Summer student 2004 report: Calculation of proton fluence by activation of aluminium foils with the program WinFluence

Lorenzo Masetti

September 2, 2004

Abstract

This report describes the work I did at CERN as a Summer student in the summer of 2004. I developed a Delphi application for acquiring a spectrum from the NaI spectrometer, finding in real time the 1368 keV peak for the ^{24}Na and computing the fluence of the irradiated aluminium sample. To make the system work with the old ISA card on Windows XP I developed a 16 bit server making the requests to the board and giving the results back to the client.

Contents

1 Background

Detector components for the experiments at the CERN Large Hadron Collider are exposed to a very high level of radiation. In order to assure the proper

Figure 1: The NaI spectrometer used for the measurements

functioning of these components they have to be radiation hard, which has to be tested before the installation into the experiment. In the CERN Proton Synchrotron East Hall an irradiation facility has been constructed to test all kind of components with respect to their radiation hardness against 24 GeV/c protons and high energetic neutrons (approx. 1 MeV). For all irradiation experiments the irradiation fluence has to be determined precisely. One possibility is to place an Al-film into the beam. Due to nuclear reactions ^{24}Na is formed in the Al-film, which decays with a half life of 15h emitting a gamma ray of 1.37 MeV. Measuring the number of such decays per unit time allows for the determination of the irradiation fluence.

2 Objectives of the project

An old software, written in Turbo Pascal and running in DOS was still working during irradiation period of 2003 and for a few measurements in 2004. However this software was outdated and had to be replaced by a new program written in Delphi 6 and running on Windows XP.

The acquisition from the spectrometer uses a TISA card by Target System-electronic company from Germany and this card had to be used under Windows XP. An industrial PC with an ISA slot was bought for this purpose.

Some other features were needed, such as the checking of the beam trend reading data from the SEC system running in IRRAD1 and the normalization of the fluence due to a non uniform flux.

The 2003 summer student, Kees Visser, started the development of the project writing most of user interface.

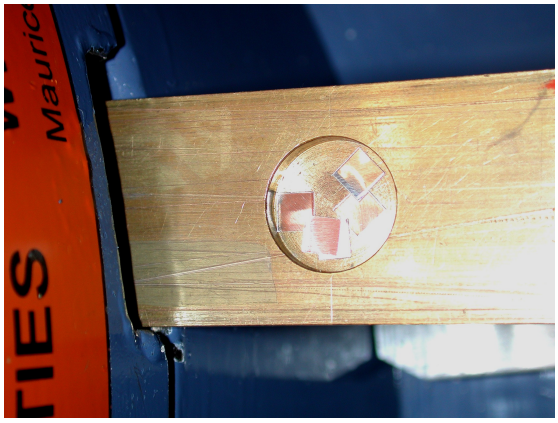

Figure 2: The aluminium samples used as dosimeters

3 Using the 16 bit DLL

The Delphi program is a 32 bit application. This means that all the addresses in memory are actually 32 bit long unsigned integers. This way 32 bit computers are able to address directly up to 4GB of physical memory.

Old applications that run under DOS and under Win16 (Windows 3.1) are 16 bit applications. The way of addressing memory used by legacy 16 bit applications is quite strange, due to a choice made by the 8086 family processors. In these processors, the addresses of memory were 20 bit long, allowing to address 1 MB of memory. But in the registers inside the microprocessor the addresses were only 16 bit long (this way only 64 KB of memory could be addressed). The 20 bit address was computed by adding the 16 bit address and the content of a segment register shifted to the left by 4 bits (i.e. multiplied by 16). By changing the value of the segment register it was possible to access more than 64 KB of data.

In the present 32 bit world, old 16 bit applications are still allowed to run on Windows in a protected simulated mode. The utility WOW (Windows Over Windows) implements the simulation of a 16 bit environment under Win32. But there are some restrictions for Win16 processes running on Win32: for example it is not possible for a 32 bit program to use a 16 bit DLL. Under Windows 9x (95, 98) there was a method called "flat thunking" that allowed 32 bit programs to use 16 bit DLL's, but under Windows XP (or Windows NT and Windows 2000) this feature is not provided. CERN doesn't allow any Windows 9x computer on the network, so we were forced to find another solution.

