IONIZING RADIATION MEASUREMENTS

A DIGITAL COINCIDENCE METHOD

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A digital coincidence method is described in which the amplitude is digitized and the time of each pulse from the ionizing radiation detectors is recorded. The features of the processing of the digital amplitude-time measurement data are described in detail. It is shown that the digital coincidence method has a time resolution defined solely by the resolving power of the detectors.

Key words: digital coincidence method, coincidence spectrum, digital data processing, measurement of radionuclide activity.

The coincidence method is one of the fundamental methods in experimental nuclear physics. It enables one to distinguish events recorded by detectors “simultaneously,” i.e., which lie within a certain resolving time. The coincidence method is widely used in investigations of radionuclide decay schemes, neutron physics, in research on nuclear reactions, etc. [1]. The coincidence method plays a particular role in the metrology of radionuclides. Systems which employ the coincidence method are the basis of many national standards [2].

At present, coincidences between pulses, arriving from detectors, are determined using analog modules, which include single-channel analyzers, delay lines, a coincidence unit, scalers, etc. The present level of development of digital and computer techniques enables the amplitude and time of appearance of each pulse arriving from the detectors to be measured with subsequent conversion of the results of the measurements into digital code, which are then written into the memory of a personal computer. The stored data can then be analyzed for the presence of coincidences. The result obtained depends less on the stability and reproducibility of the parameters of the electronics, since many analog modules become unnecessary. Moreover, the data stored on a hard disk has a primary form, which enables different methods of statistical processing to be employed and compared.

The digital coincidence method is relatively new and we know of only a small number of publications on this subject. A system is described in [3] which processes in real time the results of measurements of voltages carried out using an analog-to-digital converter with a clock frequency of the timer of 20 MHz. Because of the large volume of data obtained, this system is a fairly complex software-hardware system. The system described in [4] is a simpler hardware realization of the digital coincidence method and consists of two independent analog-to-digital converters, a timer with a frequency of 10 MHz, and a 40 Mbyte SRAM memory.

A review of the use of digital coincidence methods in the metrology of radionuclides can be found in [5].

Below we describe a software-hardware realization of the digital coincidence method. Considerable attention is devoted to the collection of the measurement data by the computer and its subsequent processing, since these are fundamental in the digital method.
The two-input measurement module is a circuit board, inserted in the ISA port of an ordinary IBM/PC compatible computer. Two independent 10-bit peak analog-to-digital converters (having 1024 channels) are mounted on the circuit board, together with a two-measurement buffer (one per input) and a timer with a sampling error of 20 nsec (a calibrated generator at 50 MHz). When a pulse arrives at any of the inputs, the circuit board records its amplitude and time in the buffer and generates an interrupt signal to the computer IRQ. The time the signal arrives at the module is measured from the beginning of the measurements and is recorded with respect to its excess over the minimum threshold level of 50 mV. Note that the analog-to-digital converter circuits are independent with respect to both inputs of the circuit board, while the presence of a single timer enables time measurements to be made at both inputs on a single scale.

We used a computer with a Celeron processor with a clock frequency of 366 MHz and a 128 Mbyte SDRAM random access memory. We must emphasize that our measurement module imposes no special requirements on the computer.

The Collection of Measurement Data. To control the system and to collect data, we wrote a program DigiRec, which processes the interruption and writes the data obtained into the RAM, and then onto a hard disk. The specific feature of the program was the need to ensure minimum delays when processing interruptions.

We chose the Borland Pascal 7.0 language as the programming language and means of processing. On the one hand, this compiler enables one to make insertions into the machine codes and on the assembler (which enables one to write a machine-oriented fast code), and on the other enables one to create a protected mode code (which enables one to use all the accessible RAM in a rational manner).

The basis of the DigiRec program is the processing of apparatus interruptions, generated by the system. Produced in a symmetrical circuit, they operate independently of one another, each expecting its own interruption, corresponding to the recording of a pulse by the measurement module. As soon as an interruption occurs, the corresponding processor reads out the codes indicating the times of arrival and amplitudes of a pulse from the buffer registers of the system and, without any additional processing, writes them in the predistributed RAM. A text file with the results of an experiment is formed from the results of measurements.

