GEANT4 simulations of a single $LaBr_3$(Ce) detector and large NaI(Tl) detector arrays

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Plan of the Talk

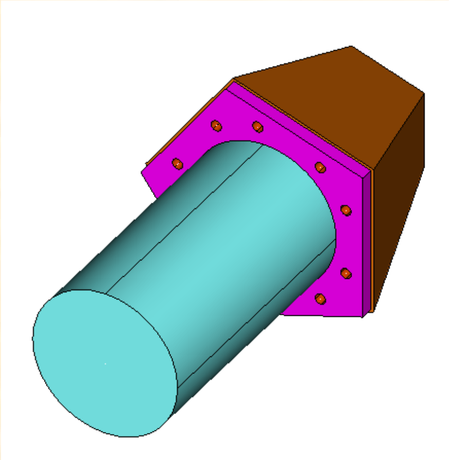
- GEANT4 simulations of large arrays of NaI(Tl) detectors in soccer-ball and castle geometries
- A comparative study efficiencies of $LaBr_3$,NaI(Tl), BaF_2.
- Close-geometry efficiency calibration and true coincidence summing correction

Aim

- To calculate the detection efficiencies of the individual detectors and the entire 4π array using GEANT4 and comparison with measurements.

- To carry out efficiency measurements and GEANT4 simulations for a smaller array of 14 straight NaI detectors of hexagonal cross sections packed in castle geometry and the comparison of the results with the 4π array.

- To calculate fold distributions for different gamma multiplicities for both the 14 elements and the 4π array.