The only available solution was the following: write a 16 bit small application, to use as a server to call the 16 bit DLL providing the driver for the TISA card, and make the 32 bit Delphi application communicate with this server using some kind of interprocess communication.

Finally I chose to use OpenWatcom C/C++ compiler to write the server, and WinSockets for the interprocess communication.

OpenWatcom C/C++ compiler is an open source compiler that can be downloaded for free from http://www.openwatcom.org/ and is probably the only

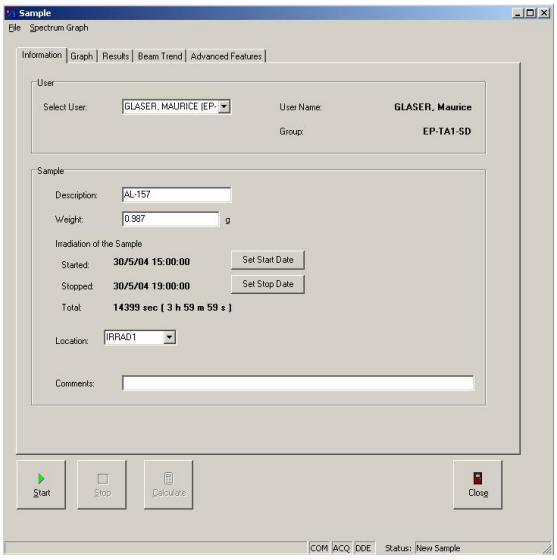

Figure 3: The Information TAB of WinFluence

Open Source compiler that allows to write Win16 applications.

WinSockets are a Windows version of the standard UNIX sockets. Sockets are used for network communication, so a socket is like a 2-ways communication over the internet. Typical use of sockets is a server/client architecture. A server is executed on a computer waiting for the connections of the clients. The client, in order to contact the server, must know the IP address of the computer where the server is located, and the port on which the server is listening. Given these two parameters the client can connect to the server and exchange data according to a prefixed protocol.

4 How to use the program WinFluence

4.1 Measuring a sample with WinFluence

To make a measurement with WinFluence, follow these steps

- Click on the "New" button to open the sample window. The form of fig. 3 will appear.
- Select your name from the list of the users. If your name is not on the list, click on "New User". If you want you can choose "Save on file" and your name will always be in the users' list.
- Enter a name for the sample you are measuring. This is usually AL-xxx where xxx is a counting number.
- Weight the sample with the balance and write the weight with the precision of four decimal digits.

- Set the dates of the start and the stop of the irradiation. The last used dates are preset, so if you are measuring many samples of the same irradiation session you don't need to change anything.
- Set the location of the irradiation. This information is used to check if the shuttle was in beam during the acquisition.
- If you have some comment or remark write it in the Comment field.
- Place the sample into the spectrometer and click on the "Start" button
- The program checks if you entered all the needed data and if the data have some errors (e.g. dates in the future or not in the correct order). The sample age is computed and you can check if it's correct. If the sample is older than 24 hours a warning message appears.
- If the high voltage (bias) is not correctly set you can choose to set it before starting the acquisition. In every case the actual high voltage is displayed so that you can check if it's correct.
- If everything is right the acquisition starts and the program switches to the Graph tab. After 10 seconds of acquisition the program starts to try to find the peak and to compute the fluence. You can check if the peak is correct on the graph and you can see the values of the fluence and of the error under the graph.
- After some time (usually 600 - 1200 seconds) you will see that the found peak is right and an acceptable error on the fluence (errors should usually be around 7%). When this happens just stop the acquisition and the final results will be computed.
- When you click "Stop" you will be asked if you want to save the results. **Answer yes** ! Results are automatically saved in the correct directory. By default the file will have the same name of the sample and the extension .flu (that can be configured to be opened with WinFluence). If a file of the same name already exists, a the name is changed.
- Print the report for the sample and store it in the proper logbook

4.2 "Advanced" features

4.2.1 Background Report for the ^{40}K

This feature provides an automatic calculation for counting the non negligible contribution of the peak of ^{40}K to the peak of ^{24}Na. ^{40}K has a peak at 1459 keV. In order to estimate the contribution of the background you need to start a long acquisition with no sample inside the spectrometer. After a long enough time (14 hours or more) there will be a significative statistic and will be possible to use the background report that computes the count per second of ^{40}K. This value is used to compute the error and should be set in the options.