The DigiRec program operates in OS DOS. This enables the time taken to transfer data from the internal buffers of the circuit board, which is a component part of the dead time of the system, to be minimized. Two versions of the compilation and operation of the program were used:

1) Compilation into the protected mode program. Here the program can only operate with the manager DPMI (the DOS Protected Mode Interface) and is able to address the entire accessible RAM directly. In our case, this amounts to 128 Mbyte, which corresponds to approximately 6,552,000 measurements, since the data on each pulse occupies 8 bytes. Large operations are carried out in the protected mode when processing interruptions, which gives rise to a long dead time of the system in this mode.

2) Compilation in the real mode program. In the real time mode program, one cannot directly circulate to the RAM above an address of 1024 kbytes, and hence the maximum number of measurements processed by the program in this mode is approximately 72,000. However, the rate of processing interruptions and circulations to the memory in this mode is a maximum, due to the shorter dead time. To start the program in this mode, one uses “pure” loading of the DOS, since certain drivers (for example, the emm386.exe) considerably increase the processing time.

The dead time is one of the main parameters of systems which realize the coincidence method [6]. Since, during the time the data is being collected the module and the computer operate in a single system, the dead time is made up of two components: the hardware dead time, governed by the operating time of the analog-to-digital converter, delays in generating the controlling interruption signals, etc., and the software dead time, due to the operation of the computer in the DigiRec program during the data collection process. The dead time was measured by a generator of double pulses and special programs.

Measurements by the generator of double pulses enabled us to determine the total software-hardware dead time. In order to calculate the software component of the dead time of both versions of the DiriRec program, we wrote a test program which measures the time taken to process one million interrupt procedures. Moreover, a series of measurements with programs that a functionally identical to the DiriRec measuring program, but with double and triple procedures for processing interruptions, enabled us to refine the hardware component of the dead time. The standard uncertainty of the measurements was calculated as described in [7]. The results are presented in Table 1.
TABLE 1. Components of the Dead Time

<table>
<thead>
<tr>
<th>Component</th>
<th>Value of the dead time for different modes of operation of the computers, μsec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>real mode</td>
</tr>
<tr>
<td>Total</td>
<td>16.8 ± 0.1</td>
</tr>
<tr>
<td>Software</td>
<td>9.3 ± 0.1</td>
</tr>
<tr>
<td>Hardware</td>
<td>7.7 ± 0.7</td>
</tr>
</tbody>
</table>

Fig. 1. Data processing algorithm.
The Algorithm for Processing the Measurement Data. To process the amplitude-time data written onto the hard disk of the computer, we wrote an interactive OpenTable program in the MathCAD medium. The OpenTable program processes files of data prepared by the DigiRec program. In the preliminary scanning mode, the user can “cut out” any subrange of data or compile a new table of previously chosen parts. The table obtained is split by the program into two data matrices, corresponding to measurements at the inputs. The data are then processed by filters, which can conveniently be split into two groups: for processing data arriving from the detectors, and for programming the coincidence channel.

After processing the data by all the filters, the program calculates more accurate mean pulse rates in all the channels (Fig. 1). The correctness of the amplitude-time data processing was checked using the example of $4\pi\beta-\gamma$ coincidences using a secondary standard of radionuclide activity (VÉT 6-1-75).

Processing of the Data Arriving from the Detectors. Preliminary processing of the data is carried out by two programmed filters and a statistical spreading procedure. The first filter is a tuned amplitude discriminator. It enables one to separate out from the flow only those pulses which satisfy the condition of the possible range of signal levels established for each input. The second filter is a dead-time filter. It removes pulses the repetition interval between which is less than that specified in the program.

