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1. Introduction

The AGS provides two very different primary proton beams for high energy physics experiments. One beam is the Fast Extracted Beam (FEB), U-line. The 12 proton bunches circulating in the AGS ring are extracted in the FEB line within one proton revolution period, i.e. 2.7 μ sec, with a repetition period typically 1.3 sec. The other beam is the Slow Extracted Beam (SEB), A-, B-, and C-line simultaneously. The spill of this beam can be as long as 1 sec and a repetition period typically 2.4 sec. The proton fluxes of the FEB are continuously monitored by a number of beam current transformers distributed along the beam. The proton fluxes of the SEB are continuously monitored by a number of Secondary Emission Chambers (SECs). The SEC can as well monitor the proton fluxes in FEB. Thus, in principle, the SEC can be calibrated against the current transformers in FEB before being installed in SEB. Unfortunately, it was found that the stability of the available SECs varies with time or rather varies with the total flux of protons that traverses them. It is, therefore, very desirable to calibrate the SEC in situ, under the actual running conditions experienced by the users. That is why these calibrations are done against the proton fluxes measured by the foil activation techniques (FAT).^{1,2} The high energy physicists, main users of the beams, often request the calibrations with the FAT.³ Many consider the FAT as a very accurate method of measuring proton beam fluxes. Accuracies of the order of 5% can be achieved if the cross section of the reaction is well known.

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2. Foil Activation Techniques

For many years now the foil activation techniques have been used to measure high energy proton fluxes around synchro-cyclotrons, proton synchrotrons and proton linacs. In any foil traversed by high energy protons a number of radioisotopes will be produced with particular radioactive constants: half-life, radiation, abundance. Now, if the activity of a particular induced radioisotope of the foil can be measured, and the cross section of the nuclear reaction of proton with foil material is known, then the proton flux that traversed the foil can be calculated. In practice, however, very few nuclear reactions induced by high energy protons with known cross sections are used.

Only two nuclear reactions induced in thin foils by high energy protons will be discussed here. This limitation is due only to the counting equipment available to us which counts the activity of the activated thin foils. These two reactions and their radioactive constants are listed in Table 1.^{4,5,6}

TABLE I

Thin foil:	polyethylene ~ 10 mg/cm ² mole CH ₂ = 14.027 g	aluminum ~ 13 mg/cm ² mole of Al = 26.98 g
Proton energy	28 GeV	28 GeV
Nuclear reaction	$p + {}^{12}_6\text{C} \rightarrow {}^{11}_6\text{C} + p + n$	$p + {}^{27}_{13}\text{Al} \rightarrow {}^{24}_{11}\text{Na} + 3p + n$
Adopted cross section σ	25 mb = 2.5×10^{-26} cm ²	8 mb = 8×10^{-27} cm ² *
Isotope	${}^{11}_6\text{C}$	${}^{24}_{11}\text{Na}$
Half life $T_{1/2}$	20.4 min.	900 min. (15 hrs.)
Decay constant $\lambda = \frac{1}{\tau}$	$0.693/T_{1/2} = 3.3977 \times 10^{-2} \text{ min}^{-1}$	$7.7016 \times 10^{-4} \text{ min}^{-1}$
Radiation energy, abundance	β^+ 0.96 MeV 100% γ 0.511 " 200%	β^- 1.389 MeV 100% γ 1.369 " 100% γ 2.754 " 100%
Counting rate at half-life from beginning of activation **	12-13 $\times 10^4$ counts for 10^{12} proton flux	4-5 $\times 10^4$ counts for 10^{14} proton flux

* Preliminary results of a new experiment to measure directly the $\sigma_{\text{Al}} ({}^{24}_{11}\text{Na})$ for 28 GeV protons in FEB against beam current transformers indicate that this cross section might be somewhat lower than the value reported here.

