Response of YAP:Ce scintillators to energetic heavy ions

M Barbui, A Andrighetto, M Cinausero, G Prete, V Rizzi, S Pesente, D Fabris, M Lunardon, M Morando, S Moretto, G Nebbia, S Pesente, G Viesti, F Bocci, K Hagel, S Kowalski, T Materna, JB Natowitz, L Qin, R Wada and J Wang

1 INFN Laboratori Nazionali di Legnaro, Italy
2 INFN and Dipartimento di Fisica dell’Università di Padova, Italy
3 Dipartimento di Meccanica dell’Università di Brescia and INFN Pavia, Italy
4 Texas A&M University, Cyclotron Institute College Station, USA-TX

marina.barbui@lnl.infn.it

Abstract. The response of YAP:Ce scintillators to energetic heavy ions in the mass range A=20-200 has been studied. The pulse height and the pulse height resolution have been explored in details for a single YAP:Ce crystal, coupled to R4141 PMT, by using $^{20}$Ne, $^{40}$Ar, $^{84}$Kr, $^{129}$Xe and $^{197}$Au beams having energies ranging from 40 A MeV to 15 A MeV. Energy degraded beams have also been employed in order to cover a large energy range. Finally, timing properties were studied in the BIGSOL spectrometer at Texas A&M by measuring the heavy fragment time-of-flight against a PPAC detector.

1. Introduction

The YAP:Ce (yttrium aluminum perovskite, YAlO$_3$) crystal is a new inorganic scintillator material that has become commercially available in recent years. Several studies have been performed so far [1-5] in order to define the properties of the crystal, such as the light yield, pulse shape and energy resolution. In such studies, gamma rays, electrons, alpha particles and heavy ions having medium $Z$ ($Z < 35$) and low kinetic energy ($E < 40$ MeV) have been used. As a result, interesting properties of the YAP:Ce crystal have been observed, such as the linearity of the light yield as a function of the energy for $\gamma$-rays and electrons and a very good energy and time resolution. However the response of the YAP:Ce scintillators shows a non-linear light yield to low energy heavy ions. In this study we extend the knowledge on the YAP:Ce properties to heavy ions with higher energies in the mass range A=20-200. This study is motivated by the use of an array of 14 YAP:Ce scintillators in the focal plane detector of the BIGSOL spectrometer at the Cyclotron Institute of Texas A&M University.

The measurements were performed mainly at the Radiation Effects Facility at the TAMU Cyclotron Institute. The light output and the resolution have been studied in detail for a single YAP:Ce crystal (from Crytur, 3 mm diameter and 3 mm thickness), coupled to R4141 Hamamatsu PMT) by using a large number of heavy ion beams: $^{20}$Ne at 40, 25 and 15 A MeV; $^{40}$Ar at 40 and 25 A MeV; $^{84}$Kr at 25 and 15 A MeV; $^{129}$Xe at 15 A MeV; $^{197}$Au at 15 A MeV.

Tests were performed using both direct beams as well as energy degraded beams to cover the largest possible energy range. Timing properties were also studied with the scintillators of the array mounted in the focal plane of the BIGSOL spectrometer by measuring the heavy fragment time-of-flight against a PPAC detector.
The results obtained so far in terms of pulse height and time resolution and light yield as a function of mass and energy of the ions are presented in this paper.

2. Experimental set-up
The measurements were performed at the Radiation Effects Facility at the Cyclotron Institute of Texas A&M University where it is possible to directly irradiate samples with low intensity heavy ion beams. A schematic drawing of the experimental area is shown in figure 1.

The YAP:Ce detector was mounted inside a 30” vacuum chamber, where all measurements were performed.

A beam degrader system was used in order to obtain beams of different energy. It consists of a set of ten Aluminum foils of thickness increasing by a factor of two from 0.001” to 0.512”. A rotation of the foils of a maximum of 60° with respect to the beam direction allows obtaining all possible thicknesses. The foil area (5.8” x 2”) is large enough to degrade the entire beam without hitting the foil support frame that holds each foil. These individual frames are attached to a larger holding system to form a single unit. This holding system is mounted into a custom-made UniSlide positioning system, which allows for vertical motion and for the selection of the desired foil in front of the beam. A UniSlide rotary table is also used to rotate the entire vertical assembly to the selected angle.

Figure 1 Schematic view of the experimental set-up. The degrader box and the 30” vacuum chamber are shown.

