A new spectrometer for muon spin rotation

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ABSTRACT

After a brief outline of the technique of Muon Spin Rotation and its experimental realization, the main features of a PL-11 language program are described. The purpose of the program is to reconstruct the vertex of a $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ decay when the positron is detected within four μ^+ mean lives, i.e. $8.8 \mu\text{s}$.

A new and simplified algorithm has been developed in order to calculate the "distance" between two tracks in three-dimensional space.

A "real time" data acquisition system is described, including a few non-trivial features concerning a very fast time-to-digital converter (clock) and a wire chamber detection system.

Finally, a few first results showing the performance of the whole spectrometer are given.

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1. INTRODUCTION

To introduce the problem and to illustrate the topics which have been and still have to be solved in order to realize an efficient data acquisition system—or even better, a proper spectrometer for Muon Spin Rotation (μSR)—I would like to say a few words about a domain which is not, strictly speaking, within the theme of this school.

Let me then tell you the story of the birth and death of our main character, the muon. The 600 MeV Synchro-cyclotron at CERN (Fig. 1) supplies the protons which hit an internal target. This target produces a certain amount of pions and, consequently, of muons. These latter particles—thanks to the static magnetic field of the accelerator—enter the transport line. At the end of this line, after a final degrading in order to diminish the energy of our particles, they stop in the final target where the actual experiment begins.

1.1 The muon family tree

Before entering into a description of the experiment, I would like to show briefly the main features of the muon (see Fig. 2).

Our particle belongs to the family of leptons, and like the electron it can be either positive or negative (we make use only of the positive one), its mother particle is the positive π^+ , and its decay is a three-body decay:

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e . \quad (1)$$

The energy of the outgoing positron has a continuous spectrum with a peak around 50 MeV. The muon lifetime is $2.199 \mu\text{s}$ and it has a half integer spin with a magnetic moment given by the formula

$$\mu = \frac{e\hbar}{2m_\mu c} , \quad (2)$$

with the usual definition of the symbols.

1.2 The last waltz of the muon

Once the muon is thermalized in the sample, it sees the local magnetic field, if there is one, and the transverse magnetic field. Hence thanks to the spin and to the associated magnetic moment, the muon will precess, and finally it will decay, emitting (preferentially along the spin direction) the outcoming positron (Fig. 3). The precession frequency is given by

$$\omega = g \frac{eH}{2m_\mu c} , \quad (3)$$

where $g = \mu/I$ is the gyromagnetic ratio; that is, the magnetic moment in natural units $e\hbar/2m_\mu c$, divided by the angular momentum in units of $\hbar$. The numerical value of Eq. (3) is usually expressed in kHz. Thus we can write

$$\nu = \frac{\omega}{2\pi} = 13.55 \text{ kHz/G} . \quad (4)$$

1.3 The experiment

And now for the experiment: The incoming muon will trigger the START chain which will send a pulse to the clock—the time-to-digital converter (TDC), which has a period of 2 ns. Once the clock has started measuring the time, no other muon is detected by the START chain for $10 \mu\text{s}$. For the whole length of this lapse of time the system will wait for the appearance of a positron which will trigger the STOP telescope. When this happens, the STOP telescope will actually stop the TDC, which will send to a small buffer (64 16-bit words) the value in units of 2 ns of the lapse of time between the STOP and the START signal. This small buffer is eventually sent to a HP 2100 minicomputer, where the data are filled into a histogram. The typical decay on which is superimposed the μ^+ precession is shown in Fig. 4. To further illustrate the concept, the reader can think of a lighthouse, where around the lantern (the peak) there is the maximum intensity of light, whilst at the foot (the valley) there is the minimum, as a sailor sees from his boat when he approaches the land.

This brief description illustrates our old and still very active spectrometer which works in “real time”. In other words, we can say we do not record the incoming muon and the subsequent outgoing positron. Once the dates of birth and death of our particle are known, we store each single muon lifetime one by one. In doing so we store only a histogram of 4000 words, which takes only a few inches of magnetic tape, and it is in this respect that we differ from the usual high-energy physics experiments. We do not store all possible information on hundreds and hundreds of tapes, but only the filtered information which allows us to see the growing of a peak via different on-line programs such as Fourier transforms or best fitting.