4.2.2 Efficiency calibration with a known multigamma source

To use this function, acquire the spectrum of a certified multigamma source and find the peak of a nuclide of which the source provides the value of activity. Then fill the needed fields copying the values reported in the source certificate and click on "Compute Efficiency". The computed value must be set in the efficiency curve (see below)

For further details about the formula used to compute the efficiency, see section 5.4

4.2.3 Interpolating the efficiency curve

To use this function, select from the Configuration menu the option "View efficiency curve". A graph will appear. To change the value of the points click on "Edit Data". A text file will be opened. On this text file all the efficiency measurement with certified sources are listed. Every row must contain 3 values separated by TAB. The first one is the value in keV of the peak, the second is the efficiency computed for that peak, and the third is the percentual error on efficiency. To apply the changes, save the file and click on update. The efficiency for ^{24}Na is computed and must be set in the options. It's possible as well to compute the efficiency in another point. For further details about interpolation curve, see section 5.4

5 Description of the algorithms

5.1 Computing the fluence

As the aluminium is irradiated the radioactive nuclide ^{24}Na is created, with a rate of accumulation given for the nuclear reaction

$$A \xrightarrow{p} B \xrightarrow{\lambda} C$$

by

$$\frac{\mathrm{d}N_B}{\mathrm{d}t} = \varphi N_A \sigma_A - \lambda N_B \tag{1}$$

where φ is the flux, σ_A is the cross section and λ is the decay constant (inverse of mean life time τ) that has the following relation with the half life time

$$\lambda = 1/\tau = \frac{\ln 2}{T_{1/2}}$$

In our case we have

$$^{27}Al \xrightarrow{p} {}^{24}Na \xrightarrow{\lambda} {}^{24}Mg$$

We can assume that N_A is constant and given by N_0

$$N_0 = \frac{Av \times P \times W}{M_A}$$

where Av is the Avogadro's number, P is the purity of the target material, W is the weight of the target in grams and M_A is the atomic mass (of the aluminium in our case). The fluence program assumes $P = 1$ since the use of

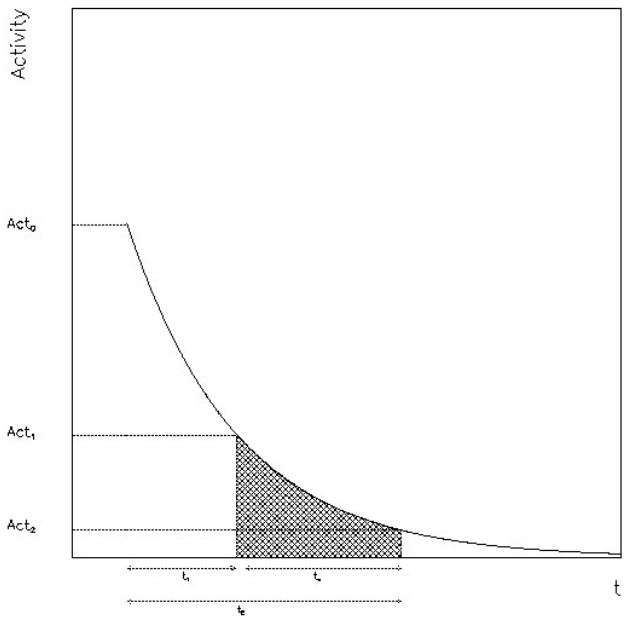

Figure 4: Decay of the activity from the end of irradiation

typical aluminium with $P = 0.995$ gives a difference that is much less than the typical error that is around 7%.