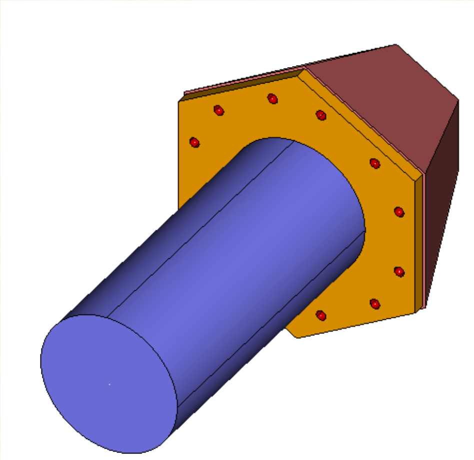


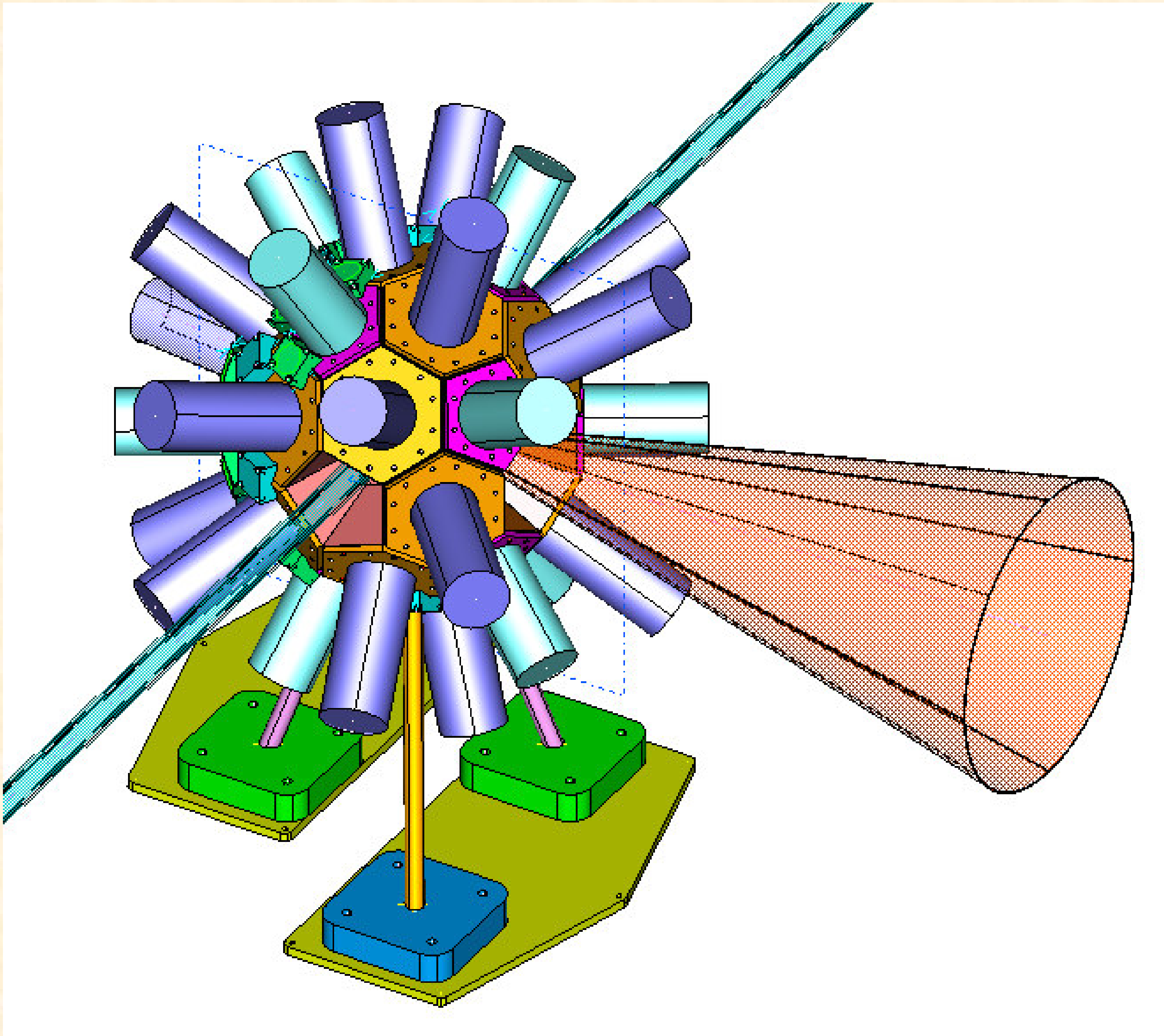
Pentaagon

Specifications

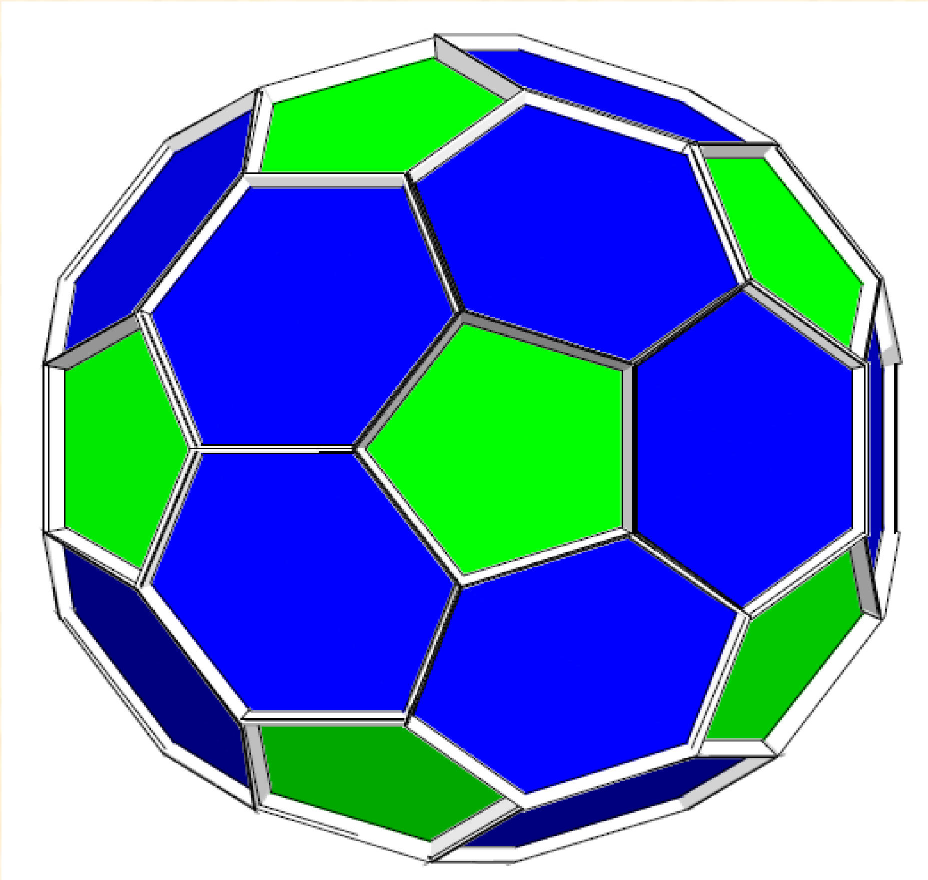
Length	76 mm
Sides	44 mm
	88 mm
PMT	3" dia XP3332/PB
Energy Resolution	~6.5% @ 661 keV
Bias	+800 V

