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# AN UPGRADED MULTIDETECTOR PULSE HEIGHT TALLY FOR MCNP

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## ABSTRACT

The paper presents a PATCH file for MCNP4c, which allows upgrading the capabilities of a standard pulse height tally F8 to the coincidence and anti-coincidence modes. A description of all modifications introduced by the proposed PATCH into the source code is provided. Examples of calculation of gamma-ray spectra for multi-detector measurement systems using coincidence and anti-coincidence techniques are presented also. The necessity of introducing of the coincidence and anti-coincidence modes to MCNP and MCNPX is emphasized.

*Key Words*: MCNP, pulse height tally, coincidence, anti-coincidence

## 1 INTRODUCTION

Currently the MCNP code [1] is widely utilized for calculating characteristics of the nuclear radiation detectors. The MCNP standard pulse height tally allows calculating energy distributions of pulses created in individual geometry cells as well as in arbitrary unions of geometry cells. This provides the possibility to calculate responses and detection efficiencies for both single-detector and multi-detector systems.

A possibility of modeling the response and efficiency for a system of detectors connected in coincidence or anti-coincidence mode seems to be quite a useful extension of the standard pulse height tally capabilities. Such extension would broaden the range of application of the MCNP code in both basic and applied nuclear fields, which extensively use such measurement techniques.

In fact, coincidence is applied in sum-coincidence and pair gamma-spectrometers and systems for detecting positron emitters in nuclear and high energy physics. Today there are three very large arrays (Gammasphere, Euroball, and Eurogam) and about a dozen smaller arrays of solid state gamma-ray detectors used for nuclear structure experiments [2]. Anti-coincidence is applied in low level/low background counting applications using Compton suppression spectrometers [3] and phoswich detectors [4]. The coincidence technique is also widely used in advanced nuclear medicine applications, such as Positron Emission Tomography [5], Coincident Compton Imaging Systems [6,7], Gamma-Camera Coincidence Imaging Systems [8]. Another field of coincidence application is NDA technologies based on correlated gammas for assay of high activity and TRU wastes by using Gamma-Neutron Assay Technique [9] and Multi-Detector Analysis Systems [10,11].

This paper presents one of the possible approaches to the realization of the coincidence and anti-coincidence modes in MCNP Version 4c. Examples of using an upgraded pulse height tally F8 card for simulating of the response of a hypothetical multi-detector system are given also.

## 2 PROBLEM DEFINITION

Let us consider a problem of simulating of the energy distribution of pulses created by radiation in a set $\nu = (n_1\ n_2\ \dots\ n_N)$ of N geometry cells. A standard MCNP pulse height tally in this case will have the following form:

$$\text{F8:p1}\ (n_1\ n_2\ \dots\ n_N) \tag{1}$$

where p1 = particle type (P or E or P,E), and $n_i$ - cell problem numbers. Let there are other two sets $\mu = (m_1\ m_2\ \dots\ m_M)$ and $\lambda = (l_1\ l_2\ \dots\ l_L)$, consisting of M and L geometry cells respectively. Then in the broader sense we would be interested in calculating the energy distribution of pulses created in cells of the set $\nu$ under the condition that the energy deposition events in cells $\nu$ will be accompanied by the energy deposition events in at least one cell of the set $\mu$ (coincidence) and in none of cells of the set $\lambda$ (anti-coincidence). In terms of the mathematical logic this condition can be written in the following way:

$$(\exists i = [1, M],\ E_{m_i} > E_\mu) \wedge (\forall j = [1, L],\ E_{l_j} < E_\lambda) \rightarrow E_{F8} = E_\nu \tag{2}$$

Here $E_\mu$ and $E_\lambda$ are the threshold energies for the energy deposition pulses $E_{m_i}$ and $E_{l_j}$ created in cells of the sets $\mu$ and $\lambda$ respectively, $E_\nu$ is the sum energy deposited in cells of the set $\nu$ by the end of each simulated history, and $E_{F8}$ is the energy analyzed by the pulse height tally F8.

The problem definition in the form (2) concerns the so-called double coincidence/anti-coincidence, which is the subject of this paper. The problem of the energy distribution calculation for triple and higher multiplicity coincidence/anti-coincidence of energy pulses created in geometry cells can be formulated using the same approach.

## 3 TECHNICAL APPROACH

The following form of an upgraded pulse height tally card seems to be the most intuitive and conceivable for the users:

$$\text{F8:p1}\ (n_1\ n_2\ \dots\ n_N\ {+m_1}\ {+m_2}\ \dots\ {+m_M}\ {-l_1}\ {-l_2}\ \dots\ {-l_L}) \tag{3}$$

Here, plus and minus signs precede the problem numbers of the geometry cells, which are connected in coincidence (cells of the set $\mu$) or in anti-coincidence (cells of the set $\lambda$) to the other cells of the tally bin (cells of the set $\nu$). The threshold energy values $E_\mu$ and $E_\lambda$ can be specified using two first elements, RDUM(1) and RDUM(2) respectively, of the floating point user array RDUM(50).

