Practical method to calibrate large arrays of detectors, the example of the HILI

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Calibration of large arrays of detectors presents a non trivial problem, especially if non linear responses have to be dealt with, and a large variety of particle species is present. Based on a recent successful description of the light induced in scintillators by diferent ions, we propose an application to the practical case of the calibration of the HILI hodoscope array (192 phoswich detectors) for any particle. We are illustrating the method using alpha particles.

Keywords: Nuclear instrumentation, article detectors, sciltillators, heavy ions

La calibración de sistemas de detección con un número muy grande de detectores ha sido un problema no trivial, especialmente si sus respuestas son no-lineales y se involucra una gran variedad de partículas. Aqui proponemos una aplicación, basada en una reciente y exitosa descripción de la emisión de luz inducida por diferentes iones en un centellador y describimos el caso de la calibración del hodoscopio del sistema de detección HILI que consiste de 192 centelladores, ilustrando el método con partículas alfa.

Descriptores: Instrumentación nuclear, detector de partículas, centelleadrores, iones pesados

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1. Introduction

Exclusive studies of particle production are nedded to distinguish among the different processes that arise in the heavy-ion nuclear reactions as the energy increases. This leads to the need of large arrays of detectors. An example is the HILI (heavy ions light ions) detection system [1], currently coupled to the Texas A&M University superconducting cyclotron.

This detection system consist of several coupled stages, the last one, which is relevant for the present work, is a hodoscope of 192 plastic $\delta E - E$ scintillator phoswiches. In reactions above 10 MeV/nucleon induced by heavy ions ($A_1 + A_2$ around 100), fast fragments with $3 < Z < 25$ are produced and reach the hodoscope. The problem of energy calibration of the array becomes then a formidable task.

Attempts to give a global formula to calibate all the detectors simultaneously have been reported [2]. In this work we describe a method to calibrate the energy of any particle species, based on a reliable proton calibration of each phoswich and on a recent model by Michaelian and Menchaca-Rocha [3] that describes the production of light induced by energetic ions in scintillator materials.

2. Basic ideas of the procedure

The model by Michaelian and Menchaca-Rocha, describes the production of light induced by energetic ions as they pass through a scintillator and is based on the distribution of energy deposited by the secondary electrons produced along the tack of the ion. An impulse approximation and a constraint to radial direction (perpendicular to the ion's track) are used to determine the initial energy of the electrons. Lindhard's potential theory [4] is used to obtain the specific energy loss and from it the residual energy of the electrons. The model then provides simple algebraic expressions for the especific luminiscence dL/dx that includes contributions from backscattered electrtons to the energy deposition. The calculation contains one parameters that depends on the scintillating material only, the so called quenching density. In our case we used the value of 10^6 erg/g recomended for plastics [5]. With this, the model yields predictions for light output as a function of particle energy and species. Since quenching effects were neglected in the model a "Z" dependence is left through an overall normalization factor to be determined by at least one experimental point. However, as it has been shown [3] the "Z" dependence of this normalization factor is only strong for the lighter particles $Z < 6$, this factor tends to reach a constant value as Z increases.

We aim to solve two problems; (i) very often, only a fraction of all detectors in a large array will have a full set of calibration data and (ii) it is practically impossible to obtain experimental calibration data points for all ion species.

To address the first problem we will try to extract a "universal" dependence of E_z on E_p (not on the light output itself). This will be carried out using the model described above. To proceed, we found that E_z has a smooth dependence on the light output. This can be modeled using a simple polynomial of second degree

$$E_z = a_z + b_z L + c_z L^2,$$

where L is the light output. To do it, we need at least one experimental data point for that particular species as point out already.