1.4 The noise problem

Despite the very good performance of our old spectrometer, obviously due to its simplicity, it has a fundamental defect: it has a very poor spatial definition. In fact the spatial definition is only

due to the size and shape of the scintillators which form the START and STOP telescopes. Before going on to describe the new spectrometer which makes use of wire chambers, it is worth while stressing the problem of the noise.

Let us consider our sample, sitting on a sample holder. Generally the sample holder is a cryostat, and using dummy samples we found that the signal of the cryostat is around 3%. So if we have to deal with a signal which is expected to be of the order of 1%, we are completely lost. Figure 5 gives us an idea of the situation: the unwanted peak is the first one starting from the origin of the axis. In the case shown here, the experimentalist has either been skilful or just lucky. However, the presence of such a peak constitutes a serious limitation. The solution of our problems and, if you like, the introduction of new ones, came with the idea of using wire chambers to define the track of the incoming muon and the track of the outgoing positron.

2. THE SPATIAL DEFINITION OF THE NEW SPECTROMETER

Figure 6 gives the reader a first hint of how the new spectrometer works. First a muon comes into the sample, and the two pairs (x'_1, z'_1) and (x'_2, z'_2) of coordinates are recorded. Then the track of the outgoing positron is recorded via the two pairs of coordinates (y'_3, z'_3) and (y'_4, z'_4) . This information is then sufficient to reconstruct the vertex $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$. At this point a suitable algorithm is needed.

2.1 The algorithm

According to our idea of reconstructing the vertex in real time, we needed an algorithm that was fast enough to do the job in say, about a millisecond. An algorithm with such an ability would have allowed us to reconstruct, in principle, 3.6×10^6 vertices per hour. This number has to be compared with the performance of the old spectrometer, which at its very best is able (without spatial resolution) to store only 2.0×10^6 events per hour. The first idea was to use the algorithm shown in Fig. 7. This picture shows that the cross-product of two vectors lying on two straight lines defines a straight line normal to both. If we now normalize the resultant vector, we get a unitary vector which defines the normal to our straight lines. And if, via the dot product, we project the vector joining the two ends of the two original vectors along the unitary vector, we get as an absolute value the distance between the tracks. This algorithm is very simple and, in principle, it can be very easily coded in any language. Still, it does contain very little information because it does not tell us the position of the vertex. Therefore we cannot take a decision as to whether the vertex is inside or outside the sample; and, worst of all, it needs a square root, not to mention the considerable amount of multiplications. As a matter of fact the reader is certainly well aware of the fact that the square root is a very slow operation.

So I abandoned this algorithm and started considering the general one, which calculates the points of intersection of the perpendicular to both lines and, finally, via a square root, the distance of this pair of points. In the general algorithm we have all the information we need, but the price we shall have to pay is still extraordinarily high. Apart from the square root, we have to evaluate a 3×3 determinant; but as it is too difficult to evaluate an "Euclidean" distance, I decided not to calculate it at all. The solution of the puzzle is shown in Fig. 8.

We can start from the obvious assumption that given two straight lines in space, there are always two planes which contain the straight lines and are normal to a third plane. If we now call "distance"—or better, I ought to say "pseudo-distance"—the absolute value of the distance of the two points defined by the intersection of the two straight lines with the line defined by the intersection of the two planes containing the two lines, we do not get a distance within the usual

meaning of the word. Still, if you allow tracks that are only a few millimetres apart, it can be shown that the difference between the Euclidean distance and our distance is very small. Furthermore, also our distance tends to the limit of zero as the real distance tends to zero.

Why should this algorithm be more simple when it sounds so complicated? Because to evaluate our distance we have only to calculate the intersection of the two straight lines, defined by the planes α and β (see Fig. 8), with the xy plane, then substitute this value in the equations of the two tracks to get the two z -values and, finally, evaluate the absolute value of the difference of the two z 's to get our "distance".

