Development and performance of the CUP

a progress report

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1 Introduction

In this paper we report on the development and in-beam tests of a newly constructed charged particle scintillator detector (CUP), designed for use as a veto device in fusion-evaporation experiments. Information on the CUP detector is available at `http://www.slcj.uw.edu.pl/experiments/cup`, where a report on the first in-beam test (March 2002) can also be found.

2 New version of the CUP

One of the conclusions of the earlier tests of the CUP is that the main source of the background in the scintillator, and the only one which is manifested in the CUP spectra, are the positrons from the radioactive β decays. The signal from the bottom disk of the scintillator is at least factor of 3 larger than the signal from the scintillator cylinder. The most important contribution to the background is thus from positrons interacting in the bottom disk. The magnitude of this effect is directly proportional to thickness of the bottom disk scintillator and could be reduced by reducing this thickness. Geant simulation show that a thinner bottom disk scintillator, 0.5 mm or even 0.25 mm instead of 1 mm would still be thick enough to generate sufficient signals for protons and α particles.

Three new scintillator cylinders have been purchased with Amcrys-h company, as well as sets of bottom disks with different thickness: 0.25 mm, 0.5 mm and 1.0 mm. The scintillator "cups" with different bottom thickness can thus be prepared (glued), depending on the needs and results of tests and calculations. For the present test a "cup" with the 0.5 mm thick bottom disk was used.

Two modifications were done to the chamber of the detector. First, the minimum diameter of the entrance to the chamber has been enlarged from 10 mm to 18 mm in order to provide better pumping conditions. Second, a ^{181}Ta collimater with the current readout has been placed inside the chamber, about 10 cm from the target.

3 Simulations

The performance of the CUP for the particular reaction can be simulated by using a combination of a fusion-evaporation code and the Geant4 program. First, list of protons and α particles emitted in the fusion evaporation reaction is event-by-event generated using the evapOR code. In case of a thick target (in terms of a large effective thickness above the Coulomb barrier) evapOR calculations are run separately for several effective beam energies, corresponding to the reactions at increasing target depth. The list of particles from evapOR is then used as an input to the Geant4 program.

In case evapOR calculations were run for several beam energies, a combined input list is created, with the numbers of events at each beam energy proportional to the compound nucleus formation cross section at this energy. The particle emission point in the Geant4 program is situated inside the target, and is randomly distributed within a 5 mm diameter cylinder, at the target depth interval which is assumed to correspond to the given beam energy.

The geometry of the detector, target, target frame, holder, absorber foils (if present), are taken into account in the Geant4 procedures. Basing on the shape of the CUP energy spectra from the March 2002 tests, it is estimated that protons generate in the scintillator 11.9 times more light than α particles (per 1 MeV energy deposited in the scintillator). For the light transportation in the cylinder it is assumed that the amount of light from the cylinder $L_{cylinder}$ is equal to:

$$L_{cylinder} = L_{bottom} \cdot (0.3333 - 0.1333 \cdot z/(85.0mm))$$

where L_{bottom} is the intensity of light from the bottom disk, and z is the position along the cylinder with $z = 0$ at the edge glued to the bottom disk. This means that a particle hitting the cylinder close to the bottom gives 1/3 of the light in the bottom disk, and a hit at the far end of cylinder gives 1/5 of the bottom signal, assuming the same kind of the particle and the same energy deposit. These assumptions about light transportation and collection are based on the scan of the CUP performed with the point-like ^{241}Am α-particle source.

4 Aim of the in-beam test

The main aims of the present in-beam tests were the following:

- Check the performance of the detector for a reaction in which neutron only evaporation channels as well charged particle channels can be observed. In particular factor e_n should be determined, defined as

  $$\epsilon_n = I^n_{CUP}/I^n_{total}$$

where I^n_{total} and I^n_{CUP} are respectively total and CUP-gated intensities of the same γ-ray line from a nucleus produced without emission of charged particles. In a sense, e_n can be interpreted as the efficiency to register neutron-only reactions, hence the notation. The intensity of a line from a neutron-only reaction in anti-coincidence with the CUP is thus reduced by $1 - \epsilon_n$.