Necessary modifications to the MCNP4c source for the realization of the pulse height tally in the form (3) are presented in Appendix A. For scoring the radiation energy, being transferred to coincidence and anti-coincidence cells during each history run, two additional memory blocks with sizes MXF each are allocated in tally array TAL(*). Attribution of geometry cells of a given tally bin to a particular set of cells ($\nu$, $\mu$, or $\lambda$) is indicated by flags (0, 1, or -1), which are stored in the memory block with size LTLD in the extended tally specification array ITDS(LIT).

According to the flag value of a cell belonging to a particular tally bin the score is accumulated in the corresponding memory block of TAL(*). Upon the completion of the next history, the scores accumulated in TAL(*) are analyzed for the presence or absence of the energy pulses in $\mu$ and $\lambda$ set cells, which then compared to the predefined energy threshold values. As a result of this analysis for every pulse height tally bin a decision is taken on whether to accept or reject the current event.

The modifications of the computational part of the source code concern only subroutines TALPH (deck tj) and FINPHT (deck fp). The other changes are connected with the analysis of cells plus and minus signs in F8 card input (deck ik, deck ny, deck tc, deck ce, deck it), with the extension of dimensions of TAL(*) and ITDS(LIT) arrays (deck im, deck ol), with the declaration and initialization of LTLD and ISIGN variables (comdeck cm, deck mc, comdeck jc), and with a provision of a correct output of the cell numbers to output file (deck bl). All proposed modifications of the MCNP source do not interfere with standard MCNP calculation modes.

## 4 APPLICATION EXAMPLE

Let us demonstrate the possibilities of the upgraded pulse height tally card on the example of a hypothetical Compton suppression system shown in Fig.1. It consists of an HPGe analyzing detector with relative efficiency about 60% and annular and plug scintillation guard detectors on the basis of bismuth germanate ($Bi_4Ge_3O_{12}$) crystals.

Dimensions of the analyzing detector internals were taken as follows: crystal - ∅74×53 mm, inactive germanium – 0.7 mm, aluminum end cap wall thickness – 1.5 mm, end cap to crystal – 5 mm, rear contact - ∅10×36 mm, crystal side cladding – 1 mm of aluminum. An additional 30-mm thick layer of aluminum was introduced at the backside of the crystal to simulate the presence of the detector components behind it. The thickness of the guard detector crystals was chosen to be 3 cm and 4 cm for annular and plug detectors respectively. The both guard detector

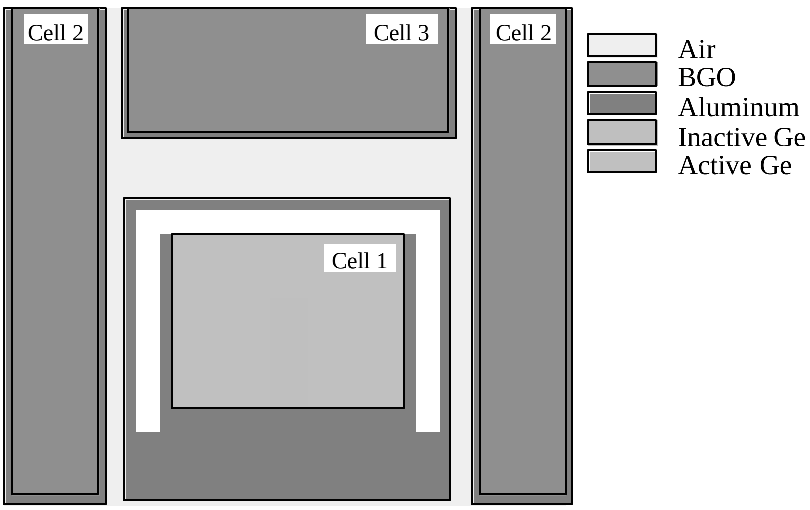


**Figure 1. Model of a hypothetical Compton suppression system on the basis of HPGe analyzing detector.**

crystals were assumed to have 1.5 mm aluminum coating. The case of a point 1 MeV gamma-ray source located in contact with the analyzing detector housing was considered.

