyzing (determination of all Channel and coincidence counting).

The two fields (item 2.1), height (2B) and instant (5B), constitute a data registry (7B). The registries, coming from a given Channel, are saved into the correspondent Channel Files. A Channel File encloses a number of registries (depending on the Channel pulse rate) of a given acquisition interval. All the Channel Files (for the complete acquisition time) constitute the Channel Data Base. At last, the whole of the Channel Data Base composes the Coincidence Data Files (CDF). The Channel File names embed information about the files themselves and about the respective acquisition. For example, **bF300405.00A** indicates, in sequence:
- **bF**: beta Channel File from the beta detector connected to DAE Channel number F (v. 2.1);
- **300405**: acquisition date (in ddmmyy format);
- **00A**: the eleventh file (file Id number, ranging from 000 to FFF, hexadecimal).

3. SOFTWARE DESCRIPTION

Two programs were written at LMN, using the C++ language:
- ^{60}Co decay Monte Carlo data simulation (for CDF emulation).
- Coincidence Data Analysis (CDA), the main program, based on the analysis algorithm.

3.1. Monte Carlo Data Simulation Program

At present, the CDF are emulated by software. From experimental data files (beta and gamma pulse height spectra, from MCA, and coincidence spectrum, from TAC, obtained from a ^{60}Co radionuclide conventional measurement), the program determines all the probabilities used in the simulation (beta and gamma detection probabilities, or efficiencies; beta and gamma pulse height probabilities; beta-gamma time jitter). The sample activity (A) and the total acquisition time (T) are supplied by the user. A Channel File emulates 60s of acquisition time (60 Channel Files are generated per Channel, per hour of simulation).

The first simulation step is to define the decay instants for ^{60}Co radionuclide, attaining the time intervals between two consecutive events following the Poisson distribution:

$$t = -(1/A)\log(R) \tag{1}$$

A is the sample activity; log(R) is the natural logarithm of a given random number R, ranging from 0.0 (exclusive) to 1.0 (inclusive); t is the probable time interval, from the last decay.

For a given decay instant, the program takes decisions on beta and gamma event detection, using the data from experimental spectra (by a random number indexing). If an event is detected (beta or gamma), a new random number defines the respective pulse height. The detected gamma pulse instant is made equal to the decay instant. For a detected beta, another random number defines the time jitter to be added to the decay instant for the beta pulse instant attaining. Time jitter ranges, approximately, from 1.0 to 3.0μs. The pulse heights and instants of detected events are then saved into the respective Channel File (as explained above).

3.2. Coincidence Data Analysis Program

The main purpose of this work, the implementation of a coincidence analysis algorithm (the basis for the CDA program), is now discussed. By reading the data from the beta/gamma pair files (CDF, item 2.2), CDA program searches for the coincident pair instants, taking into account the beta-gamma time jitter (in real cases, that jitter depends on the electronics delays and time fluctuations). Then, CDA determines the beta, gamma and the coincidence total counting, respectively N_β, N_γ, and N_c, used to the sample activity (A) determination, for a given acquisition time (T):

$$A = (N_\beta N_\gamma / N_c)/T \tag{2}$$

CDA program can neglect a narrow range at the beginning of the beta spectrum (the lower height beta events). Thus, different beta detection efficiency values can result from analysis of the same CDF set, by slightly changing the neglecting range (v. item 4.2). In this way, a first approach for the beta efficiency changing was included in the program.

4. SOFTWARE RESULTS

Many tests were performed for software evaluation. Different sample activities and acquisition times were simulated with very satisfactory results. A special simulation was performed, in order to reproduce the conventional system measurement conditions (T = 4000s; A = 2616.48Bq - ^{60}Co radionuclide). In this case, a software obtained activity value matching to the experimental one is expected. The comparison between measurement and software results are presented in the following sections.

4.1. Data Simulation Program Results

The simulated CDF comprises 67 beta/gamma pair files, which are the most significant simulation output. However, their binary contents do not represent a good way to show results. The program, in addition, generates other related files, such as the beta and gamma pulse height spectra, and beta-gamma delay distribution, as showed in Fig. 2. The consistence of the simulated CDF is described in the item 4.2.