- Check the performance of the detector for high beam currents — rate of reactions with charged particles similar to the rates expected in the EUROBALL experiments (about 100 kHz).

5 Experimental setup and targets

The test setup consisted of the CUP and 3 Germanium γ-ray detectors placed 5–20 cm from the target (depending on the beam intensity). A ^{32}S beam with the energy of about 160 MeV was provided by the Warsaw Cyclotron. Three targets were used: (a) ^{27}Al, 13.2 mg/cm^2, (b) ^{27}Al 19.4 mg/cm^2, and (c) ^{124}Sn, 23 mg/cm^2.

Targets used with the CUP should have the minimum thickness necessary to stop all the beam particles. Targets (a) and (c) were supposed to fulfill this condition. It turned however out that the thickness safety margins assumed for both these targets were too small and the beam could reach the forward scintillator. A black trace of the beam was thus burn in the scintillator. This trace was situated directly behind the beam spot on the target and had a diameter of 4–5 mm. Such defect of the scintillator reduced the efficiency of the detector by about 5% both for protons and α particles (estimate based on the simulation). All the tests described here were performed with the same scintillator, with the defect present, and thus with the reduced efficiency.

The thickness of target (b) was on the other hand too large, thus the particle detection efficiency obtained with this target was smaller than in the optimal case (see below).

Target (a) was used in the preliminary part of the experiment when the electronics was still not properly tuned, thus only data collected with targets (b) and (c) are discussed below.

Backward absorber foil made of ^{181}Ta had to be used in the case of target (c) in order to prevent backscattered beam particles from entering the scintillator.

6 Results

Gamma ray spectra collected with the ^{124}Sn and the ^{27}Al targets are shown in Figures 1 Figures 2, respectively.

The strongest γ-ray lines in the ^{32}S (160 MeV) + ^{124}Sn reaction are from residua which are produced with the emission of 5 and 6 neutrons, i.e. ^{151}Dy and ^{150}Dy, respectively. Lines from evaporation channels p5n (^{150}Tb), p4n (^{151}Tb) and α4n (^{148}Gd) are only slightly weaker. This reaction is thus suitable for determining at the same time charged particle detection efficiency and the influence of the CUP coincidence requirement on the intensity of lines from neutron-only evaporation channels (factor e_n).