The inclusion in the processing of data of the statistical spreading procedure is due to the binary nature of the data obtained from the system. This is due to the fact that both scales – time and amplitude – in this system have a discrete form, defined by the frequency of the timer (50 MHz) and a number of digits in the analog-to-digital converter (10 bits). In mathematical processing of these data its dichotomy structure becomes important; this manifests itself when constructing the amplitude spectrum of the signal from one of the detectors (for example, a proportional counter). When an arbitrary number of display channels is specified, the pattern shown in Fig. 2a occurs. A similar situation arises when constructing any spectra, both amplitude and time. The observed vertical bands or other characteristic periodic nonuniformities are formed as a consequence of the different data width of the channels.

We will illustrate this using an example. We will assume that an analog signal, uniformly distributed in the range (0–3) V, is converted by two-bit analog-to-digital converters so that 0 corresponds to the range (0–1) V, 1 corresponds to the range (1–2) V, 2 corresponds to the range (2–3) V, and 3 corresponds to the range (3–4) V. When constructing the spectrum with four visual measurement channels, corresponding to the possible number of measured quantities (from the zeroth – minimum to the fourth – maximum), we obtain four similar lines. However, if there are three visual channels, we obtain two similar lines and one which is twice as large. But if we have five visual channels, then in one of them we obtain 0. The
The amplitude of the beats may be considerable even for a large number of possible numerical values of the input signal. An analysis of such spectra may lead to erroneous conclusions regarding the characteristics of the initial signal.

A typical solution of the problem is to choose an appropriate number of spectrum channels. The necessary criterion for the choice is that there should be the same number of possible digital values in each channel. For example, if there are 256 channels there will be no periodic nonuniformities in the spectrum, and spectrum will be similar to that shown in Fig. 2b. However, since the mathematical processing of the input data in the digital coincidence method is more complex than visualization of the spectrum of the initial values, in some cases the choice of the optimum number of channels (and more precisely their width) is incorrect or even an impracticable problem.

In the general case, to solve the problem of the discreteness of the initial signal, one can subject it to a statistical spread. To do this, a random number in the range from 0 to $\Delta I$ or from $-\Delta I/2$ to $\Delta I/2$ is added to each measured parameter, where $\Delta I$ is the minimum possible quantization step. The random distribution in the absolute majority of cases can be uniform. An exception may be measurements with a small number or nonlinear characteristics of the measurement channels. In practice, this spreading has only a small effect on the accuracy of the result of measurements, since the uncertainty introduced does not exceed the value of a scale division (the quantization step).

In our procedure, a random delay from 0 to 20 nsec was added to the measured time interval, and a random value from 0 to 256 was added to the signal amplitude. As a result, the spectrum shown in Fig. 2b is obtained. The statistical spreading procedure is carried out by the OpenTable program before the data is processed by all the subsequent filters. Note that distortions of the results of the processing due to the discreteness of the quantities are fundamental and are a feature of the processing of any digital data.

The coincidence channel is formed using a special filter and an amplitude-time correction procedure. The filter separates from the data matrix the pulses of different channels which coincide in time with an accuracy determined by the resolving time. To choose the resolving time, a time coincidence spectrum (the distribution of the pulses as a function of the time interval between them) is formed. To do this, the time interval between pulses in different channels is calculated within the range investigated and a histogram of their distribution is constructed (Fig. 3a).

The program also enables one, if necessary, to obtain a coincidence curve (the readout rate in the coincidence channel as a function of the delay time in each of the channels). In this case, a delay with a step specified by the operator is added to the values of the time interval of one of the channels, and the counting rate in the coincidence channel is calculated. The number obtained is stored in the data matrix and the operation is repeated in the cycle.

The amplitude-time correction procedure enables one to increase the accuracy of measurements of the time when a pulse is recorded. In our system, the time of arrival of a pulse from the detector is indicated by attaching it to a threshold.
level (50 mV). It is well known that in this case an uncertainty arises in the measuring of the time the pulse is recorded due to the finite slope of the leading edge (see, for example, [6]). This leads to the fact that a relationship occurs between the recorded time of arrival of pulses and the amplitude. Pulses generated by the system amplifiers have a leading-edge duration of about 0.5 µsec.