** Counts per minute on the scaler associated with the Well Counter #1 in the Chemistry Department counting room of CH₂ foils of 10-11 mg/cm² thick bombarded with 10^{12} protons ~ 20 minutes after activation, of Al foils of 12-13 mg/cm² thick bombarded with 10^{14} protons ~ 15 hours after activation. The duration of the irradiation is assumed to be very short compared with the

A number of other nuclear reactions are also used to monitor high energy proton fluxes, however, the measurement of the radioactivity necessitates a more sophisticated counting equipment. The FAT can also be used to measure other high energy proton beam parameters. For instance, interchanging the plain foil with a fine mesh the size of the FEB was measured.⁷

The following formula is used to compute the proton flux if the activity of a bombardment foil is counted:

$$\text{proton flux} = \frac{\Delta t A(t) e^{((t-\Delta t)\lambda)}}{N \sigma (1 - e^{-\lambda \Delta t})} \text{ protons}$$

If $\Delta t \ll \tau$ (very short duration of bombardment in minutes) where $\tau = \frac{T_{1/2}}{\ln 2}$

$$\rightarrow \text{proton flux} = \frac{A(t) e^{t\lambda}}{N \sigma \epsilon \lambda} \text{ protons}$$

Where Δt = duration of bombardment in minutes

$A(t)$ = counting rate per minute of activated foil t minutes from beginning of bombardment (cool-off period) background subtracted.

Correction of counting rate for long counting periods is necessary.

$$\lambda = \frac{1}{T_{1/2}} = \frac{1}{\text{half life of radioisotope}} \cdot \frac{1}{\ln 2} = \text{decay constant (min}^{-1}\text{)}$$

N = number of atoms/cm² of the foil material

$$N = \frac{6.023 \times 10^{20}}{\text{molecular weight of the foil material}} \times \frac{\text{mg/cm}^2}{\text{foil-cut.}} \text{ of the activated}$$

mole of CH₂ = 14.027 gr.

mole of Al = 26.98 gr.

σ = cross section of the nuclear reaction used in cm²
(1 mb = 10⁻²⁷ cm²)

ϵ = efficiency of the counting equipment including evaporation for polyethylene foils.

All our activity measurements were done using either the Well Counter #1 or Well Counter #3 in the Chemistry Department counting room.

The maintenance and calibration of these counters is the responsibility of James Cumming. He and his co-workers know all about the counting equipment including the counter efficiency for each radioisotope.

We mentioned for reference the efficiencies we have used for all the activity measurements we have done.

Well Counter #1: efficiency for $^{11}_6\text{C}$ = 0.649, efficiency for $^{24}_{11}\text{Na}$ = 0.517

Well Counter #3: efficiency for $^{11}_6\text{C}$ = 0.636, efficiency for $^{24}_{11}\text{Na}$ = 0.513

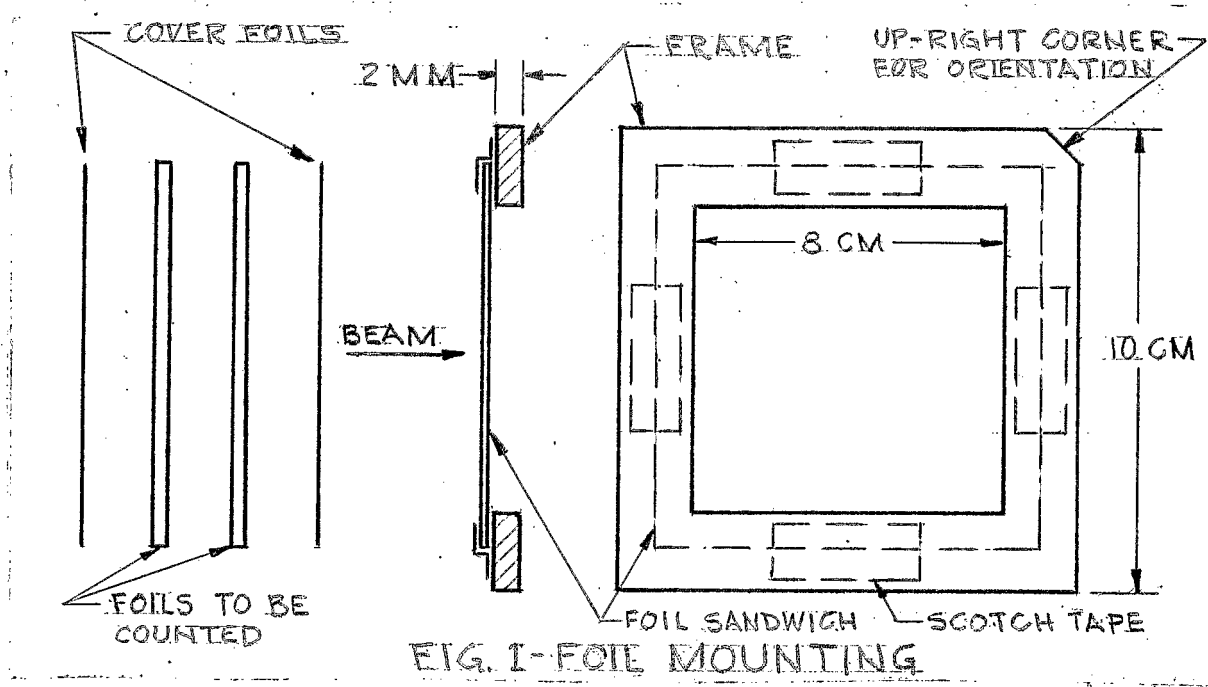
We have used Well Counters frequently during the last two years, and we noticed that the well counter efficiencies remained remarkably constant.