By solving the differential equation 1 and assuming $N_B(0) = 0$ (at the beginning of the irradiation we have no radioactive nuclei) we obtain

$$N_B(t) = \frac{\varphi N_0 \sigma_A}{\lambda}(1 - e^{-\lambda t})$$

We can define the activity of the irradiated material as

$$Act = -\frac{\mathrm{d}N_B}{\mathrm{d}t} = N_B \lambda$$

The activity of a material irradiated for the time t_i and left to decay for the time t_e is

$$Act(t_e) = \varphi N_0 \sigma_A (1 - e^{-\lambda t_i}) e^{-\lambda t_e}$$

at the end of the irradiation $t_e = 0$ and we can write

$$Act_0 = \varphi N_0 \sigma_A (1 - e^{-\lambda t_i}) \tag{2}$$

and we can rewrite the expression for an activity after the end of irradiation as

$$Act(t) = Act_0 e^{-\lambda t}$$

In the measurements with the aluminium the sample is left to decay for a time t_1 and then measured for an interval of time (counting time) $t_c = t_2 - t_1$.

The average activity during the counting time, $\overline{Act}$, is given by

$$\overline{Act} = \frac{Act_0}{\lambda t_c} \int_{t_1}^{t_2} e^{-\lambda t} dt = \frac{Act_{t_1}}{\lambda t_c}(1 - e^{-\lambda t_c})$$

We measure $\overline{Act}$ and compute Act_{t_1} and Act_{t_0}

$$Act_{t_1} = \frac{\overline{Act}\lambda t_c}{1 - e^{-\lambda t_c}}$$

$$Act_0 = Act_{t_1} e^{\lambda t_1} \tag{3}$$

Using the equation 2 we can compute the flux

$$\varphi = \frac{Act_0}{N_0 \sigma_A (1 - e^{-\lambda t_i})}$$

and the fluence

$$\Phi = \varphi t_i$$

5.2 Computing the peak area

To compute the average activity the program fluence uses the same algorithm of the Pascal program.

In order to compute the activity of the sample, the area of the full energy peak at 1368 keV must be computed. As the detector is not 100% efficient and the source is emitting radiation over the whole solid angle, this value must be corrected taking in account the efficiency of the detector.

The first problem is how to find the integration marks of the peak. The algorithm starts the search from two bounds given by the user by moving the two lines on the graph. By default these lines are placed around the region where the 1368 peak should approximately be.

The values of the channels are summed ten by ten to avoid the sensing of false integration marks.

The search of the left bound begins by the left line moving on the right. The stop condition involves three groups of 10 channels, G_i, G_{i+1} and G_{i+2}. When the following condition holds

$$G_{i+1} > G_i + 2\sqrt{G_i}$$

we check if the same condition holds for the following two groups of channel. If it holds the starting mark is found.

The right mark is searched starting from the right bound and it is found when the following condition holds for three groups of 10 channels

$$G_{i-1} - \sqrt{G_{i-1}} > G_i$$

This condition is not the exact symmetric of the previous one, but this choice seemed to give the best results.

Once the marks have been found, we can compute the total area of the peak by simply summing all the channels between the two integration marks.

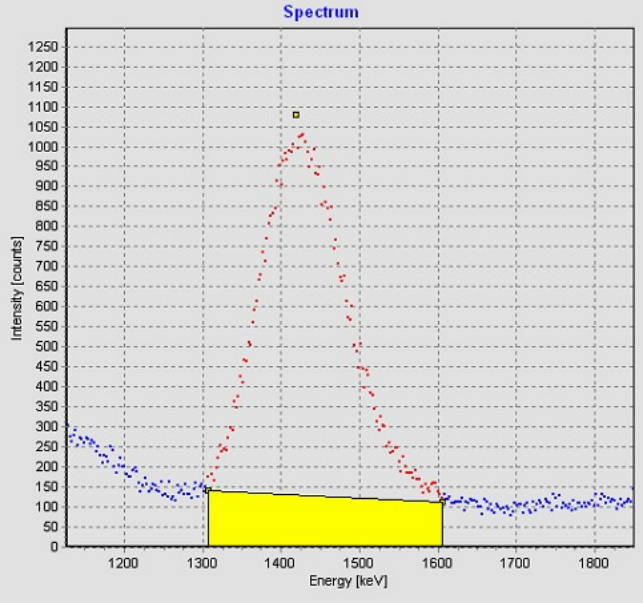

Figure 5: The background area subtracted by the peak area

As the peak is superimposed on a continuum caused by background noise and other effects we must subtract the additional unwanted counts that are included in the area. A simple way to do this is to subtract the area of trapezoid of coordinates $(A, 0)$, $(B, 0)$, $(B, AvgB)$ and $(A, AvgA)$ where A and B are the integration marks and $AvgA$ and $AvgB$ are given by the linear interpolation of 20 channels on either side of the peak, as in fig. 5