Putting everything down in formulae, with the obvious meaning of the subscripts, we can write

$$\begin{cases} \frac{x - x_1}{x_2 - x_1} = \frac{y - y_1}{y_2 - y_1} , \\ \frac{x - x_3}{x_4 - x_3} = \frac{y - y_3}{y_4 - y_3} . \end{cases} \quad (5)$$

Putting these equations in a more suitable way, we get

$$\begin{cases} x - y \frac{x_2 - x_1}{y_2 - y_1} = x_1 - y_1 \frac{x_2 - x_1}{y_2 - y_1} , \\ x - y \frac{x_4 - x_3}{y_4 - y_3} = x_3 - y_3 \frac{x_4 - x_3}{y_4 - y_3} . \end{cases} \quad (6)$$

Then putting

$$\frac{x_2 - x_1}{y_2 - y_1} = \alpha , \quad \frac{x_4 - x_3}{y_4 - y_3} = \beta , \quad (7)$$

we get

$$\begin{cases} x - \alpha y = x_1 - \alpha y_1 , \\ x - \beta y = x_3 - \beta y_3 . \end{cases} \quad (8)$$

Putting again

$$\begin{cases} x_1 - \alpha y_1 = \alpha' , \\ x_3 - \beta y_3 = \beta' . \end{cases} \quad (9)$$

which gives

$$\begin{cases} x - \alpha y = \alpha' , \\ x - \beta y = \beta' , \end{cases} \quad (10)$$

finally:

$$x_i = \frac{\begin{vmatrix} \alpha' & -\alpha \\ \beta' & -\beta \end{vmatrix}}{\begin{vmatrix} 1 & -\alpha \\ 1 & -\beta \end{vmatrix}} = \frac{\alpha\beta' - \alpha'\beta}{\alpha - \beta} ,$$

$$y_i = \frac{\begin{vmatrix} 1 & \alpha' \\ 1 & \beta' \end{vmatrix}}{\alpha - \beta} = \frac{\beta' - \alpha'}{\alpha - \beta} .$$

To get our intersection point, we then need a total of eight multiplication-type operations. We get the final “distance” d :

$$z_\beta = z_3 + \frac{x_i - x_3}{x_4 - x_3} (z_4 - z_3) ,$$

$$z_\mu = z_1 + \frac{x_i - x_3}{x_2 - x_1} (z_2 - z_1) ,$$

$$d = |z_\beta - z_\mu| ,$$

by a total of 12 multiplication-type operations.

What is shown is the worst and the most expensive case in terms of CPU time. There are other cases: for instance when one of the tracks is parallel to one of the planes of the reference set in which the algorithm is much more simple and thus saves quite a considerable amount of CPU time. The performance of the algorithm will be shown later in connection with the performance of the whole data-acquisition system.

2.2 The new START-STOP logic

Once the algorithm has been found, we have to insert the time information which, as far as the μ SR is concerned, is still the fundamental one. Figure 9 shows a first view of the whole data-acquisition system. Here the situation is still very schematic, but I will try to make it more understandable later.

First of all I must mention that one of the features of our TDC is to supply the absolute value of the lapse of time between two successive pulses. The situation is the following. Let us set the clock to zero and start the experiment. When the first $START_1$ arrives, the TDC will send out a $|0-START_1|$ time which is exactly the absolute time of the occurrence of the event. When a $START_2$ arrives, the clock will send a $|START_1-START_2|$ time, which is the value in units of 2 ns of the lapse of time between the previous and the latest pulse. When the time is recorded the system will add to the temporal coordinate the spatial coordinates obtained from the wire chambers. These latter coordinates are in byte form. Thus two pairs of coordinates make two 16-bit words, plus the 16-bit word defining the time we get the START event, which is defined by these three 16-bit words. If now a STOP arrives, the TDC will send out the $|START_2-STOP|$ time, adding the two pairs of spatial coordinates correlated to the occurrence of this event plus the STOP address. Because there

is more than one STOP telescope, we get a total of four 16-bit words for the definition of one STOP event. The minimum length of a global event is then of seven words: the STOP and its parent the latest START. If still we are not sure that the last START is the generator of the STOP event [as the ancient Romans would have said "Pater semper incertus" (loosely translated: "It's a wise child that knows its own father")], we can ask the system to keep a record of the second-to-last START as well. In this latter case the global event is of 10 words. We can ask the system to keep a record which can go even further into the past to look for the possible ancestor of the STOP and which can be pushed even to the tenth generation. Still we must consider that the more we go into the past the smaller is the likelihood of finding the STOP generator. Our "father" is not so "incertus" (uncertain) after all. The most efficient way to build the global event is probably to keep a record of only the latest START. In doing so, the length of the global event is kept to a minimum, the packing in a long buffer is better optimized, and we can transfer more events with fewer interrupts. A sketch of the global event is given in Fig. 10.