3. Preparation of Foils for Activation

As we have mentioned, two different foils have been routinely used: aluminum foils and polyethylene foils. The Beam Diagnostics Group possesses good quality pure aluminum foils of $\sim 50 \mu\text{m}$ of $12\text{-}13 \text{ mg/cm}^2$ thick and also good quality polyethylene foils of $\sim 100 \mu\text{m}$ of $10\text{-}11 \text{ mg/cm}^2$ thick. However, we noticed that the thickness of both foils varies from foil-cut to foil-cut. Variations of foil thicknesses as high as $\pm 5\%$ were observed. J. Cumming possesses aluminum foils with much less variation in thickness. The foils must be plain, flat, uniform in thickness, and have clean surfaces without wrinkles or holes. For supplementary security the foil to be counted must be sandwiched between two very thin foils of the same material so that recoils leaving the foil are replaced by recoils from the cover foils. The cover foils also protect the foil to be counted from contamination by recoils from other materials struck by the beam, i.e. air, vacuum windows, other foils, etc. The foils, however, cannot be protected from neutrons produced in the immediate vicinity. Both radioisotopes used are very sensitive to low energy neutrons. In order to increase the statistics of a proton flux measurement by the FAT, two or more counted foils of the same material can be covered by the same cover foils. A very thick sandwich will introduce errors in the measurement itself because of secondaries produced by interactions of the primary protons.

The sandwiches are then carefully mounted on lucite or cardboard frames. These frames help to keep the foils flat and place them as perpendicularly as possible into the beam. The preparation of the foil sandwiches and the mounting on the frame must be done on a very clean table and always using cotton gloves and tweezers. The outer dimensions

of the frames depend on the geometry of the available gap in the beam and the surrounding equipment. When the position of the beam spot is not well known the foils surface must be large enough to cover all possible beam position spots. For foil activation in CE012 instrument box in SEB a special plug-in foil support has been constructed. We found this support very useful and we suggest wherever it is possible to construct similar supports. The plug-in support permits one to mount the sandwiches with all the necessary attention in the lab. The CE012 instrument box is under vacuum. It is necessary, therefore, to follow a well predetermined procedure of closing a vacuum valve, stopping a rotary pump, bleeding the vacuum before opening the instrument box to plug in the foils for activation. A. Soukas must be informed in advance each time an activation must take place in CE012 instrument box.



4. Activation of Foils

Whenever it is necessary to activate foils for calibration purposes in a high energy proton beam, the following conditions must be met:

a) The AGS and extraction channel are set up and tuned for maximum efficiency.

b) The beam spot at the location of the foils is small and remains fixed. Large beams or moving spot beams introduce errors in counting the activity.

c) There is no large beam loss occurring in the vicinity of the foil location, especially in the upstream direction. Such losses very easily effect the activation, i.e. obtaining a very erratic result of the proton flux.

The locations of foil activation around the AGS are very well defined and almost all are near focusing points of the beam. The duration of activation is a function of two main parameters:

a) Flux of protons per machine cycle, the fluxes of the AGS beam cover the range of $10^9 - 10^{13}$ protons per cycle.

b) The radioisotope to be counted, i.e. $^{11}_{6}\text{C}$ or $^{24}_{11}\text{Na}$, see Table 1. In order to avoid complicated corrections for the variation in beam intensity during activation it is desirable to activate the foils for a period of time less than 10% of the isotope half-life.