Hexagon

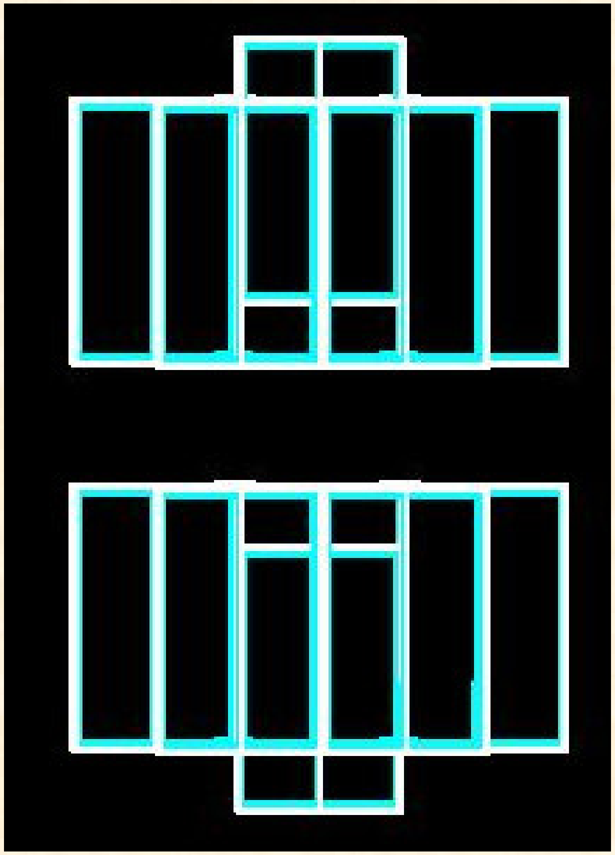




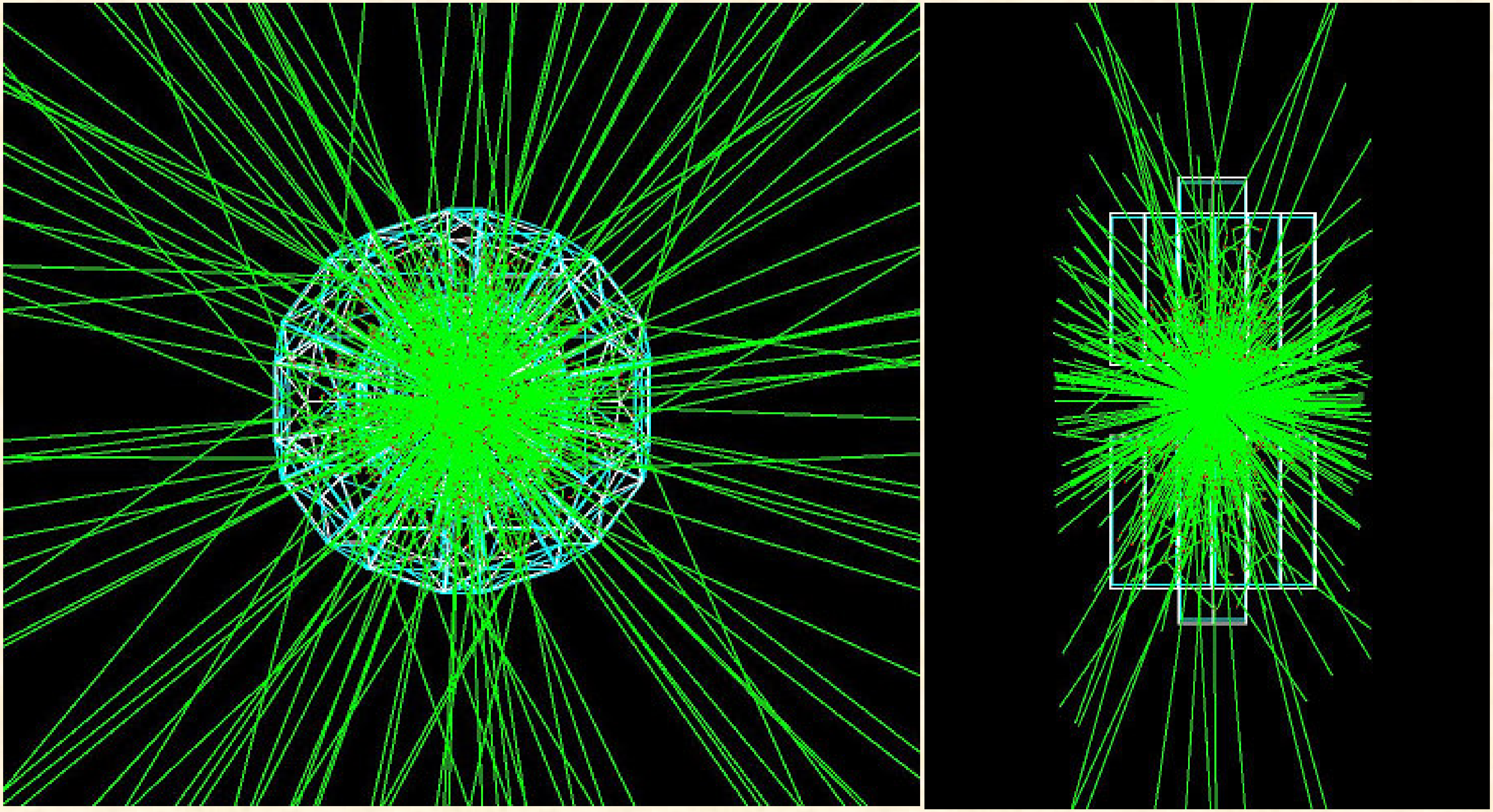
32 detectors,
Soccer ball geometry



14 detectors,
castle geometry



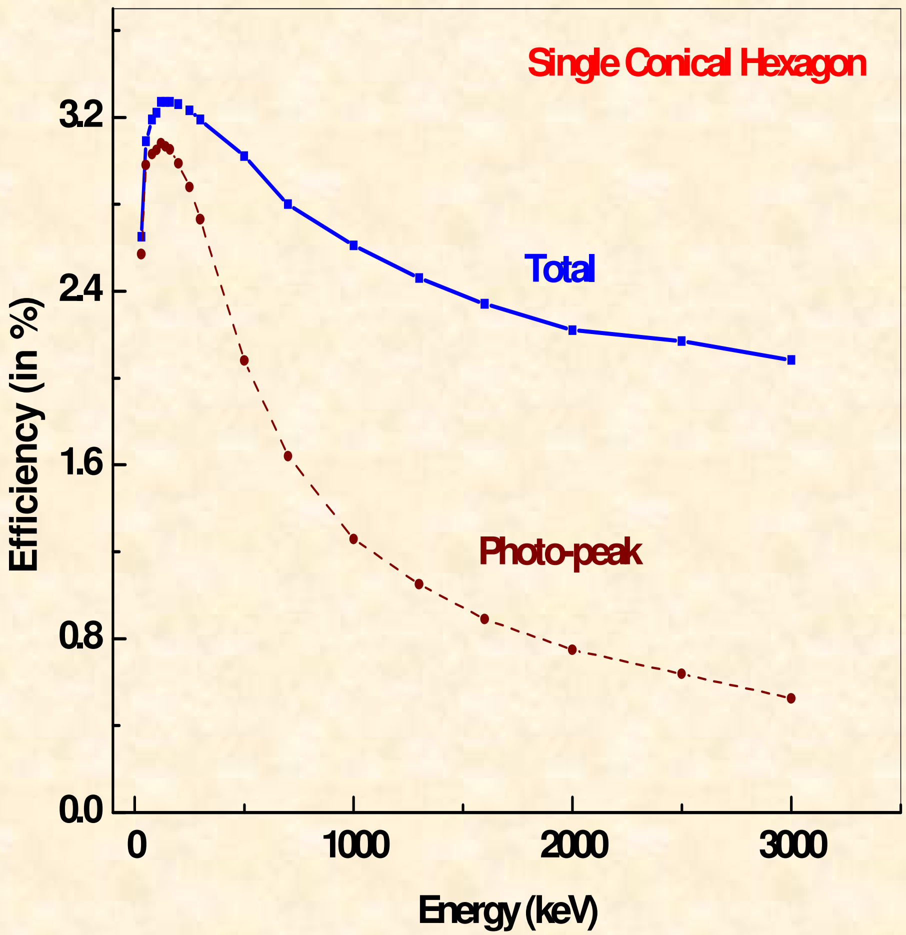
Simulated diagrams using GEANT4

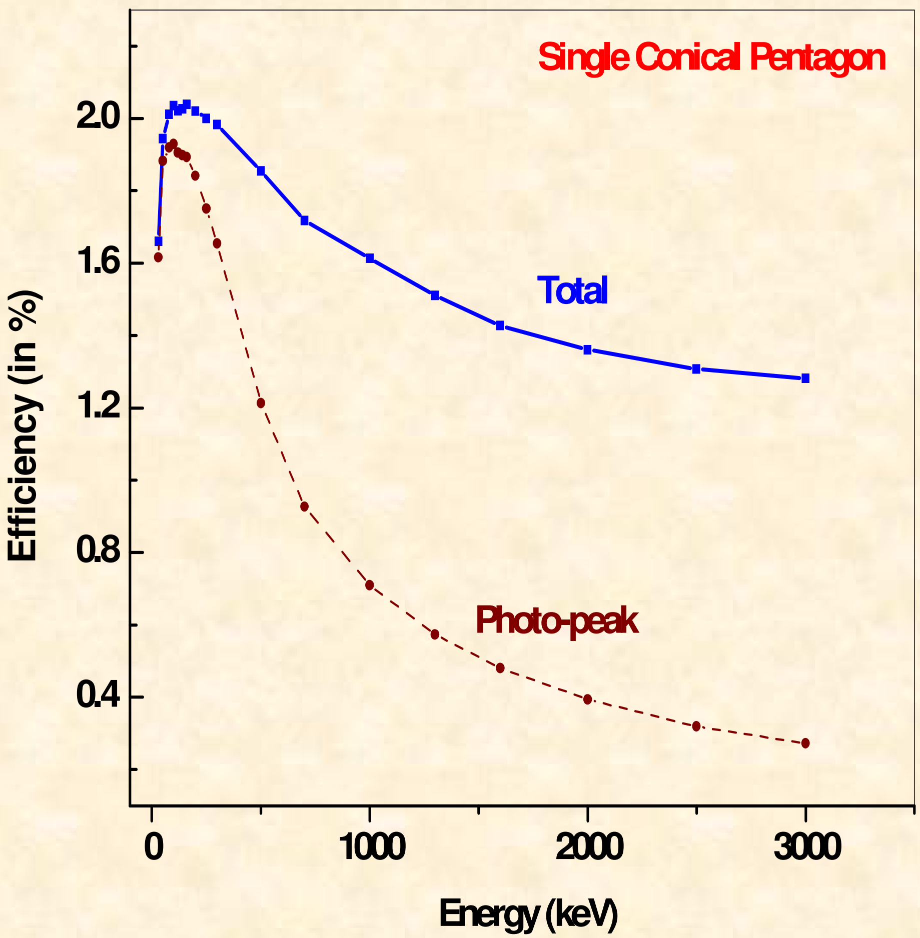


Simulated and measured efficiencies for a single detector for 662 keV at a distance of 10 cm from the centre of the face of the detector.