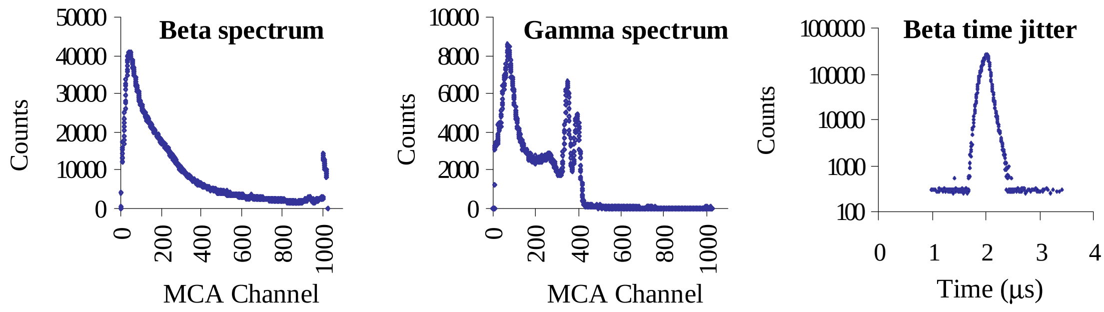

Figure 2. Simulated beta and gamma spectra and beta-gamma time distribution (jitter).

The experimental spectra are very similar to those in Fig. 2 and were not showed. The beta spectrum does not represent the real beta emission energy, since the higher energy particles lose a large part of their energies in detector wall collisions. The final region of beta spectrum is due to the saturated pulses. The beta time jitter corresponds to the TAC coincidence region.

4.2. Analysis Program Results

The CDF (emulated data, item 4.1) constitute a useful data base for the CDA program testing. Eighteen of the performed analyses are presented, corresponding to a beta efficiency changing emulation. The obtained activities, versus beta inefficiency, are plotted in Fig. 3 (the error bars represent the relative errors between the points):

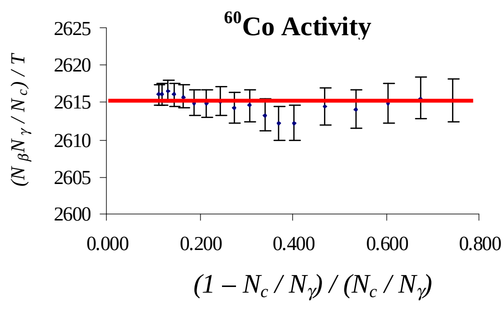

Figure 3. ^{60}Co sample activity versus beta inefficiency.

The extrapolation method is particularly useful in radionuclide standardization involving a significant Internal Conversion (IC) coefficient. At present, simulation program does not consider this effect, since IC is not significant for ^{60}Co. In this case, the linear extrapolation is not necessary and the fitting of a constant value is sufficient (the red line in Fig. 3; value reproduced below with the respective uncertainty for 95% of confidence):

- Constant fitting: 2615.2 ± 1.4 Bq; (0.054% uncertainty).

The beta inefficiency (Fig. 3) ranges from 0.11 to 0.74 and the difference between the minimum and maximum activity values is only 4.33Bq (0.17% on the fitted constant). When IC is not significant, the activity value can be obtained from a single measurement, for the maximum beta counting efficiency (the linear extrapolation is not necessary, as explained above). This measurement (the Analysis program output) corresponds to the very left point of the graph (Fig. 3) and must match the simulation program input value (here called *Experimental/Simulated*, since the input value was forced to be equal to the experimental obtained value, as explained in the item 4). These values are confronted below:

- Experimental/Simulated: 2616.5 ± 2.1 Bq; (0.080% uncertainty);
- Analysis program output: 2616.0 ± 2.2 Bq; (0.084% uncertainty).

All the values shown above are in very good agreement within the uncertainties.

5. CONCLUSIONS

Since no special software tools have been used for Monte Carlo simulation neither for number randomizing, the simulation and analysis programs, testing and results can be considered satisfactory. The comparison between experimental and software obtained ^{60}Co sample activities, results in a maximum difference around 0.09%. The developed coincidence analysis basis algorithm was considered approved. New features will be now implemented, such as the Internal Conversion phenomenon and Background data simulation, aiming at more realistic testing and software improvement, providing the necessary base for the subsequent project phase: the evaluation of the Digital Acquisition Electronics circuitry, and real data collecting and analyzing.

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