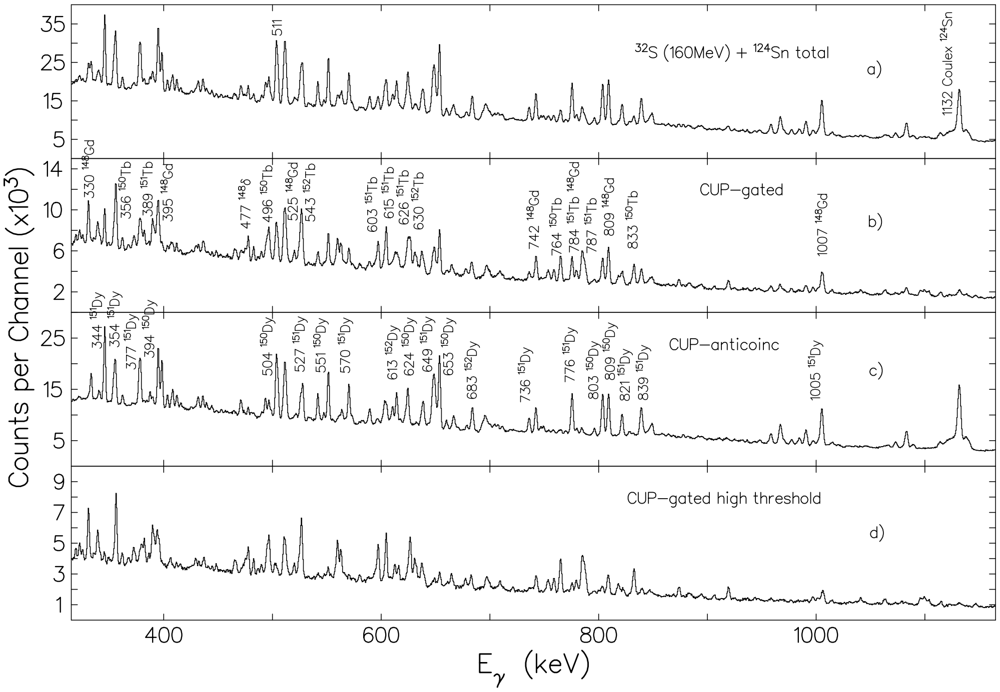

Figure 1: Gamma ray spectra collected with the ^{124}Sn target

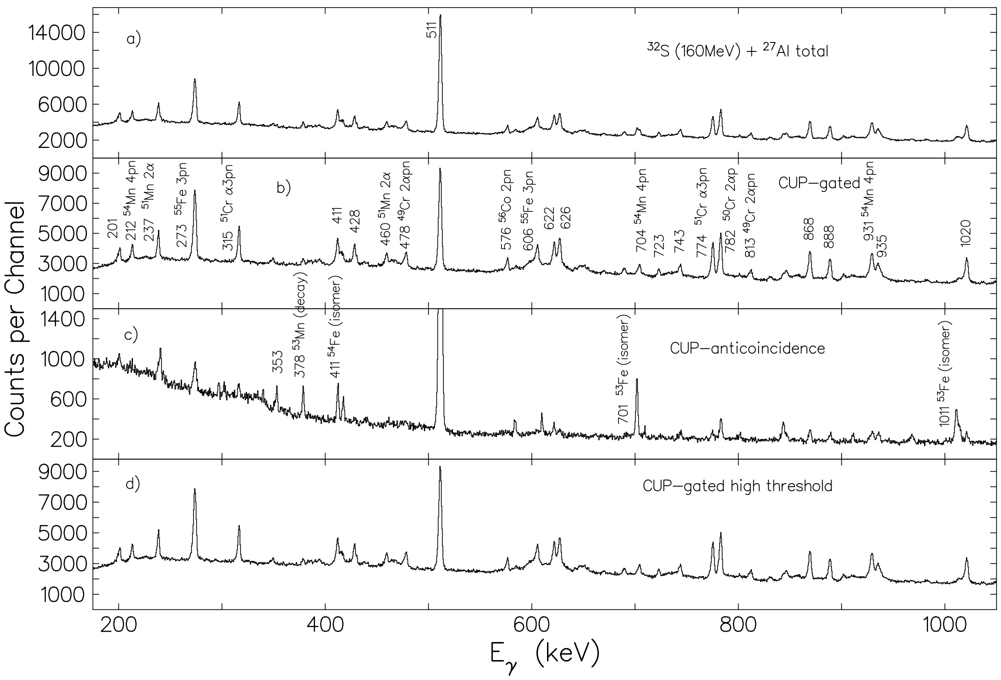

Figure 2: Gamma ray spectra collected with the ^{27}Al target

The reactions on ^{27}Al give a high charged particle yield — a few particles per reaction. The calculated reaction rate in this part of the test was 200 kHz on average or 400 kHz, if the cyclotron duty cycle of about 50% is taken into account (2 μs period). Such reactions rates are higher than reactions rates expected in the EUROBALL+CUP experiments (about 100 kHz). A possibility was anticipated that a high reaction rate, especially with large light output per reaction in reactions in which a few protons are registered, may lead to overloading the PM tube and the voltage divider (too high current), which would result in change of the gain of the PM tube. No such affect was observed for the data presented here. In fact the effect was observed only when the beam current was increased by additional factor of 2.

The proton and α-particle detection efficiencies determined in the tests are presented in Table 1. The efficiencies presented in the table are obtained with the minimum threshold for CUP energy signal and wide CUP time gates (about 70 ns). For comparison results from earlier tests performed with the ^{40}Ar beam are also included in the table. Note that the defect of the scintillator mentioned above is included in the simulations run for the reactions with the ^{32}S beam.