Results of the response computation for different guard detector and spectrum acquisition modes combinations are shown in Fig.2. The corresponding pulse height tally and RDUM cards in the input file were as follows:

```
F8:P  1  (1 –2)  (1 –3)  (1 –2 –3)  (1 +2)  (1 +3)  (1 +2 +3)
E8  0  0.0005  1100I  1.1005
FT8  GEB  0.00054  0.00102  0.10942
RDUM  0.1   0.1
```

The results shown in Fig.2 demonstrate the wide capabilities of the modified pulse height

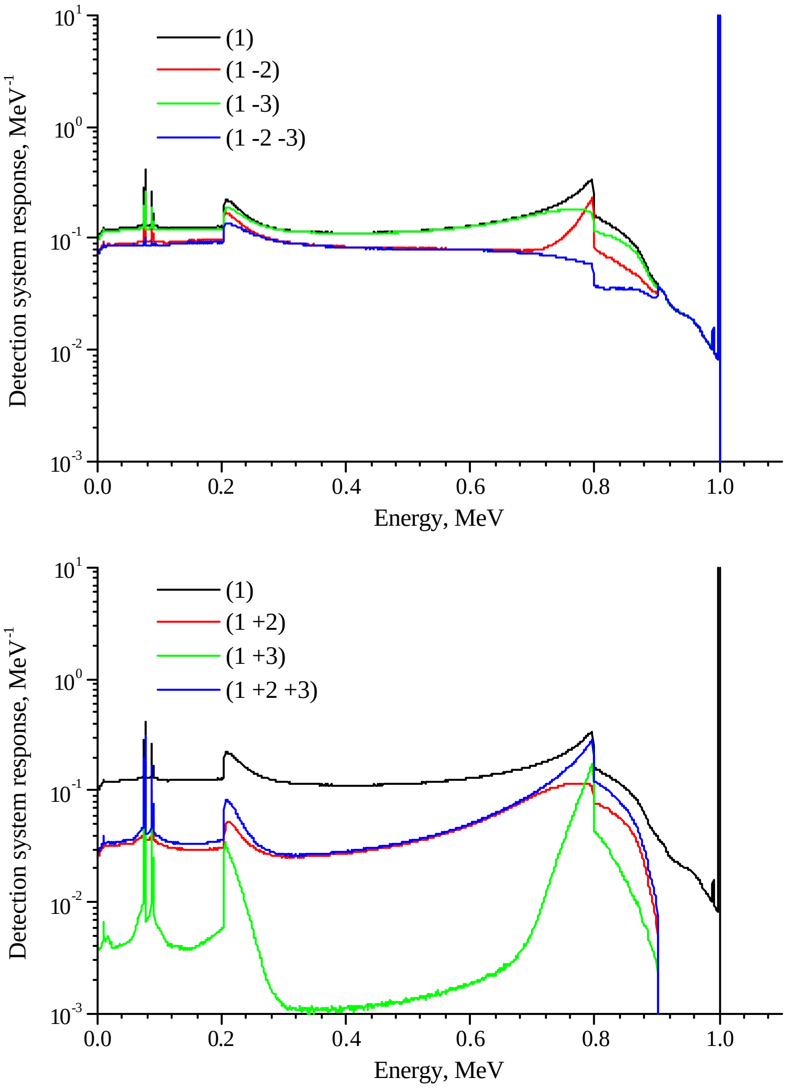


**Figure 2. Compton suppression spectrometer responses calculated for different guard detector and spectrum acquisition modes combinations (results of $10^7$ trials).**

tally for predicting performance and optimizing the construction and working modes of the spectrometry systems, which use the coincidence and anti-coincidence techniques. For example, as it was shown in [12], the upgraded F8 tally together with the ENSDF based cascade gamma-ray source [13] allow to solve completely a very actual problem of the true-coincidence correction factors calculation for the Compton suppression systems.

## 5 CONCLUSIONS

It is shown that by introducing minimal changes to the MCNP4c source the coincidence and anti-coincidence modes for the pulses detected in different sets of geometry cells can be easily realized for the pulse height tally F8. This capability significantly extends the scope of the MCNP application, allowing to predict the performance characteristics as well as to optimize the construction and working modes of the gamma and beta-spectrometry systems employing the coincidence and anti-coincidence measurement techniques.

At the same time it needs to point out that the proposed pulse height tally upgrading seems to be somewhat artificial. Therefore it would be desirable to realize such pulse height tally capabilities in future versions of MCNP and MCNPX in more consistent way. Also it would be desirable that this realization will allow carrying out calculations for a system of detectors with arbitrary coincidence multiplicities that will significantly extend the scope of application of these codes in the fields of nuclear and high energy physics, astrophysics, nuclear medicine etc.