Computer-controlled stepping motors are used for both the vertical positioning and the rotary table. These motors interface with software (SEUSS) based on the Ziegler stopping power algorithm. The SEUSS software calculates the foil to be used and the corresponding rotation angle necessary to obtain the requested energy of the degraded beam. Cameras are used to verify accurate vertical and rotary positions. The complete assembly is housed in a large-diameter stainless steel vacuum chamber.

A standard ORTEC power supply (Mod. 556H) was used for the YAP:Ce photo-multiplier allowing different bias from 400 to 800 V. The PMT anode signal was sent directly to an ORTEC Dual Spectroscopy Amplifier (Mod.ORTEC 855) for proper shaping and gain setting. The output of the
amplifier was sent to a CAMAC Phillips ADC (Mod. Phillips 7164 16ch peak ADC) of the data acquisition system. Data analysis was performed on-line and off-line using ROOT based software tools.

3. YAP:Ce pulse height
In the off-line analysis, we derived the pulse height as a function of the kinetic energy of the ion beams for PMT voltages of 400 V, 600 V and 800 V. The measured pulse height depends on the intrinsic light output of the scintillators and on the PMT gain. Deviation from a linear relationship between kinetic energy and measured pulse height might indeed be due both to the quenching of the scintillation light inside the crystal and to saturation effects at the PMT level. Changing the PMT applied voltage allows to identify this latter effect.

In this analysis both direct and degraded beam data have been included. In order to directly compare the pulse height for different ions, we plotted the measured pulse height per unit energy as a function of the kinetic energy per nucleon of the ion beam. Figures 2 (a, b, c) report the data for PMT voltage of 400 V, 600 V, 800 V respectively. We are mostly interested in the 400 V and 800 V data. In fact, the 400 V data exhibit a linear behavior for heavy ion energies above 10 A MeV. On the other side, the YAP:Ce detectors in the BigSol array were operated mainly at 800 V during the test runs of the spectrometer. This is motivated by the requirement of detecting both the implanted heavy fragment and its possible alpha particle decay.

When the applied voltage is 400 V, the pulse height per MeV energy increases with the ion kinetic energy up to 10 A MeV and then remains roughly constant. At low kinetic energies, the rising of the light output is due to the well-known quenching effect associated with the detection of heavy fragments [6]. Moreover, in the kinetic energy range above 10 A MeV, where the pulse height per MeV results to be rather constant, the absolute value of the light output per MeV depends on the ion mass, decreasing with increasing the mass of the detected fragment. This is certainly an effect due to the different range of the ions inside the crystal and is associated with quenching effects. When the data relative to a given beam are considered, the measured maximum dispersion of the pulse height per unit energy for Ar and Xe beams is about 6% and about 3% for Au, whereas it is 13% and 14% for Ne and Kr beams, respectively. This higher dispersion characterizing the data sets may be due to the quality of the beams not perfectly focused on the detector, or to the reproducibility of the applied voltage during the measurements.

When the higher voltages are applied to the PMT (see figures 2b and 2c) the saturation effect inside the photo-multiplier is clear. At 800V applied voltage, for example, the pulse height per MeV increases up to energies of 5 A MeV for all the ions and then it decreases for higher energies. Consequently, the functional dependence of the pulse height on fragment kinetic energy is more complicated than for low values of the applied high voltage and its slope is lower. However it is still possible to obtain a suitable detector calibration also when the higher voltages are applied to the PMT.
4. YAP:Ce pulse height resolution
The measurements of the pulse height resolution were performed using the direct beam data only. For each beam energy, the photo-multiplier voltage was set between 400 V and 800 V in step of 100 V. In this way the pulse height resolution was studied as a function of the voltage and the energy of the ions. From the collected energy spectra, the relative resolutions were determined as the ratio of the Full Width at Half Maximum (FWHM) and the peak position generally obtained by the proper peak fitting. Two typical pulse height spectra obtained from the YAP:Ce detector with a 15 A MeV Kr beam and a 15 A MeV Au beam are reported as example in figure 3 for HV = 800 V.
In a subsequent step, a linear fit of the pulse height resolution data versus voltage and versus energy was performed for each ion. In all cases, we found that the pulse height resolution decreases linearly with the PMT applied voltage. The slope of the linear fit is similar for all the ions beams, its value being $(-0.0242 \pm 0.0027)$ V$^{-1}$. In figure 4, the pulse height resolution data are reported as a function of the ion energy for the PMT applied voltages of 400 V and 800 V, respectively. By comparing results in figure 4, it appears that by increasing the photo-multiplier voltage the pulse height resolution decreases by a factor of two for lighter ions (as Ne) and a factor of four for heavier ions (as Au).