On the other hand, the model predicts an almost linear relation between the proton energy E_p and the light output in a proton energy range much large than what we need here, at least up to 350 MeV. One can express it as a function of the other by a linear equation of the other by a linear equation or include a small quadratic correction. So we write:

$$L = r + sE_p + tE_p^2$$

an idea of the accurafy of the fit is investigated through the χ^2 value with up to 100 points evenly spaced in the proton energy range from 0 to 200 MeV. These values are typically very small: 10^{-5}. The coefficients (r, s, t) carry the experimental calibration information since the model needs those data to calculate the normalization factor as described above. Combining the previous two equations one gets a fourth degree polynomial for E_z as function of E_p:

$$E_z = A_z + B_z E_p + C_z E_p^2 + D_z E_p^3 + F_z E_p^4.$$

This equation will only be of interest if all the coefficients A_z, B_z, C_z, D_z, and F_z for all detectors have close values, so an average or "universal" equation can be used for all detectors for a given Z. This completes the procedure that gives a general recipe to make an energy calibration for all ion species, based on a proton energy calibration and a few calibration points in some detectors for heavier ions. The E_p calibration should take care of individual detector particularities such as: light collection efficiencies, geometry, transmission and conversion into an electric pulse amplitude. Its precision is critical in the calibration of other ions.

In our experiments we are interested in energies above our particle energy thresholds (about 7 MeV for protons), lower energies are beyond the scope of the present study. It should be pointed out however that, since we are dealing with non linear responses, specially at low energies, we need not expected our equations to give $E_z = 0$ for $E_p = 0$.

The second problem, that is energy calibration for all ion species, in principle one needs at least one experimental data for each particle kind (Z), to find the corresponding normalization factor. But this becomes unnecesary with this model once we take advantage of the approximately constant value reached by the normalization factor for heavy particles and use the same constant for all particle species heavier than carbon or oxygen.

To summarize; (1) Get an accurate calibration for protons. (2) Transform every signal from the array into an energy E_p assuming it may be a proton. (3) Use the ability of HILI to identify particles, to determine the real "Z" of the detected particle. (4) Convert E_p to E_z for the correct Z of the particle using the global equation.

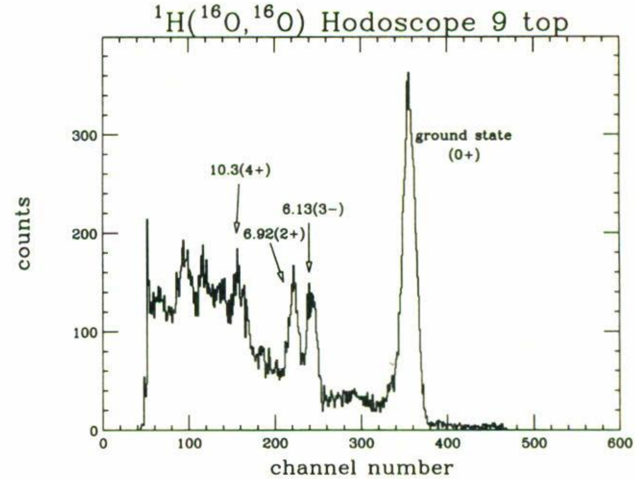

Figure 1. Typical proton spectrum observed in the hodoscope for proton calibration. The system used was ^{16}O beam at 200 MeV on a polypropilene target. The observed peaks are indicated in the figure.

3. Experimental techniques

The procedure described in the previous section was tested using the hodoscope array of HILI. A 200 MeV oxygen beam was put on a polypropilene target in order to detect recoil protons in the HILI. Figure 1 shows a typical proton light output spectrum recorded in one of the phoswich elements. The observed peaks correspond to states in $^{16}\mathrm{O}:\mathrm{O}^+$, ground state, the $6.13\,(3^-)$, $6.92\,(2^+)$, and the $10.35\,(4^+)$. Sometimes the $9.9\,(4^+)$ state was also seen.

Simultaneously, alpha particles were recorded and identified using standard $E - \delta E$ techniques with the phoswiches. A typical light output spectrum for alphas is shown in Fig. 2.