With the help of the data in Table 1, one decides which of the radioisotopes will be adequate for each particular activation. In many cases both isotopes can be used. The use of $^{11}_{6}\text{C}$ isotope is limited by its relatively short half-life (20 min.). But because of this short half-life and its large cross section (25 mb), this isotope is frequently used for low intensity beams. However, the activity of the foil has to be measured within a few half-lives. That means that everything has to be done quickly and everything must be available on hand. Another advantage of the $^{11}_{6}\text{C}$ isotope is the quick result of the measurement. Therefore, another activation can take place within say, one hour, if something in the procedure of activity counting went wrong. The long half-life of $^{24}_{11}\text{Na}$ permits long activation periods. But long activation periods necessitate very stable machines. With the $^{24}_{11}\text{Na}$ isotope the result is obtained 24 hours or more after the activation took place.

For each activation a number of people are involved and coordination is necessary. In general, the following procedure is observed:

a) The machine, the extraction and beam transport are in normal operation.

b) The rf is cut off at a predetermined time.

c) A cool-down period of the order of 10 minutes for radioactive hot areas is observed.

d) The installation of the foils is then done as quickly as possible.

e) Stop and reset scalers in MCR.

f) Start machine by energizing the rf, start scalers. Write down exact time of start of activation. (A stop watch is very useful, especially for polyethylene foils.) A pulse-by-pulse registration of the scalers is an advantage as it permits us to know the stability of the machine during the activation. This can be obtained only if the computer and Datacon are used. R. Witkover wrote a number of programs which register on the computer disk data for some of the foil activation runs.

g) The end of activation is obtained again with the push button of the rf at off-position. Write down exact time of stop of activation, also write down the number of machine bunches and the machine cycle. Stop scalers. (DO NOT RESET SCALERS.)

h) Write down scaler readings and check readings once again.

If an interruption of the activation occurred or erratic bunches bombarded the foil, it is necessary to start the activation with new foils. The new activation will take place only after conditions 1-3 are again fulfilled.

5. Handling of the Activated Foils

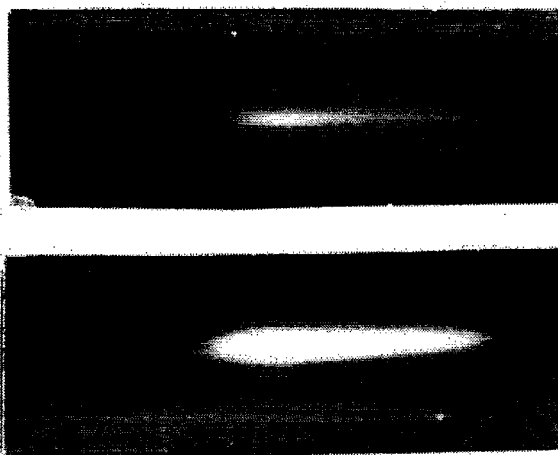
Immediately after an activation, the induced radioactivity of the foils is very high. Dose rates as high as 5 rem/hr on contact have been measured (foils bombarded with $\sim 10^{14}$ protons).⁹ However, most of this radioactivity is due to very short half-life radioisotopes. The dose rates decay very quickly. In order to transport the foils to the counting room at the Chemistry Department building, a steel box of 2 mm thick will stop practically all the beta particles emitted from the foils.

A number of manipulations of the foils to be counted are necessary and because of the radioactivity they have to be treated with care. Avoid direct contact with the spot, wear gloves and preferably use tweezers and keep yourself as far as possible from the foils. The manipulations are as follows:

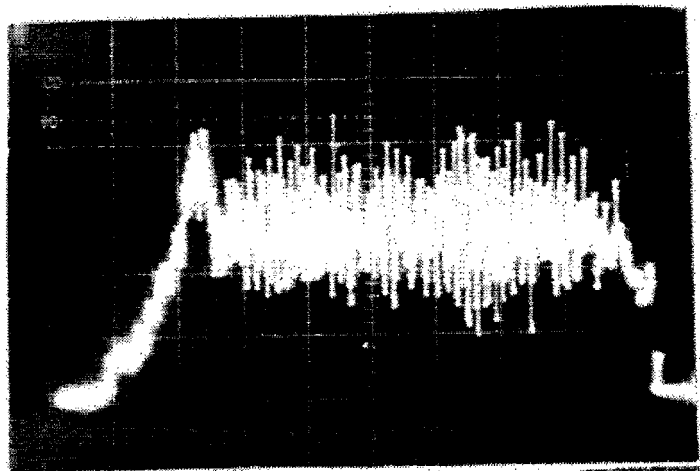
5.1 Making Autoradiograph

In order to locate the center of radioactivity of the foils to be counted it is necessary to make an autoradiograph. A correctly exposed autoradiograph gives the shape and dimensions of the beam during