Configuration	Absolute efficiency (in %)		Photo peak efficiency (in %)	
	GEANT4	Exp	GEANT4	Exp
Conical Hexagon (3”)	2.98 ± 0.03	3.03 ± 0.15	1.70 ± 0.04	1.63 ± 0.08
Conical Pentagon (3”)	2.00 ± 0.03	2.06 ± 0.10	1.06 ± 0.03	1.03 ± 0.05
Small Hexagon (4”)	1.03 ± 0.06	1.08 ± 0.05	0.47 ± 0.03	0.47 ± 3.90

(G. Anil Kumar, I. Mazumdar, D.A. Gothe, 2008 IEEE Nuclear Science Symposium conference record, N17-1, p. 1640, Dresden, Germany)


Single Conical Hexagon
Total
Photo-peak
3.2
2.4
1.6
0.8
0.0
0
1000
2000
3000
Efficiency (in %)
Energy (keV)


Single Conical Pentagon
Total
Photo-peak
2.0
1.6
1.2
0.8
0.4
0
1000
2000
3000
Efficiency (in %)
Energy (keV)

Simulated and measured efficiencies for different configurations of conical pentagons and hexagons

Configuration	Absolute efficiency (in %)		Photo peak efficiency (in %)	
	GEANT4	Exp	GEANT4	Exp
12 pentagons + 20 hexagons	83.8 ± 1.13	77.5 ± 3.95	59.5 ± 1.31	54.5 ± 2.41
10 pentagons + 20 hexagons	79.4 ± 1.10	76.8 ± 3.84	49.0 ± 1.23	46.5 ± 2.32
10 pentagons + 19 hexagons	76.4 ± 1.09	74.1 ± 3.70	46.5 ± 1.08	43.8 ± 2.19
9 pentagons + 20 hexagons	77.5 ± 1.06	75.0 ± 3.75	47.5 ± 1.38	45.2 ± 2.26
14 NaI system	40.9 ± 1.90	40.0 ± 2.00	17.2 ± 1.32	16.0 ± 0.80

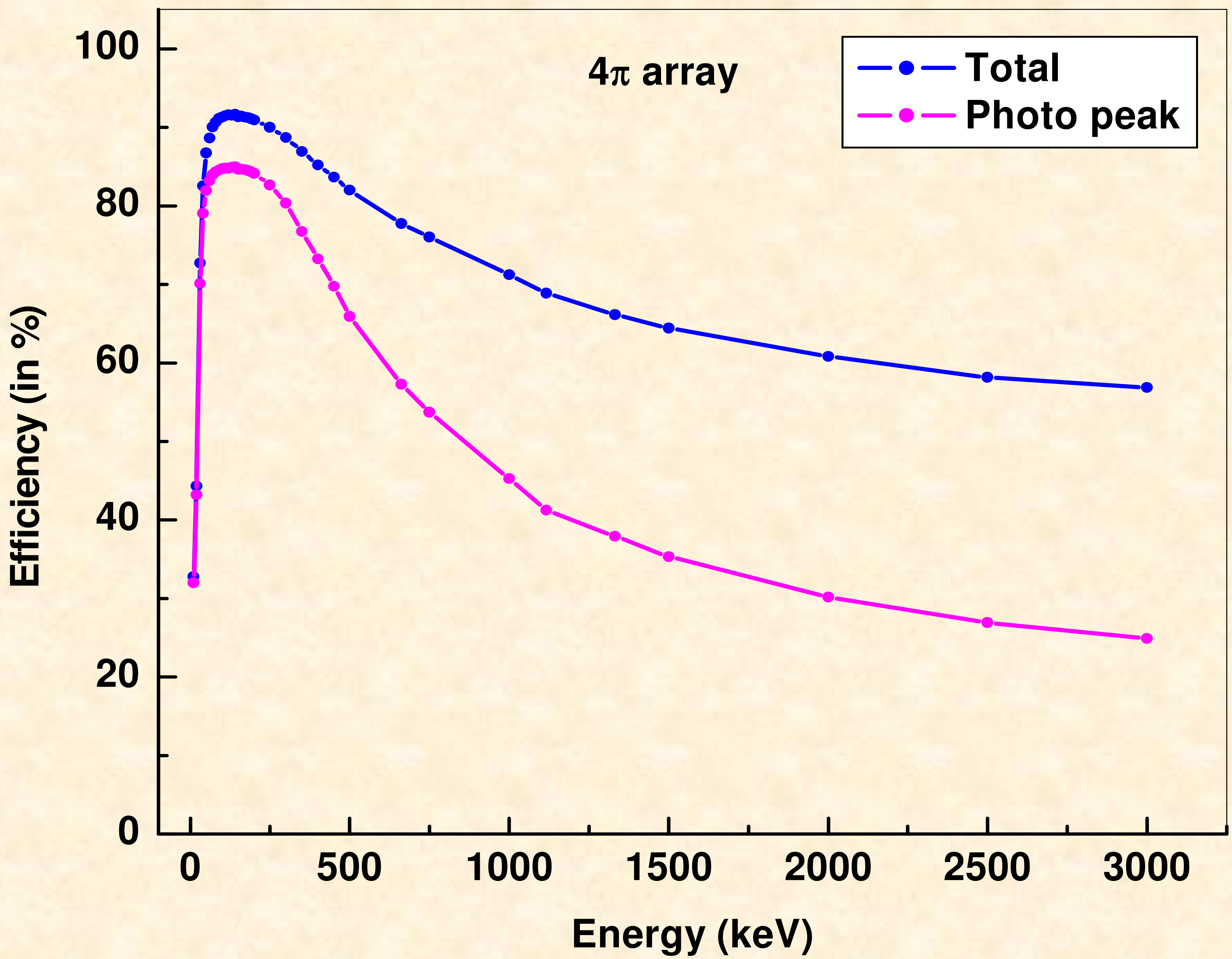
Summary of results on simulated absolute efficiencies for full 4π array and for the castle geometry of 14 elements for different mono energetic gamma rays