$$AvgA = \frac{\sum_{i=A-19}^{A} C_i}{20} \quad AvgB = \frac{\sum_{i=B}^{B+19} C_i}{20}$$

So the Net Peak Area is given by

$$Net = \sum_{i=A}^{B} C_i - (B - A)\frac{AvgA + AvgB}{2}$$

The average activity over the counting time is

$$\overline{Act} = \frac{Net/t_c}{Abs\_Eff\_\%} \times 100 \tag{4}$$

and can be substituted in the previous formulae in order to compute the fluence

5.3 Errors

To estimate the error on the final measure we must have an estimation of all the different sources of error and sum them quadratically according to the theory of error propagation.

The percentual error on the peak area is

$$Err\_PA_{\%} = \frac{200\sqrt{PeakArea - 2BGArea}}{PeakArea}$$

The error on the activity of the end of the irradiation is

$$Err\_Act0_{\%} = \sqrt{Err\_PA_{\%}^2 + Err\_Ge_{\%}^2 + Err\_Eff_{\%}^2 + Err\_K_{\%}^2}$$

where Err_Ge is the error due to the calibration of the Germanium spectrometer, Err_Eff is the error due to the estimation of efficiency and Err_K is due to the non-negligible contribution of ^{40}K counts (^{40}K has a peak at 1459 keV) in the net area of the 1368 peak.

The error due to the calibration with Germanium and the error on efficiency can be set on the options. The error on efficiency and the error on germanium spectrometer are saved in every result file since it can change in the years. Using the new calibration method with a certified source described in 5.4, the error on germanium should be set to 0 in the options (and the error on efficiency should be changed)

The Err_K is computed as

$$Err\_K = \frac{Cps\_K}{Cps} \times 100$$

where $Cps = Net/t_c$ and Cps_K are the counts per second due to the ^{40}K peak that can be computed by acquiring from the empty spectrometer for a long enough time. This value can as well change in the years, for example by adding a thicker shielding it was possible to reduce this value from 3 cps in 2003 to the present value of 0.866 cps. Since this value can change it is saved in each result file.

The error on fluence is

$$Err\_Fluence_{\%} = \sqrt{Err\_A0_{\%}^2 + Err\_CrossSect_{\%}^2 + Err\_Weight_{\%}^2}$$

The error on the cross section is known to be 4%.

The relative error on weight is computed as the ratio between an absolute error of 0.05 mg (this is the average error since the balance has a precision of 0.1 mg) and the weight of the sample

$$Err\_Weight_{\%} = \frac{5 \times 10^{-5}\,\mathrm{g}}{SampleWeight\,(\mathrm{g})} \times 100$$

The previous fluence program always took $Err\_Weight = 1\%$ and so overestimated or underestimated the error, depending on the weight of the sample.

5.4 Efficiency calibration with a certified source

In equation 4 we have to set the value of $Abs\_Eff\_\%$. One possible way to estimate the value of this parameter is to use a certified multigamma source, of which we know the value of activity at a certain time.

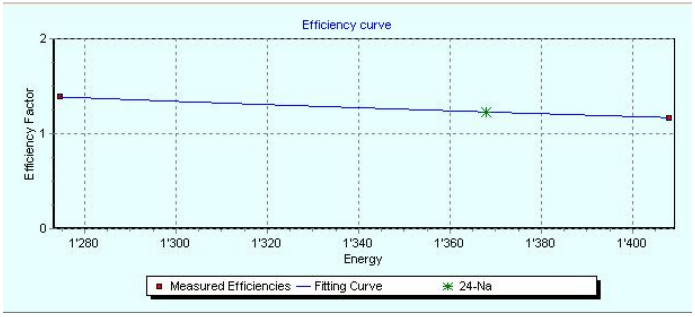

Figure 6: An example of efficiency curve interpolating two measured efficiency. The value for the energy of 1368 is computed by interpolation