The value $\epsilon_n = 0.25$ was determined from the intensity of lines from ^{150}Dy and ^{151}Dy. This value may be reduced at the cost of the efficiency by applying stricter gates on CUP time and by increasing the CUP energy threshold. For example $\epsilon_n = 0.05$ can be obtained with CUP the gates which give $\epsilon_p = 0.7$.

	Reaction	measured		simulated	
		p	α	p	α
1.	^{32}S (160 MeV) + ^{124}Sn (23 mg/cm^2)	0.82 ± 0.03	0.62 ± 0.03	0.86	0.37
2.	^{32}S (160 MeV) + ^{27}Al (19.4 mg/cm^2)	0.6 ± 0.1	0.63 ± 0.05	0.67	0.38
3.	^{40}Ar (120 MeV) + ^{27}Al (9.7 mg/cm^2)	0.88 ± 0.05		0.83	0.67
4.	^{40}Ar (120 MeV) + ^{62}Ni (12.5 mg/cm^2)	0.75 ± 0.05		0.88	0.57

Table 1: Efficiency of the CUP detector. Alpha particle detection efficiency in case of reactions 3. and 4. were not determined due to too low statistics collected in these tests.

7 Discussion

Quite significant discrepancy of the α-particle detection efficiency between the simulation and the measurement was observed, We tend to attribute this discrepancy to one of the following two reasons:

1. Charged particle energy distributions generated by evapOR, and their dependence on the emission point (depth in the target) are wrong. In the simulations the particle which are not registered α particles are in most cases stopped in the target, so the the assumptions about the scintillator properties cannot strongly affect the simulated efficiencies in this case. This interpretation is corroborated by the fact that yields of nuclei produced in the reactions are in general not well reproduced.

2. It is possible that in the experiment the reaction channels interpreted as emission of α-particles and used for the determination of α-particle efficiency (α4n and 2αin case of reactions 1. and 2., respectively) partly proceed through the emission of 2 protons and 2 neutrons instead of one α-particle, thus the measured value of the α-particle efficiency is too large.

Proton detection efficiencies are in principle in agreement with the simulation, within the error bars, with the exception of reaction 4. However, if the first interpretation above is correct, one can also expect that proton energy distributions are not well reproduced, and this would certainly lead to the discrepancy of the efficiencies. This could explain the discrepancy in reaction 4., which is otherwise not well understood. In fact the large simulated value of ϵ_p in case of a reaction with absorber foils is intuitively surprising.

Note that a large error bar for the proton detection efficiency in reaction 2. is due to the error propagation in the formula used to determine the efficiency basing on γ-ray intensities from nuclei produced with the emission of 3 protons (3p and 3pn):

$$\epsilon_p = 1 - (1 - r)^{1/3}$$

where r is the γ-ray line intensity ratio.

The measured value $\epsilon_n = 0.25$, although acceptable, seems to be rather high and can be decreased only at a quite high efficiency cost. This is at least partly due to the noise level, which was still too high in the present test. We plan to improve the PM tube and the voltage divider shielding, which should result in lowering the noise level. In order to detect particles which leave a minimum amount of energy in the scintillator it is necessary to operate the detector with the lowest possible threshold, and accept rates which are much higher than the reaction rate in the target. The largest CUP rates measured during the test were close to 1 MHz, with the calculated average reaction rate about 200 kHz.

With the present threshold value, which corresponds to 4–5 MeV α particles stopped in the bottom disk, low energy energy α particles escape the detection if they hit the cylinder.

As it was mentioned earlier, in reaction 1. beam was not properly stopped in the target and was hitting the scintillator. However only low energy beam particles (at most a few MeV, likely much less) could reach the scintillator. The amount of light per MeV generated by such heavy ions is very low, so single beam particles could not generate a significant signal. Taking into account the fact that there was about 400 particles in the beam bunch, this could anyway lead to a non-zero DC level of the PM tube, which would deteriorate its performance. Most likely, the part of the scintillator which was directly hit by the beam was destroyed shortly after the start of the measurement, and then become inactive, thus the measurement could be continued with the efficiency slightly lowered.