the activation as well. Correct exposures are obtained by trial and error. For instance, a sandwich of 3 polyethylene foils and cover activated with 10^{13} protons will give a good autoradiograph for contact exposures of the order of one minute at about 10 minutes after activation. A sandwich of 3 aluminum foils and cover bombarded with 10^{14} protons needs 10 minutes contact exposure at about one hour after activation. For autoradiograph the Polaroid 4" X 5" Land film packets, Type 57 (high speed), are used. For correct development of the exposed film the Polaroid Land film holder #500 is needed. The procedure of making autoradiographs is as follows: The activated sandwich still on its frame is placed in direct contact with the outside of the film packet over the sign: "This side towards lens". Tape the foil down with masking tape and mark its location on the packet by tracing around the frame with a ball-point pen. Now identify the upright corner of the frame so the orientation can be obtained on the autoradiograph. Count exposure time and develop the film. After development, open the packet but do not remove autoradiograph. Reposition the frame and the mark on the foils the center of radioactivity as well as the outer dimensions of the spot. The spot appears much larger than it actually is when the film is overexposed. Figure 2 is a reproduction of two beam spots obtained from the same activated foil but with different exposure times. The spill of the beam during the foil activation is also shown.



AUTORADIOGRAPHS OF
THE ACTIVATED FOIL WITH
DIFFERENT EXPOSURES



SEB SPILL 100msec/cm
DURING THE FOIL ACT-
IVATION ON 9/23/76

FIG.2 SEB CEOIO BEAM SHAPE & SPILL

5.2 Cutting the Foils

In order to measure the activity of the foils only the part of the foil containing the spot is necessary. Therefore, the foil is cut in a regular geometric form. This will permit measurement of the area of the foil piece to be counted. For small spots, circular punching dies are used. For large spots rectangular pieces are carefully cut. The dimensions of the foil cuts are then measured very carefully. The foils are then separated and numbered and inserted in separate envelopes. Each envelope identifies a particular foil-cut. The surface in cm^2 of each foil is also noted on each envelope. In order to measure the radioactivity of the foil outside the spot, another piece is cut around the hole made by the foil-cut with the spot, of a total surface equal to the foil-cut. The counting rates of this background specimen will indicate the presence of a halo or big losses occurring upstream of the sandwich. This background foil-cut is treated exactly in the same way as the foil-cut with the spot.

5.3 Weighing the Foil Cuts

In order to determine the number of atoms/ cm^2 of the foil material activated by the protons it is necessary to know the thickness of the foil-cut in mg/cm^2 . The foil-cut area is known by the previous operation. Measuring its weight will permit us to determine the thickness in mg/cm^2 . The Chemistry Department possesses a number of very sensitive balances. Therefore, the weight of each foil cut is easily obtained. The weight of each foil-cut is also written on the corresponding envelope. This means that the N atoms/ cm^2 for the formula which will give the proton flux is then known. We assume that there is very little variation of the thickness on the particular foil-cut. Notice that the weighing of the foil-cuts can be done after the counting of the foils.

5.4 Preparation for Counting

The foil-cuts are now folded with the aid of tweezers and inserted into special copper cups available in the counting room of the Chemistry Department. The given counting efficiency of a particular Well-Counter is correct only if the copper cups are used and if the foil-cut is at the bottom of the cup.

5.5 Counting the Foils

Introduce the copper cups with the folded foil-cut to be counted in the well counter and start and stop the scaler for the time period desired. Then write down the exact time counted from the beginning of the activation in minutes. As well as the readings of the scaler, i.e. the counted disintegrations of the adopted isotope. For most cases a one-minute counting period is sufficient. For better statistics, longer periods can be used but then the counting rate has to be corrected. This correction is very important for the $^{11}_6\text{C}$ isotope with its short half-life. From time to time you also count the background counting rate. Place the copper cups and any other radioactive material outside the counting room. If you have say 4 copper cups to count, one after the other, proceed as follows: Keep the cups on the table opposite the well-counter. Take one cup and introduce it in the well counter. The other three cups are always on the table far from the well counter.