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## APPENDIX A

Patch for upgrading the MCNP pulse height tally

```
*/ --- Multidetector (anti)coincidence F8 tally enhancement ---
*ident acf8
*/ -------------------------------------------------- comdeck cm
*d,cm4c.8
     2 +3*(mxss)+1*(nmkey)+1
*d,cm4c.71
     2 lkxd,llbb,ltld,
*/ -------------------------------------------------- deck mc
*d,mc.39
      data ib/9*0/,hn/' '/,ltld/0/
*/ -------------------------------------------------- comdeck jc
*d,jc4a.2
     2 m5c,m6c,m7c,m8c,m9c,m10c,isign,
*/ -------------------------------------------------- deck im
*d,im4a.63
```

```
      lgbn=ltal+(nmxf*mxf+ktls)*(mtasks+1)+2*mxf
*/ --------------------------------------------------- deck ol
*d,ol4a.4
      lit=lit+2*m9c
      ltld=ltld+m9c
*/ --------------------------------------------------- deck ik
*before,ik.24
      is=0
*before,ik.31
      is=index('+-',klin(it:it))
*before,ik.104
      isign=is
*/ --------------------------------------------------- deck ce
*d,ce4a.92
      k=namchg(1,abs(iitm))
*/ --------------------------------------------------- deck ny
*before,ny.324
      if(isign.eq.1)rtp(lrtp+ipl+nwc)=-rtp(lrtp+ipl+nwc)-100000
*/ --------------------------------------------------- deck it
*d,it4a.21
      ddd=rtp(lrtp+l+i)
      if(ddd.lt.-100000) ddd=ddd+100000
      k=abs(nint(ddd))
*d,it4a.23
      ddd=rtp(lrtp+l+i+1)
      if(ddd.lt.-100000) ddd=ddd+100000
      if(i.lt.n1) kn=abs(nint(ddd))
*d,it4a.25
      ddd=rtp(lrtp+l+i-1)
      if(ddd.lt.-100000) ddd=ddd+100000
      if(i.gt.1) kp=abs(nint(ddd))
*before,it4a.191
      if(rtp(lrtp+l+i).lt.0) kc=-kc
      if(rtp(lrtp+l+i).lt.-100000) kc=kc-100000
*/ --------------------------------------------------- deck tc
*d,tc.25
      ddd=itds(itds(lr+i)+j)
      if(ddd.lt.-100000) ddd=ddd+100000
      if(abs(ddd).ne.k)go to 30
*d,tc.45
      itds(lw+mxa)=0
      ddd=itds(itds(lr+i)+j)
      if(ddd.ge.0) go to 22
      itds(lw+ltld)=-1
      if(ddd.gt.-100000) go to 21
      itds(lw+ltld)=1
      ddd=ddd+100000
   21 itds(itds(lr+i)+j)=abs(ddd)
   22 itds(li+1)=itds(li+1)+1
*before,tc.53
      lw=lw+ltld
*/ --------------------------------------------------- deck tj
*before,cor4-1.180
      iacf=itds(lx+ir+ltld)
      if(iacf.eq.1) j3=j3+(nmxf*mxf+ktls)*(mtasks+1)
      if(iacf.eq.-1) j3=j3+(nmxf*mxf+ktls)*(mtasks+1)+mxf
*/ --------------------------------------------------- deck fp
```

```
*before,fp.16
c     Setting (anti)coincidence flags for bin ir of tally ital
      icf=0
      iaf=0
      j4=itds(iptal(lipt+1,1,ital)+ir)
      do 4 kk=1,itds(j4)
      lli=locph(llph+itds(j4+kk))+1
      do 2 ii=1,itds(lli-1)
      if(itds(lli).ne.ital) go to 2
      do 1 jj=1,itds(lli+1)
    1 if(itds(lli+jj+1).eq.ir) go to 3
    2 lli=lli+itds(lli+1)+2
    3 if(itds(lli+jj+1+ltld).eq.1) icf = 1
      if(itds(lli+jj+1+ltld).eq.-1) iaf = 1
    4 continue
*before,fp.17
c     Retriving energies for coincidence and anti-coincidence cells
      j4=j3+(nmxf*mxf+ktls)*(mtasks+1)
      Ec=tal(j4)
      Ea=tal(j4+mxf)
      tal(j4)=0
      tal(j4+mxf)=0
*before,fp.20
c     Check coincidence and anti-coincidence thresholds
      if(icf.eq.1.and.Ec.le.rdum(1)) go to 60
      if(iaf.eq.1.and.Ea.gt.rdum(2)) go to 60
*/ --------------------------------------------------- deck bl
*d,bl4a.19
      iof=0
      if(kf8.eq.0) go to 4
      li=locph(llph+itds(j))+1
      do 2 ii=1,itds(li-1)
      if(itds(li).ne.ital) go to 2
      do 1 jj=1,itds(li+1)
    1 if(itds(li+jj+1).eq.ib) go to 3
    2 li=li+itds(li+1)+2
    3 iof=itds(li+jj+1+ltld)
      if(iof.eq.1) write(hf,'(SP,i7)')nint(r)
      if(iof.eq.-1) write(hf,'(i7)')-nint(r)
    4 if(iof.eq.0) write(hf,'(i7)')nint(r)
      l1=l1+abs(iof)
*/ --------------------------------------------------- end
```