The reported data on the pulse height resolution demonstrate that the PMT statistics still play an important role in the dynamic range studied in this work. The use of a higher PMT gain (800 Volt) results, indeed, in a significantly better resolution. However, as reported in the previous section, the pulse height at 800 V suffer from strong saturation effects making the use of such a detector to measure the energy of the incoming heavy fragment very difficult. The effect of the saturation might be compensated by a careful calibration of the detector. On the other hand, operating the detector at 400 Volt offers very good linearity but with a moderate pulse height resolution.
5. Study of the YAP:Ce detector array in the BIGSOL spectrometer

In this paragraph results are reported in term of pulse height and pulse height resolution obtained with the YAP:Ce detectors of the array installed in the BIGSOL spectrometer. All the measurements were performed with a high voltage of 800 V, using Kr, Xe and Au beams at 7.5 A MeV. The timing properties of the crystals are also reported, as obtained from time of flight measurements between the PPAC4 and the scintillators. The PPAC4 is mounted at the entrance of the focal plane detection system that also employs a 40 cm long ionization chamber with the YAP:Ce array mounted as its end cup. The time of flight resolution measured between PPAC3 (mounted about 1 m upstream) and PPAC4 is also reported in the following, in order to monitor the quality of the beam hitting the scintillators. It has to be noted indeed that the fragments are passing through a number of tracking transmission detectors placed along the BIGSOL spectrometer before arriving to the focal plane. The measurements were performed sending low intensity beams directly through the spectrometer with the target removed. However the energy of the beams is degraded due to the presence of the detector material. For that reason we calculated, using the SRIM code, the energy of the beams at the entrance of the YAP:Ce array. The results are reported in table 1. It is clear from the data in table 1 that more than 50% of the initial energy is lost before hitting the scintillators. An estimate of the energy loss due to straggling in this case is quite complex due to the presence of a number of different layers and is not yet performed. Consequently the time resolution reported below can be considered as an upper limit of the detector performance.

| Beam | Initial Energy (MeV) | Energy in the YAP:Ce (MeV) | Average pulse height resolution (%) | Average time resolution (ns) |
|------|----------------------|---------------------------|-----------------------------------|----------------------------|
| Kr   | 630                  | 305.7                     | 14.5                              | 0.38                       |
| Xe   | 982.5                | 379.5                     | 13                                | 0.35                       |
| Au   | 1485                 | 672.7                     | 15.5                              | 0.54                       |

The pulse height and the time resolution (against PPAC4) were measured for those detectors that registered a number of events larger than 20% of the entries of the crystal that fired the largest number of times.

For each beam, the extrapolated expected pulse height resolution was calculated by using the data relative to the single crystal as measured previously at the Radiation Effects Facility. We obtained an expected pulse height resolution of 6% for Kr and Au and of 8% for Xe. Those values are to be considered, as representative of a case in which the energy straggling induced by the BIGSOL tracking system is completely negligible.

Moreover, the measured data show that the beam strikes mainly the more central scintillators in the array as expected from the optic of the spectrometer. However, due to the angular straggling, a number of detectors in the array see the beam particles and this effect is more evident for higher mass beams. Therefore, for each ion beam the average of the measured pulse height resolution was computed, as obtained by weighting of the detector entries. We found a pulse height resolution of 14.5%, 13% and 15.5% for Kr, Xe and Au beams respectively. This resolution is about a factor of two worse with respect to the “extrapolated expected values” from the direct beam measurements at the Radiation Effects Facility. This worsening is certainly due to the energy loss straggling in the tracking detectors. Moreover a second contribution is also expected due to differences in the performance of the detectors considered in the averaging.

The measured time of flight resolution (YAP:Ce against PPAC4) ranges form 300 to 600 ps depending on the ion beam and, for a given beam, is generally better for the detector with the higher counting rate and the higher pulse height resolution. This is also an indication of the effects related to the straggling. Again, as done for the pulse height resolution, for each ion beam, the average time resolution was calculated, weighted on the number of hits in the detectors. A time resolution of 380 ps was found for...
Kr beam, 350 ps for Xe beam and 540 ps for Au beam, respectively. The result is that the beam with the best pulse height resolution also has the best time resolution. Numerical results are also shown in table 1.