2.3 The event and the buffer

Once an event is built, it is sent to a small computer (PDP 11/04) whose main function is to pile up all the events in order to build a buffer whose length can be varied from 1 event up to 500 events per buffer, which gives a total of 3500 words. Eventually the buffer is sent via CAMAC, in Direct Memory Access, to a PDP 11/60. Here the main data-acquisition program analyses the buffer, reconstructs the vertices, and stores in an histogram the STOP times belonging to the good events.

2.4 FIFO and RAM

Figure 11 shows in more detail how the buffer is built. The box called EXTERNAL LOGIC means all the paths of the coincidences of the scintillators and of the wire chambers aiming at the definition of a good event. Let us then suppose that a positive muon triggered the START chain. In this case the two pairs of coordinates supplied by the chamber processors are stored in the CHAMBER CONTROL boxes, which send an OUT pulse. This pulse is put in coincidence with the scintillators, and if everything is all right the external logic will send a pulse to the TDC. The time and the STOP address are then stored in the TDC CONTROL. The TDC CONTROL will send a "trigger out", which will be transformed via a normal FAN OUT module in a threefold pulse which is sent into the "IN" of the TDC control and into the respective "IN" of CHAMBER CONTROL (1) and CHAMBER CONTROL (2). This pulse makes the coordinates ready for use and for transfer to the BUS line. It is at this stage that the interface between the different CHAMBER CONTROLS and the PDP 11/04 reveals its importance in organizing the event. As can be seen from Fig. 11, the RAM MICROCODE is a small memory which can be accessed by the user through the PDP 11/04, and by means of which the user tells the interface how he wants the event organized. In our case we usually tell the interface to store all the STARTs in RAM. The small RAM can contain 32 16-bit words. When a STOP occurs we store it in FIFO and subsequently transfer the content of the RAM (the STARTs collector) into the same FIFO (the STOP + START + START + ... collector). The capacity of the FIFO is 64 16-bit words.

3. CONCLUSIONS AND RESULTS

I will give here a few indications concerning the performance of the whole system.

The speed of the event definition supplied by the photomultipliers plus the logic concerning the decoding of the wires and the definition of time is at the moment of the order of 500 ns. This, in principle, limits the data acquisition to a maximum number of events, which is 2×10^6 events per

second. This limitation is, as far as we are concerned, very good, because very rarely do we have a beam intensity which produces more than a thousand good events per second. Still, the limit of half a microsecond can be bettered; and I hope, by making use of faster wire decoders and with a proper trimming, to improve things considerably. The rest of the system is, however, very satisfactory. The data-acquisition program has the ability to reconstruct a vertex in an average time of $500\ \mu\text{s}$, which gives a maximum theoretical limit of 2×10^3 events analysed per second. This number is a factor of two higher than the maximum beam intensity. The time of $500\ \mu\text{s}$ is the average time spent by the algorithm to reconstruct a vertex among all the possible cases. If you consider that in the case of two tracks parallel to the planes of the reference set the whole algorithm is reduced merely to a subtraction, it can be very easily understood what is meant.

At the moment, I am writing a program to get the actual distributions of the μ^+ and e^+ tracks. Unfortunately, the first results show a nasty behaviour of the tracks — it seems that they viciously prefer the general case, which is the most time consuming. However, this first result suggests that the average value of $500\ \mu\text{s}$ has to be ascribed to the general case, which is quite comforting. To get an idea of the flow chart of the program, see Figs. 12 and 13. However, the situation can certainly be improved, and I am quite confident that another $100\ \mu\text{s}$ can be squeezed out.