Figure 3 is a photocopy of the proton flux measurement by foil activation data sheet, with all the data of a particular activation run and the associated computation of the proton flux.

6. The Well-Counter

Figure 4 illustrates schematically the well-counter or γ -ray counter and the associated electronics.

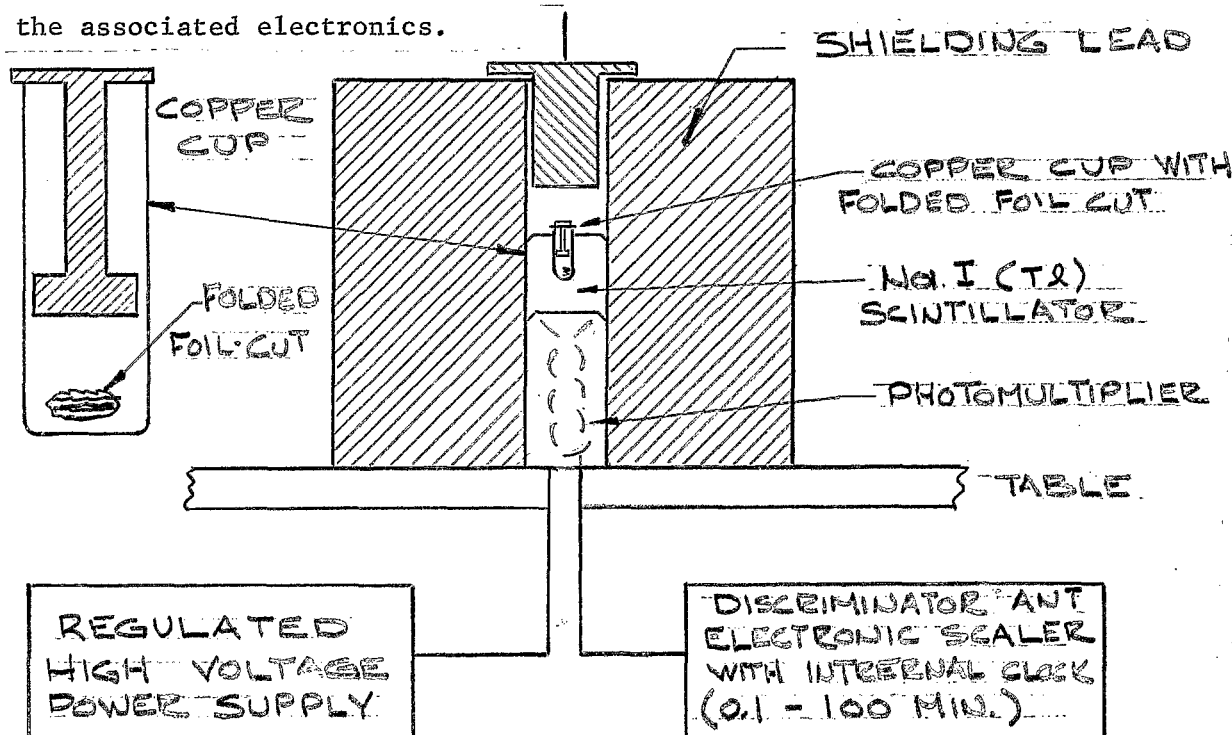


FIG. 4. WELL-COUNTER AND ASSOCIATED ELECTRONICS

PROTON FLUX MEASUREMENT BY FOIL ACTIVATION DATA SHEET

GENERAL DATA

Foil Activation # 18-A1-2 Date 9.23.76 Machine Pulses 10
 Start 8:02:34 Stop 8:02:58 T(min) 0.25
 Beam location CE 012 Energy (GeV) 28 Machine cycle (sec) 2.4
 Beam Intensity Monitor SEC CE010 Reading (protons) 5.13×10^{13}
 Foil Material ALUMINUM Mole: M(g) 26.98 Density 2.7
 Foil-cut: Area (cm²) 5.9 Weight (mg) 76.5 Thickness (mg/cm²) 12.796
 $N(\text{atoms/cm}^2) = (6.023 \times 10^{20}/M) \times \text{thickness} = \underline{2.857 \times 10^{20}}$
 Radioisotope ^{24}Na $\sigma(\text{mb})$ 8 Half life $T_{1/2}(\text{min})$: 900 (15h.)
 $\tau = \text{half life}/\ln 2 (\text{min})$ 1298 $\lambda = 1/\tau = \underline{7.7016 \times 10^{-4}}$
 Well Counter: # 3 Counting efficiency: 0.513