Energy (MeV)	Absolute efficiency (in %)		Photo peak efficiency (in %)	
	4π array	14 NaI	4π array	14 NaI
1	74.48 ± 1.16	37.09 ± 1.77	43.46 ± 0.96	13.50 ± 1.12
5	57.81 ± 1.23	29.65 ± 1.41	19.92 ± 0.72	4.10 ± 0.47
10	59.73 ± 0.82	32.00 ± 1.19	13.79 ± 0.66	2.00 ± 0.30
15	62.60 ± 1.30	33.93 ± 1.39	8.67 ± 0.56	0.96 ± 0.21
20	64.53 ± 0.88	35.28 ± 1.76	4.75 ± 0.32	0.41 ± 0.08
25	66.30 ± 1.16	36.43 ± 1.58	2.47 ± 0.18	0.17 ± 0.06
30	67.60 ± 1.18	37.15 ± 1.69	1.24 ± 0.08	0.06 ± 0.03
35	68.90 ± 1.11	37.98 ± 1.71	0.57 ± 0.14	0.02 ± 0.01
40	69.80 ± 1.07	37.46 ± 1.47	0.27 ± 0.03	0.009 ± 10^{-3}
45	70.54 ± 1.09	39.09 ± 1.87	0.12 ± 0.02	0.004 ± 10^{-3}
50	70.63 ± 1.13	39.38 ± 1.72	0.04 ± 0.01	0.001 ± 10^{-4}

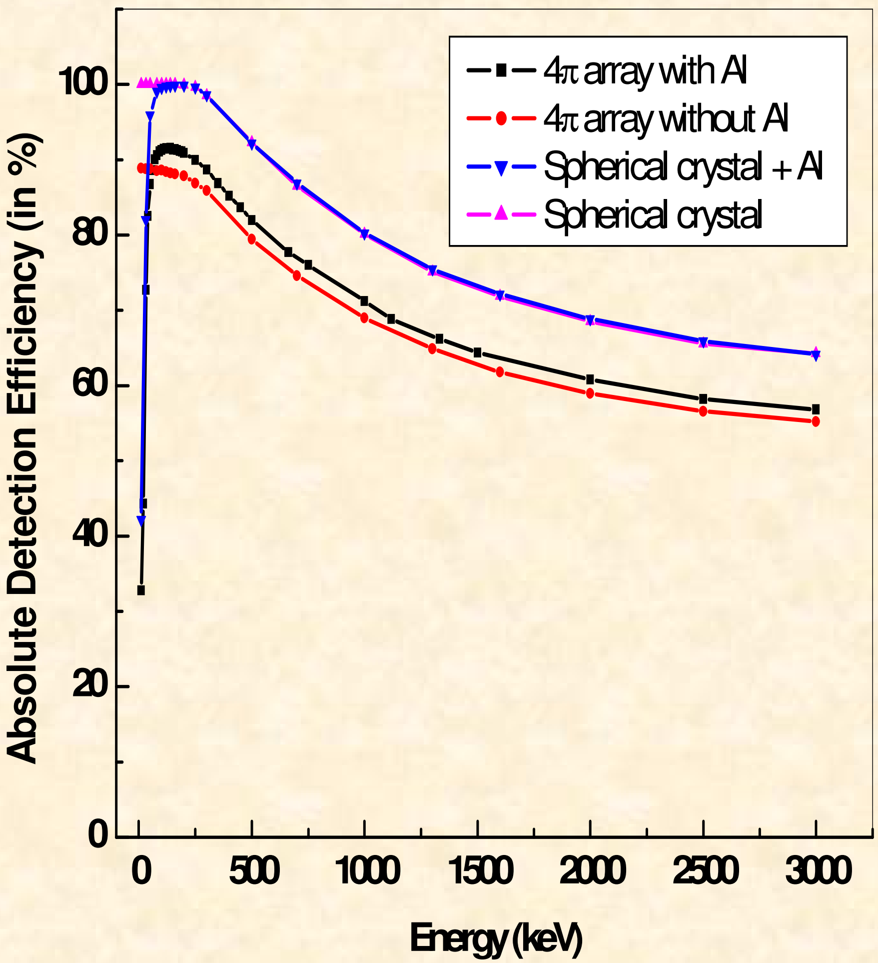
Summary of results on simulated absolute efficiencies for full 4π array of $LaBr_3$(Ce) detectors for different mono energetic gamma rays

E (MeV)	Absolute Efficiency (in %)	Photo peak efficiency (in %)
0.662	90.00	71.00
1.173	82.60	55.63
1.332	81.00	52.75
5	68.42	32.63
10	71.25	25.64
15	72.70	18.38
20	75.03	11.37
30	78.31	4.41
40	79.73	1.56
50	81.56	0.55