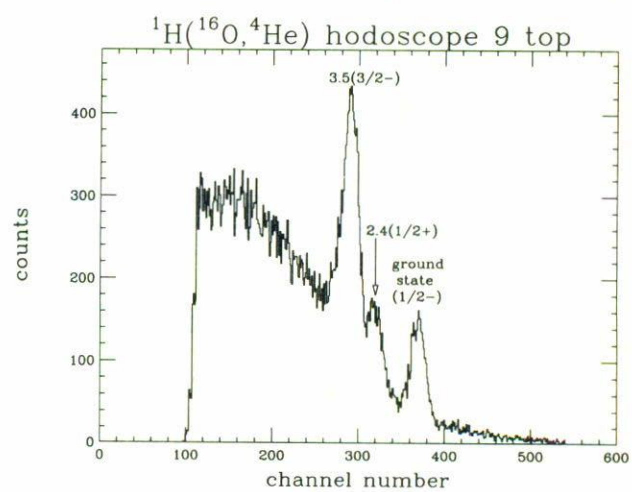

Figure 2. Alpha spectrum registered simultaneously in the calibration run. The three ^{13}N levels are indicated in the figure.

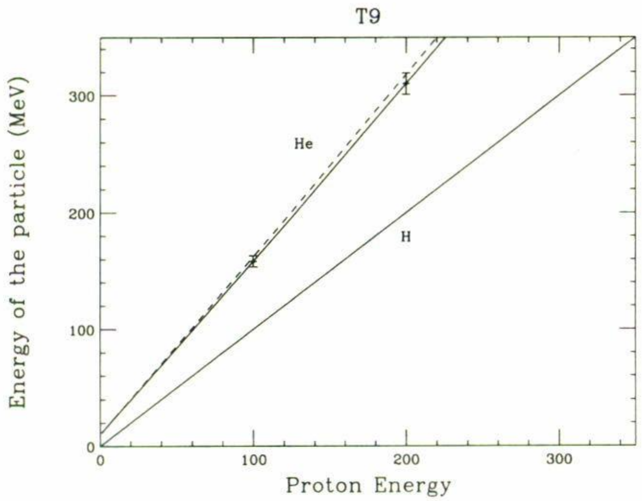

Figure 3. Calibration curves for different ions and a typical detector. Solid lines are quadratic polynomials calculated with the method. Experimental points for protons (diamonds) and alphas (crosses) are indicated.

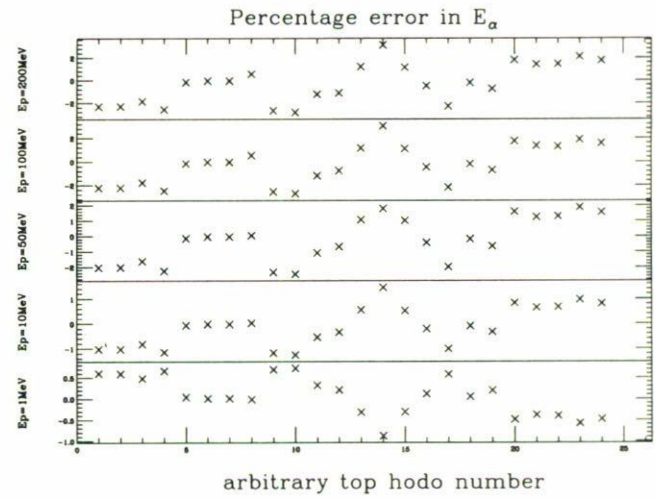

Figure 4. Percentage error in E_α, for each of the detectors having an alpha spectrum and for different E_p values (1, 10, 50, 100, and 200 MeV). The phoswiches are numbered arbitrarely.

Peaks here correspond to states in ^{13}N : ground state $(1/2^-)$, $2.37\,(1/2^+)$, and $3.50\,(3/2^-)$.

Calculated light output curves as function of particle energy in comparison with experimental data points are shown in Fig. 3 for one of the central-most elements of the array. It can be noted that the shape of the dependence is well predicted both for protons and alphas since all data points lie on the appropriate curve, once the normalization factor is found.

Elastic and inelastic scattered protons reach all 192 elements of the hodoscope ($\theta < 25°$), so a fairly accurate energy calibration in the low energy range can be achieved. We take the results of the calculation as the appropriate way of the extrapolating to higher energies. This completes our full range proton energy calibration procedure.