Figure 5 On the left panel the pulse height spectrum of the YAP:Ce detector with the higher counting rate is reported. Red, blue and green markers indicate the windows marked as GATE1 (740-780), GATE2 (720-830), GATE3 (630-940), respectively. On the right panel a two dimensional scatter plot of the time PPAC4-YAP:Ce as a function of the YAP:Ce pulse height is reported. Data are relative to the Xe beam with initial energy of 7.5 A MeV.

Table 3 Comparison of the time-of-flight resolution measured between PPAC3 - PPAC4 and PPAC4-YAP:Ce. Three windows have been selected in the YAP:Ce pulse height spectrum with the higher counting rate, as shown in figure 5. Data refers to the Xe beam. The reported resolution values are the result of a gaussian fit of the gated time of flight spectra. Quoted errors are those from the fit procedure.

| Selection | Time-of-flight resolution between PPAC3-PPAC4 (ps) | Average time resolution PPAC4-YAP:Ce (ps) |
|-----------|-----------------------------------------------|--------------------------------------|
| GATE1     | 447 ± 5                                       | 318 ± 4                              |
| GATE2     | 447 ± 3                                       | 331 ± 3                              |
| GATE3     | 447 ± 3                                       | 345 ± 2                              |
| NO GATE   | 450 ± 3                                       | 352 ± 2                              |

Finally, a more accurate analysis has been performed in the case of the Xe data. The YAP:Ce scintillator with the highest counting rate was selected. The pulse height spectrum for this YAP:Ce is shown in figure 5. Three different energy windows have been considered around the peak as shown in figure 5 to study the effect of the energy broadening (induced by the energy loss straggling) on the measured time resolution.

For the events belonging to each of the considered pulse height interval the time of flight resolution between PPAC3 - PPAC4 and between PPAC4 - YAP:Ce has been derived. Results are shown in table 3.

The data reported in table 3 show that the time resolution measured by using PPAC3-PPAC4 is generally worse than the one between PPAC4-YAP:Ce and does not change with the energy window. This means that the bulk of the broadening is due to the material after PPAC4, i.e. the ionization chamber.

The energy loss straggling plays an important role in the time resolution measured between PPAC4 and the YAP:Ce detectors. In fact the time resolution improves by about 10% when selecting a narrow window in the YAP:Ce pulse height spectrum with respect to the measurement without any GATE.
We also note that the data in table 3 suggests that the intrinsic time resolution of PPAC detectors is certainly worse than the one of the YAP:Ce scintillator.

6. Conclusions
The properties of YAP:Ce scintillators in detecting energetic heavy ions was investigated in a wide range of energy and masses at the Radiation Effects Facility at Cyclotron Institute of the Texas A&M University. This work was motivated by the use of an array of YAP:Ce scintillators as the final detector of the focal plane detection system in the BIGSOL spectrometer in operation at the Cyclotron Institute at Texas A & M University.

The focal plane detector was designed to detect heavy fragments and record possible sequential alpha particle decay after being implanted in the scintillators. In such conditions the scintillators must have a large dynamic range in mass and energy.

In studying the performance of the YAP:Ce scintillators coupled to an R4141 PMT, we found that the YAP:Ce pulse height response is linear with the energy of the ion, for ion kinetic energies greater than 10 A MeV only when the PMT is operated at low voltage (400 Volt). For lower kinetic energies a non-linearity of the pulse height response appears, due to the well-known quenching effect. When the PMT is operated at higher voltage (800 Volt), a saturation effect appears and the pulse high response of the whole detector is no longer linear. However, the pulse height resolution is much better in the latter case, when compared with the results obtained at lower operating voltage in the regime of PMT linearity.

The performance of the YAP:Ce scintillators array has also been studied directly in the BIGSOL spectrometer. In this case, the measured pulse high resolution is worse by a factor two compared to the expectations from the measurements performed at the Radiation Effects Facility due to the straggling induced by all the tracking detectors in the spectrometer. Nevertheless, a time resolution as low as 320 ps has been measured relative to a PPAC detector for 380 MeV Xe ions. This means that the YAP:Ce scintillators should exhibit a much better time resolution in detecting energetic heavy ions.

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