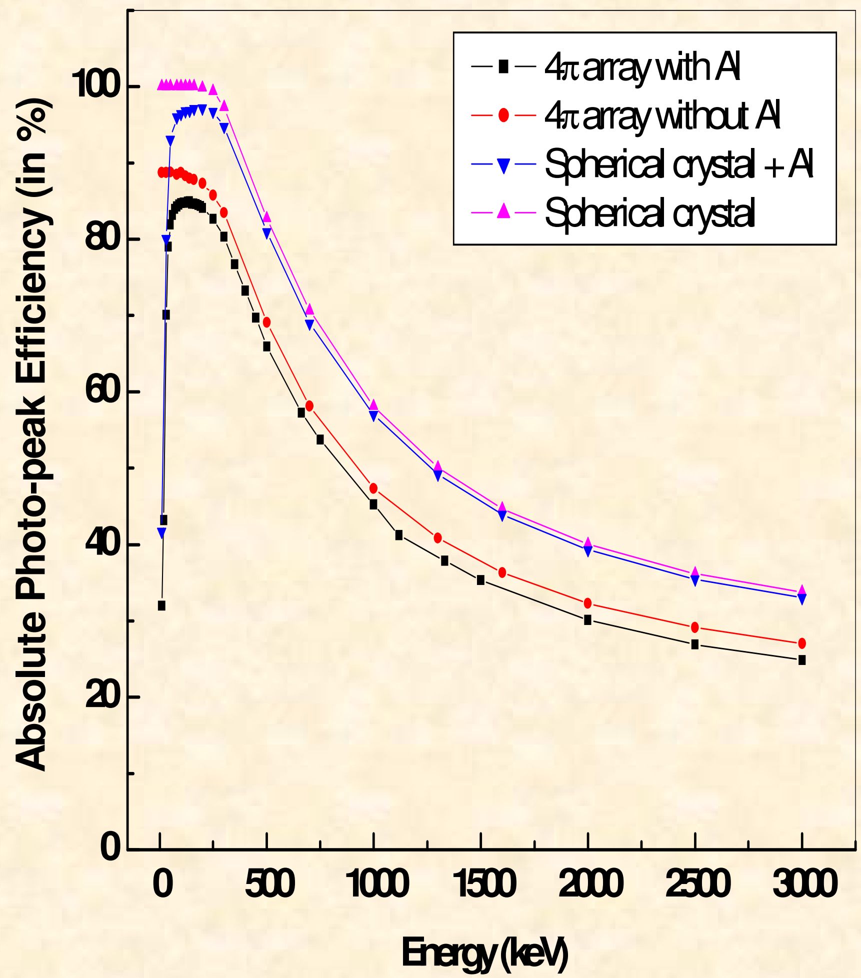
4pi-PARIS – 32 hexagons and pentagons (Dec. 2008) – by G.A. Kumar and I. Mazumdar
http://paris.ifj.edu.pl/documents/sim/



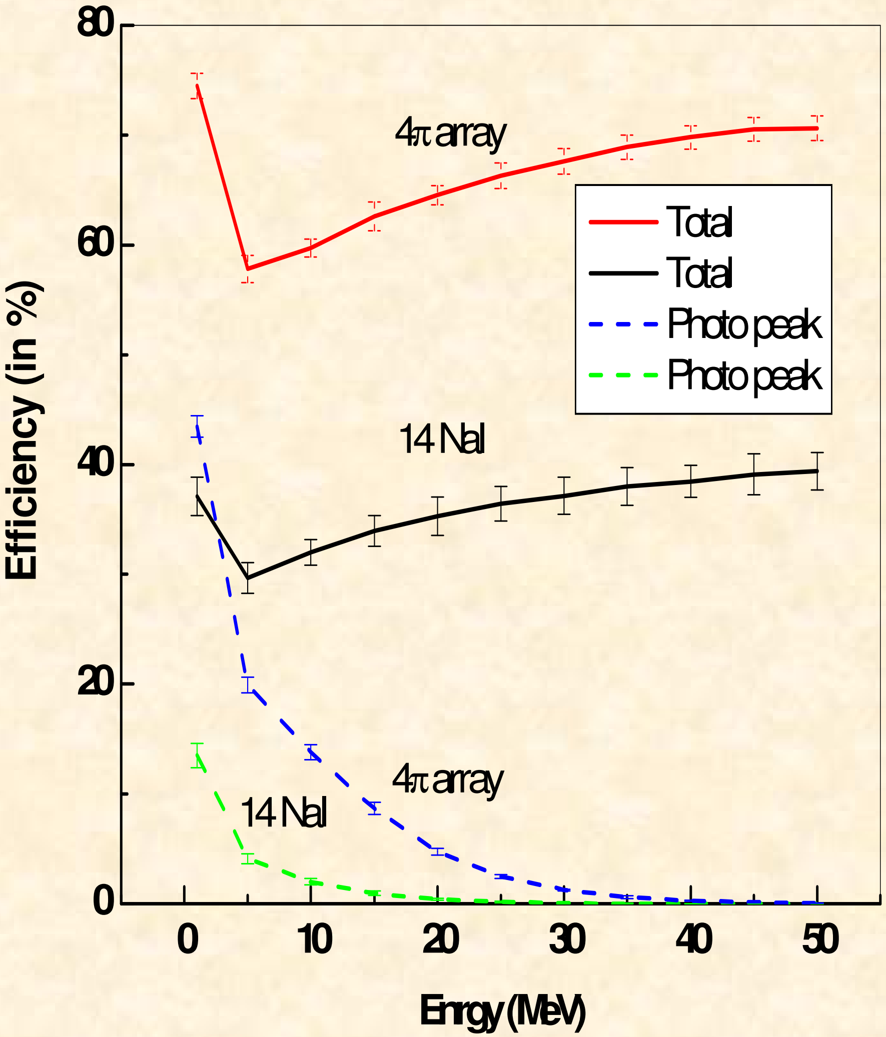
4π array
Total
Photo peak
Efficiency (in %)
Energy (keV)
0
20
40
60
80
100
0
500
1000
1500
2000
2500
3000