Before closing I would like to mention the experimental results which we obtained during the run of July 1981. We used a $3 \times 3 \times 3$ cm cube of graphite in order to test the performance of the entire system: histogramming and two-dimensional imaging. Figure 14 shows the typical spectrum of the graphite. It can be seen in this time histogram that the background is reduced virtually to zero. The background, evaluated by one of the on-line programs, is of a few parts per thousand. Figure 15 shows the image of the sample, and one can see that there is something which is not trivial. As a matter of fact one can see the blob formed by the $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ vertices; in other words, the region of the sample where the muons have the maximum likelihood of stopping and decaying. This is the reason why one side of the picture shows nice sharp edges, whereas the opposite side shows a more circular contour. This effect is even more evident in Fig. 16.

Finally, Fig. 17 shows a front view of the sample, taking the beam direction as the reference direction. Here the image is slightly more square than the previous ones and gives us a hint about the structure of the beam.

Acknowledgements

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FIGURE CAPTIONS

- Fig. 1: Beam layout for the two μ SR experimental stations at the SC.
- Fig. 2: The muon decay and its spectrum.
- Fig. 3: A schematic view of the experiment.
- Fig. 4: A typical quartz spectrum at low field.
- Fig. 5: The unwanted signal of the sample holder is shown.
- Fig. 6: A sketch of the $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ decay within the sample is shown. The neutrino and antineutrino are not drawn because they are not detected by the wire chambers. The big arrow "BEAM" shows the direction of the incoming muon beam.
- Fig. 7: The "Euclidean" distance d between the μ^+ and the e^+ track is shown.
- Fig. 8: The "pseudo-distance" d is shown. Actually this distance is the length of the segment defined by the two intersections of the μ^+ and e^+ tracks with the straight line, which is the intersection of the planes α and β and is parallel to the z -axis of the reference set.
- Fig. 9: A global sketch of the flux of data from the wire chambers down to the PDP-11/60 in which resides the program for analysing the "events". Note that DMA stands for Direct Memory Access, so that "FIFO" sends the data in DMA to the PDP-11/04, which then sends the data in DMA, via CAMAC, to the PDP-11/60.
- Fig. 10: Example of a buffer event. The event is built with one STOP followed by four STARTs.
- Fig. 11: Detailed sketch of the "trigger logic" to define either a START or STOP event.
- Fig. 12: Flow chart of the most external "Block", which shows the main logic entering the internal blocks.
- Fig. 13: Detailed flow chart of the Minimal Block; the logic entering the innermost blocks is shown. Note that GOOD and BAD are synonyms of accept and reject.
- Fig. 14: First graphite spectrum obtained with the new spectrometer. The very little background is apparent.
- Fig. 15: First image of the $3 \times 3 \times 3$ cm³ block of graphite. The unit is 1 mm.
- Fig. 16: The same image of the graphite; the sharp edge of the back of the sample is more evident. The direction of the beam is from right to left.
- Fig. 17: Frontal image of the graphite sample. The beam is perpendicular to the plane of the picture and is pointing towards the same plane.

Fig. 1

Fig. 2

μ^+ spin rotation (transversal field)

Fig. 3

Fig. 4

Fig. 5

Fig. 6

$$d = \frac{|(P_{12} - P_{11}) \times (P_{22} - P_{21}) \cdot (P_{12} - P_{22})|}{\sqrt{[(P_{12} - P_{11}) \times (P_{22} - P_{21})] \cdot [(P_{12} - P_{11}) \times (P_{22} - P_{21})]}}$$

Fig. 7

Fig. 8

Fig. 9

BUFFER

ADDR	
STOP	
BY4	BZ4
BY3	BZ3
START	
BX2	BZ2
BX1	BZ1
START	
BX2	BZ2
BX1	BZ1
START	
BX2	BZ2
BX1	BZ1
START	
BX2	BZ2
BX1	BZ1
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Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

0 04 JUL 81 09:33:33

Fig. 15

TOTAL=21003 XBIN=2 YBIN=2 BIAS=20 MAX BOX =140

Fig. 16

Fig. 17