Recoil alpha particles on the other hand cannot kinematically reach the outer most elements of the hodoscope. For those elements for which alpha data points exist, we can get individual calibrations. In order to test our procedure, we also calculate the coefficients of the fourth order polynomial that gives alpha energy, calculating it first as proton energy and then transformating it as described above. We extract a global transformation, using averaged coeficients taking into account the 24 phoswiches where an alpha spectrum was recorded in the top part of the array (over beam direction), that yields:

$$E_\alpha = 10.0975 + 1.5011E_p + 2.0891 \times 10^{-4}E_p^2 - 6.3617 \times 10^{-8}E_p^3 - 7.3453 \times 10^{-12}E_p^4.$$

In order to have an idea of how much we will deviate from the calibration obtained for each detector, by using this average or global equation, Fig. 4 shows the percentage error commited in the alpha energy for several values of E_p. It is worth noting that deviations remain in all cases on the order of 3% or lower for the top hemisphere and less than 10% for the bottom part. We point out that, as discussed above, the energy range for protons in our detectors goes from 7 to less than 100 MeV, however in the figure the range has been extended from 1 MeV to 200 MeV. The lower energy range, from 1 to 7 MeV is never used. However, heavy ions in our detectors produce light output equivalent to very energetic protons, and then the high energy extension of the proton energy is used, not for protons, but for heavier particles.

In Table I, we reproduce in tabular form, what is shown in Fig. 4 but for the detectors that have been used as example in all figures (top 9) and to the symmetric one at the bottom hemisphere (bottom 9).

Figure 5 shows the He energies as a function of proton energy calculated with the exact transformation function for phoswich T9 with a solid line. The dashed line is the curve given by the global transformation function.

We will use this global equation as our energy calibration for all elements of the array. This also gives us a calibration for alpha particles for the outer most elements, with estimated accuracy better than 10%.

TABLE I. Differences in percent between the global and the specific calibration for two different phoswich. The election of the detectors is explained in the text.

E_p(MeV)	T9%	B9%
1	0.66	1.22
10	1.15	1.99
25	1.86	3.12
50	2.27	3.81
75	2.35	3.87
100	2.48	4.13
200	2.57	4.27

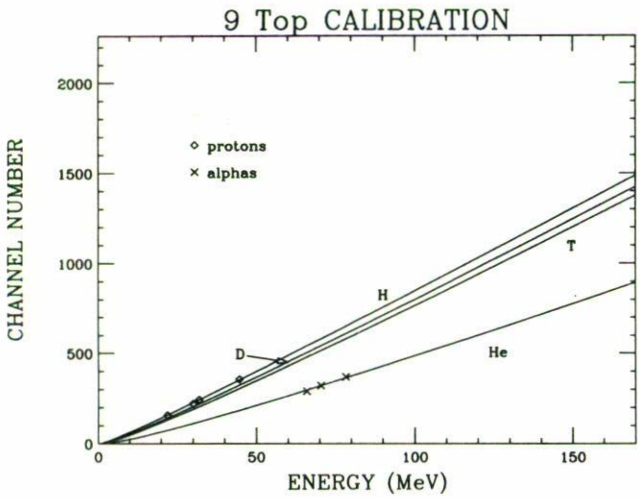

Figure 5. Example of the He energies as function of the proton energy for one of the detectors. Solid lines are the exact calculation for this particular detector while dashed lines correspond to the calculation using the global transformation function. The error bars drawn for $E_p = 100$ and 200 MeV are 3%.

As mentioned before, we need at least one experimental data point to calibrate the heavier elements. At the moment we lack experimental data points to test our procedure there. However, an experiment is being planned just to measure the needed data points, in the near future. A full report on our procedure will then appear.

4. Conclusions

Based on a model that describes the light output for scintillating materials accurately, we developed a method for energy calibration of large arrays of scintillators. We applied it to the specific case of the HILI detection system and found good results for alpha particles. It was found that one single equation can be used successfully to get alpha energy for any elements of the array provided a good proton calibration is available for each individual detector. If the proton calibration is not very good, the global calibration will also yield poorer results. The extension of this method for particles other than alpha is indicated.

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