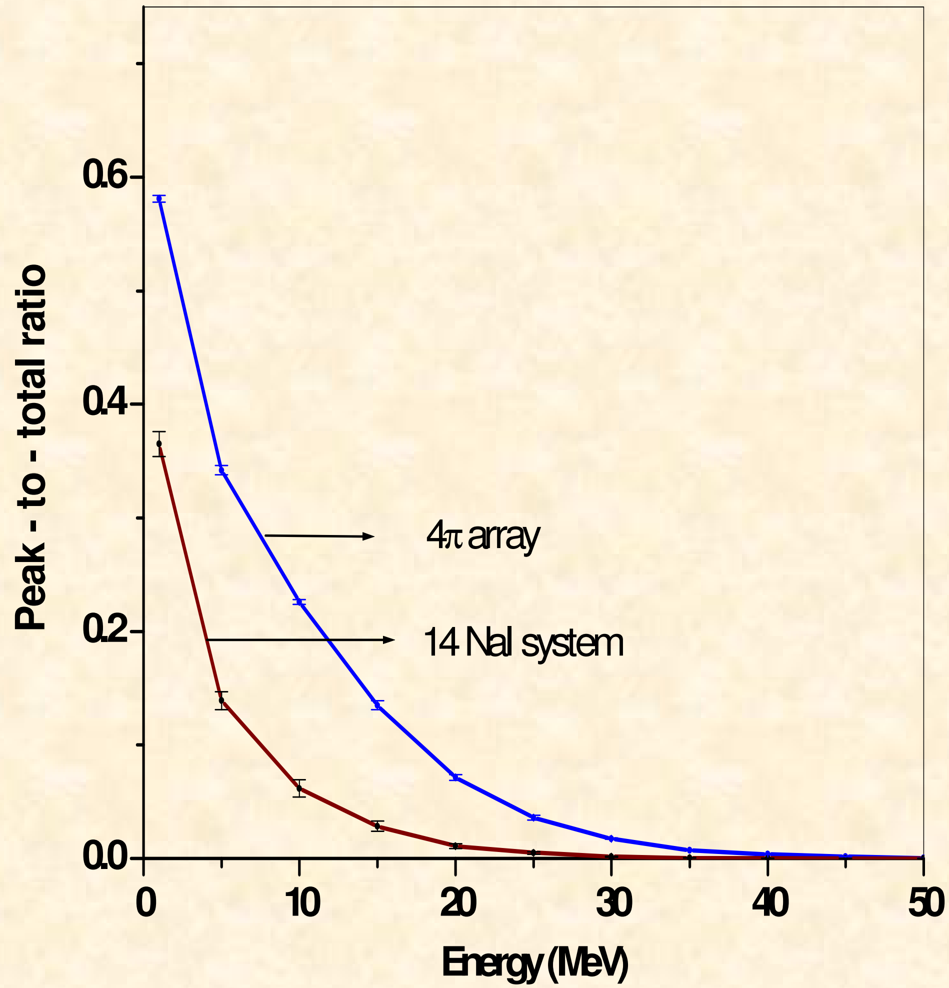


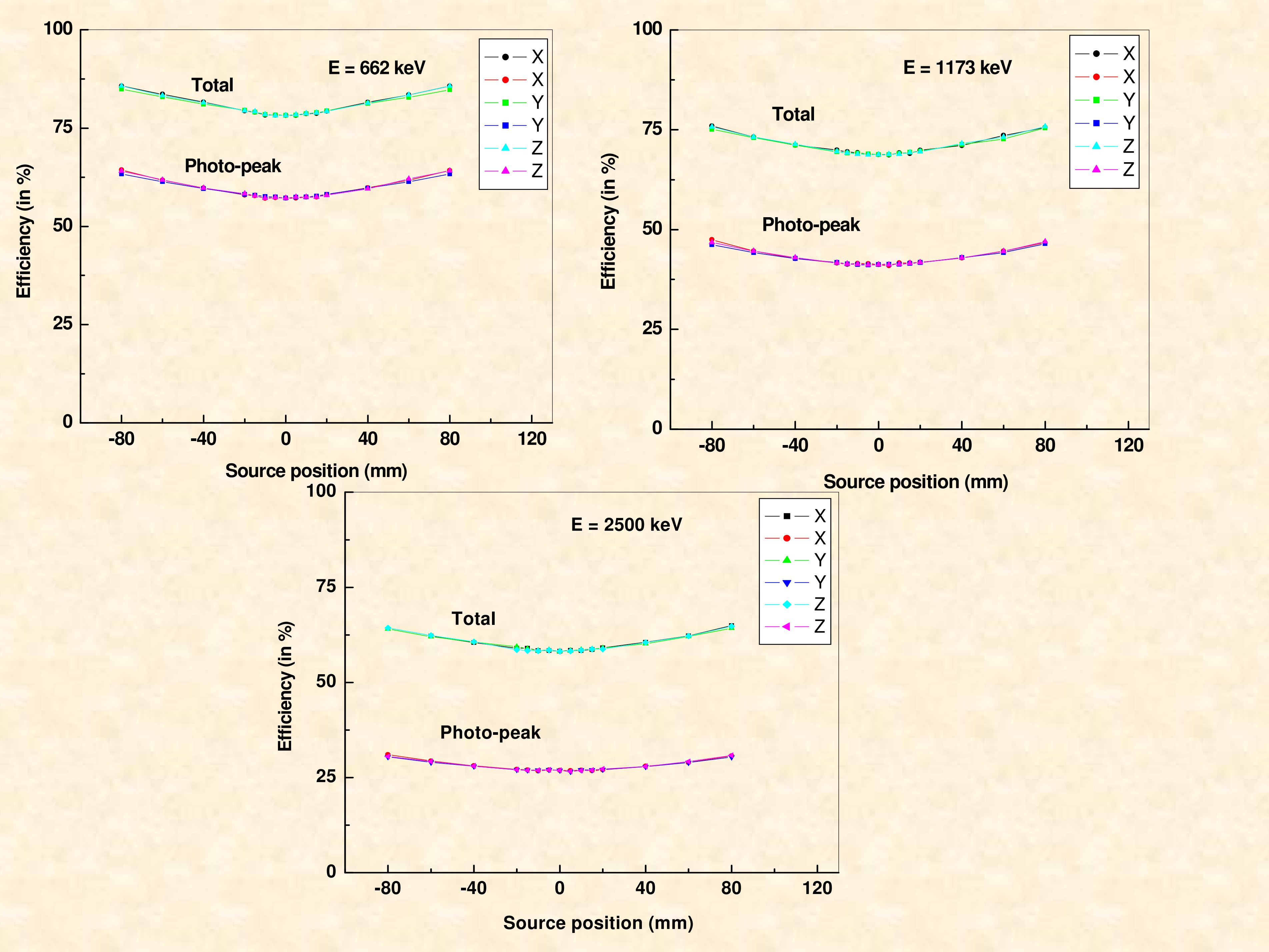
Absolute Detection Efficiency (in %)
Energy (keV)
4π array with Al
4π array without Al
Spherical crystal + Al
Spherical crystal
0
20
40
60
80
100
0
500
1000
1500
2000
2500
3000