The amplitude-digital data obtained enable one to analyze the shape of the leading edge of the pulse and to introduce a corresponding correction to the recorded time of arrival of pulses [8]. In order to record the amplitudes in one of the channels with the programmable discriminators, we obtained the relations between the delay in the coincidence channel and the amplitude in the other channel (Fig. 4). These relations are determined by the forms of the leading edges of the pulses and are inverse functions of them.

For the proportional counter used in the measurements, the relation for the leading edge of the voltage pulse on the anode is given by the expression [9]

$$U = U_0 \left( \ln \frac{t}{\tau} + 1 \right).$$

For a photomultiplier, the form of the leading edge is given approximately by the formula [9]

$$U = U_0 \left( 1 - e^{-t/\tau} \right).$$

Taking into account the conversion of the signals along the path to the data-selection circuit board, we obtain the delay time for the proportional counter:

$$\Delta t_{pr} = \Delta t_{0\beta} - \tau_\beta \ln \left( 1 - \frac{U_\beta}{U_{0\beta}} \right),$$

and for the photomultiplier

$$\Delta t_{phm} = \Delta t_{0\gamma} \frac{U_\gamma}{U_{0\gamma}} - 1 - \tau_\gamma e^{\frac{U_\gamma}{U_{0\gamma}} - 1}.$$
Hence, the time difference $\Delta t$ between the signals in the coincidence channel due to the forms of the pulses will be

$$\Delta t = \Delta t_0 - \tau_\beta \ln \left(1 - \frac{U_\beta}{U_0\beta}\right) - \tau_\gamma e^{\frac{U_\gamma}{U_0\gamma}} - 1,$$  \hspace{1cm} (1)

where $U_\beta$ and $U_\gamma$ are the voltage amplitudes of the measured signals in the $\beta$-channel and the $\gamma$-channel respectively; and $\Delta t_0$, $\tau_\beta$, $U_0\beta$, $\tau_\gamma$, and $U_0\gamma$ are unknown coefficients, determined by the specific mode of operation of the detectors. The coefficients of Eq. (1) are chosen by the Levenberg–Markvardt method in the MathCAD package. We chose as the minimization parameter the root mean square deviation of the time intervals between pulses arriving in the coincidence channel. The values of $\Delta t_{pr}$ and $\Delta t_{phm}$ are automatically introduced in the form of corrections to each time of arrival of a pulse measured by the system.

As a result, the standard deviation of intervals between pulses for coincidences was reduced almost threefold (from 3.4 µsec to 1.2 µsec), which can be seen quite clearly on the time spectrum (see Fig. 3b). The root mean square deviation is identical in order of magnitude with the time resolution of the proportional counter, due to the drift time of an electron in the gas. Hence, the amplitude correction of the time introduced by the program enables a resolving time to be obtained which defines the resolving power of the detectors employed.

An analysis of the coincidence channel produced enables the number of random coincidences to be estimated directly [4]. To do this the number of pulses in time-spectrum channels far from coincidences was computed. In our measurements the number of random coincidences amounted to not more than 0.5% of the total number of coincidences.

**Conclusion.** We have described the main approaches to processing digital amplitude-time data and constructing a coincidence channel to obtain reliable results in a digital coincidence method. Further analysis of the data depends on the specific application of the method.

To improve the hardware part of the method, it is possible to establish an intrinsic memory in the measurement module and change the type of analog-to-digital converter. This should enable the dead time to be reduced to a minimum.

In this research, the digital coincidence method was used for the absolute measurement of the activity of sources of low activity (not greater than $10^4$ Bq). For appropriate low loads, the dead time only slightly affects the accuracy of the measurements. Moreover, it is possible to take into account counting errors when processing the data.

Among the drawbacks of the system we should mention that it is not possible to display the results during the experiment. But, as the results obtained show, the data processing is an independent problem and is best carried out separately.

**REFERENCES**