Counting Data

Date	Time Scaler On	Counting Period $\Delta t(\text{min})$	Cool-off Period t(min)	Total Counts	BKG per min.	Net and Corrected $A_t(\text{CPM})$	$A_0 = A_t e^{\lambda(t-\Delta t)}$	
9.24.76	9:29	1	1527	18728	108	18600	6.029×10^4	
..	9:41	..	1541	19079	..	19000	6.225 ..	
..	9:52	..	1550	18602	..	18500	6.104 ..	
..	15:37	..	1895	14141		14050	6.045 ..	
..	15:45	..	1903	14175		14100	6.105 ..	
..	15:53	..	1911	13960		13900	6.056 ..	

$$\bar{A}_0 = (6.094 \pm 0.0713) \times 10^4$$

$$\text{Proton flux} = \frac{\Delta t \bar{A}_0}{N \sigma (1 - e^{-\lambda \Delta t})} \text{ or if } \Delta t \ll \tau \text{ Proton flux} = \frac{\bar{A}_0}{N \sigma \lambda} = 6.74 \times 10^{13} \pm 1.2 \%$$

The main parts of the well-counter are:

a) A sodium iodide thallium activated (Na I Tl) an inorganic scintillator. The γ -ray counting efficiency of such a scintillator is very high and its fluorescent efficiency is also very high. Because of its high Z it easily stops electrons.

b) A photomultiplier which will transform the photons produced in the scintillator into a good and measurable electrical pulse for each converted γ -ray.

c) A thick lead absorber all around the scintillator and the phototube. The copper cups are inserted in the counter from the top through a coaxial hole, the "well". That is why the system is called well-counter.

d) A very well-regulated high-voltage power supply which provides the voltage for the photomultiplier voltage divider.

e) An electronic scaler with pulse height discriminator and with internal timing unit can count the counting rates of the activated foils. The internal timing unit is in intervals of 1/10 of minute.

No saturation phenomena were observed even in cases of counting rates higher than 300,000 counts per minute. A few times, however, we observed an overall variation of the counting efficiency. We did not arrive to understand to what these variations are due. That is why for each foil a number of counting rates are measured at different times. A plot of these rates against time in an adequate semilogarithmic paper will give a straight line, the decay line of the particular isotope. If the points obtained are not in a straight line then something is wrong and the proton flux cannot be obtained.

7. Conclusions

Since November 1975 we performed about 40 foil activations of polyethylene and aluminum. The results obtained were consistent and the overall accuracies obtained were within $\pm 5\%$. With a modern scaler and time counter as well as more uniform thickness aluminum and polyethylene foils, even better results can be obtained. In order to avoid evaporation phenomena in polyethylene foils it will be preferable to use plain carbon foils (graphite)

8. Acknowledgments

I am grateful to Jim Cumming for his continuous help I received since the first day of my work at Brookhaven National Laboratory. All the measurements were done in his counting room and the established procedures described in this paper are mostly due to the continuous discussions I had on the subject with him. I am also grateful to Sam Baker of Fermilab with whom I also had the pleasant opportunity to discuss, in detail, the foil activation techniques for monitoring high energy proton fluxes.

The foil activations would not have been possible without the help and cooperation of the AGS Division Staff, especially the members of the Operations Group, Beam Diagnostics Group, Electronic Support Group and the External Beam Group. Many measurements could not have been done without the direct collaboration of J. Balsamo, A. Soukas, Y.Y. Lee, R. Witkover, S. Naase, R. Dryden and J.D. Klein. I am grateful to them all. I am especially indebted to Lyle Smith for the opportunity and continuous encouragement he gave from the beginning of the study of intensity monitoring techniques.

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