The user is requested to select a peak from the spectrum of a known multi-gamma source. The certificate provides the values of half life time for the nuclide that produces the peak and the activity measured at a given time. Substituting the known values in equation 3 and solving for $Abs\_Err\_Eff\_\%$ we obtain

$$Abs\_Eff\_\% = \frac{100\, Net\, \lambda\, t_c\, e^{\lambda t_1}}{Act_0\, t_c\, (1 - e^{-\lambda t_c})}$$

where Net is the net peak area found by the program, t_c is the acquisition time, and the other parameters (λ, t_1, Act_0) are provided by the certificate of the source.

The error on this value is given by the propagation of two errors: the error on activity (provided in the certificate) and the error on peak area, computed as usual.

It is possible to measure the efficiency with several sources with peaks at different energies. The efficiency for the ^{24}Na is found interpolating the given points with a polynomial on logarithmic scale. For example if we measure the efficiencies in two points we obtain a line that interpolates the points $(\ln E_1, \ln Eff_1)$ and $(\ln E_2, \ln Eff_2)$ that is a function of the type

$$\ln(E) = a \ln(Eff) + b$$

For three points we obtain

$$\ln(E) = a(\ln(Eff))^2 + b \ln(Eff) + c$$

and so on. It's possible to use a maximum of 20 points to interpolate. Nevertheless polynomial interpolation is not good for a very large number of points, so it's better to use max. 4-5 points.

The interpolation curve is computed using the Newton basis for the space of polynomials Π^n. For an ordered set of points $(x_i, y_i) \quad i = 1 \ldots n$ the elements of the Newton basis are defined as

$$\begin{cases} \omega_0(x) &= 1 \\ \omega_k(x) &= (x - x_{k-1})\, \omega_{k-1}(x) \quad k = 1 \ldots n \end{cases}$$

so that $\omega_k(x) = (x - x_0)(x - x_1) \ldots (x - x_{k-1})$

The interpolating polynomial can be written as

$$p(x) = \sum_{i=0}^{n} c_i \omega_i(x)$$

where the coefficients are the divided differences, defined as

$$c_k = f[x_0, \ldots, x_k] = \sum_{i=0}^{k} \frac{y_i}{\prod_{j=0, j\neq i}^{k} (x_i - x_j)} \quad k = 0 \ldots n$$

The divided differences are computed using a recursive algorithm based on the following properties

1. $f[x_i] = y_i$
2. $f[x_0, x_1, \ldots, x_{k+1}] = \frac{f[x_1, \ldots, x_{k+1}] - f[x_0, \ldots, x_k]}{x_{k+1} - x_0}$

The value of the interpolating polynomial in the point $\overline{x}$ is computed using the Horner algorithm

$$p(\overline{x}) = c_0 + (\overline{x} - x_0)(c_1 + (\overline{x} - x_1)(\ldots + (\overline{x} - x_n - 1)c_n)\ldots)$$

The polynomial interpolation is computed on the points $(\ln E, \ln Eff)$, the real values are then recomputed applying an exponential function.

With the menu Configuration - View efficiency curve it is possible to compute the value of the efficiency based on the interpolation points, and to add other measured efficiencies. The value of the efficiency for the peak of ^{24}Na is shown and should be set in the preferences. If you want to use WinFluence for other nuclides you should look at the value of efficiency here and change it in the sample (in the tab "Advanced Features", button "Change Sample Parameters").

6 Acknowledgements

During this period of study and work at CERN I had the possibility to live an unique experience and to learn something about very interesting topics that I had never studied before.

I would like to thank my supervisor, Maurice Glaser, for the time he dedicated to me and for always caring about my work even when he was very busy; Federico Ravotti for his many advices and explanations (in italian) that I found very useful; all the people of PH/TA1 group, especially to Michael Moll and Alison Gouldwell for the very interesting workshop on silicon detectors. And finally thanks to everyone else I met here at CERN for making this summer be such a great time.