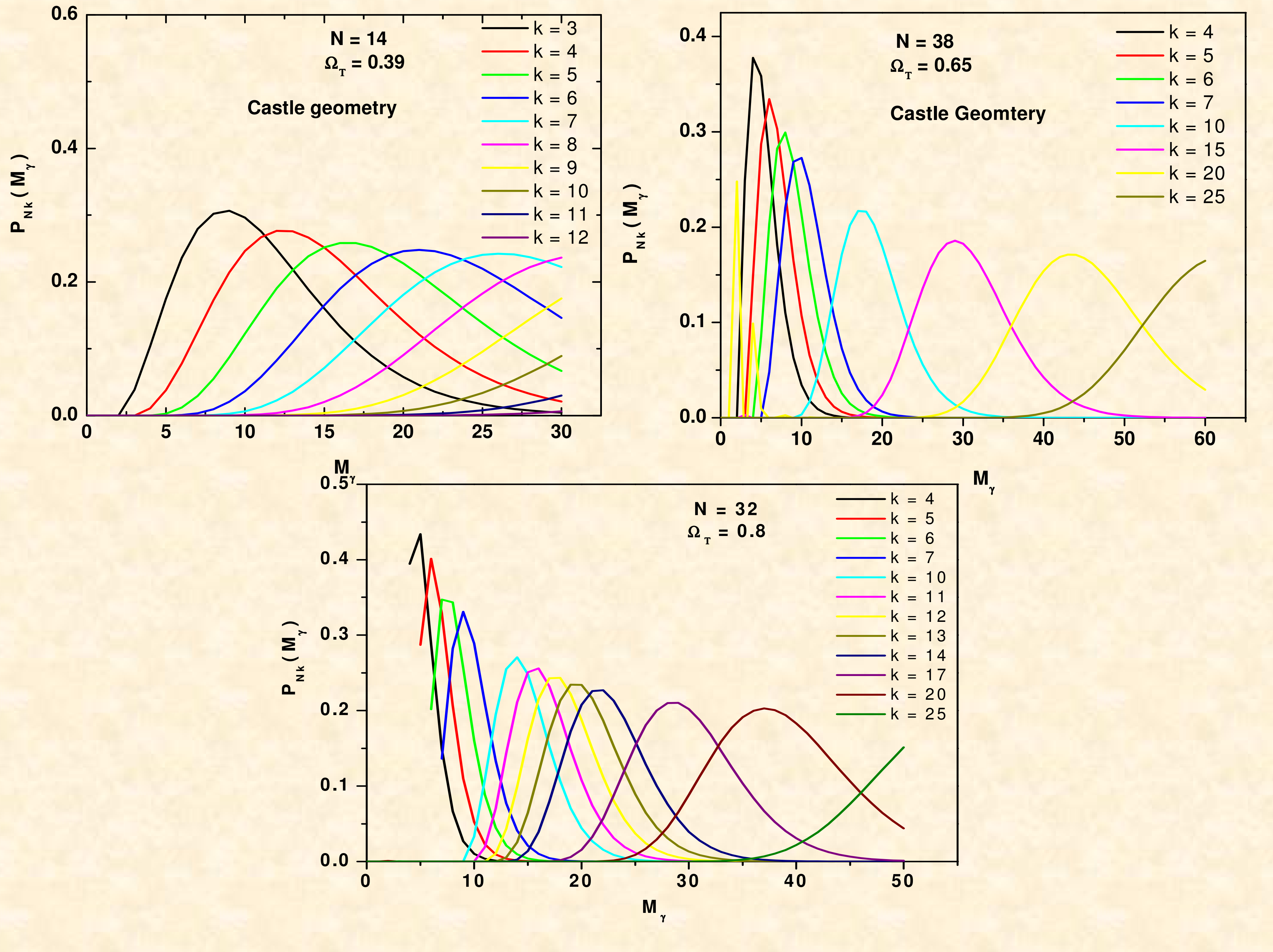


Absolute Photo-peak Efficiency (in %)
Energy (keV)
4π array with Al
4π array without Al
Spherical crystal + Al
Spherical crystal
0
20
40
60
80
100
0
500
1000
1500
2000
2500
3000


80
60
40
20
0
0
10
20
30
40
50
Efficiency (in %)
Enrgy (MeV)
Total
Total
Photo peak
Photo peak
4π array
14 NaI
4π array
14 NaI


0.6
0.4
0.2
0.0
0
10
20
30
40
50
Peak - to - total ratio
Energy (MeV)
4π array
14 NaI system

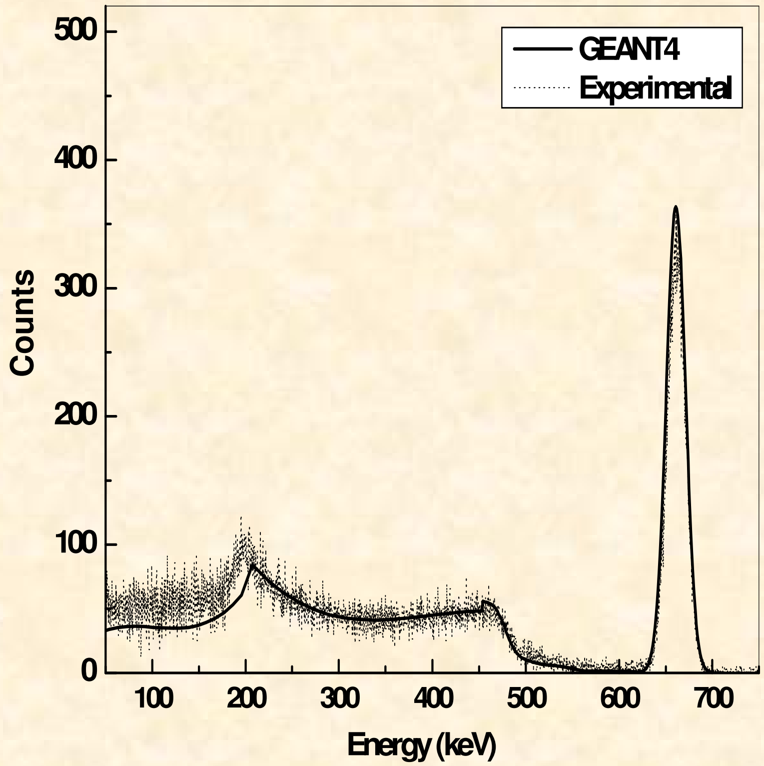

E = 662 keV
Total
Photo-peak
Efficiency (in %)
Source position (mm)
X
X
Y
Y
Z
Z
E = 1173 keV
Total
Photo-peak
Efficiency (in %)
Source position (mm)
E = 2500 keV
Total
Photo-peak
Efficiency (in %)
Source position (mm)


N = 14
Ω_T = 0.39
Castle geometry
k = 3
k = 4
k = 5
k = 6
k = 7
k = 8
k = 9
k = 10
k = 11
k = 12
P_Nk (M_γ)
M_γ
0.0
0.2
0.4
0.6
0
5
10
15
20
25
30
N = 38
Ω_T = 0.65
Castle Geomtery
k = 4
k = 5
k = 6
k = 7
k = 10
k = 15
k = 20
k = 25
P_Nk (M_γ)
M_γ
0.0
0.1
0.2
0.3
0.4
0
10
20
30
40
50
60
N = 32
Ω_T = 0.8
k = 4
k = 5
k = 6
k = 7
k = 10
k = 11
k = 12
k = 13
k = 14
k = 17
k = 20
k = 25
P_Nk (M_γ)
M_γ
0.0
0.1
0.2
0.3
0.4
0.5
0
10
20
30
40
50

Summary

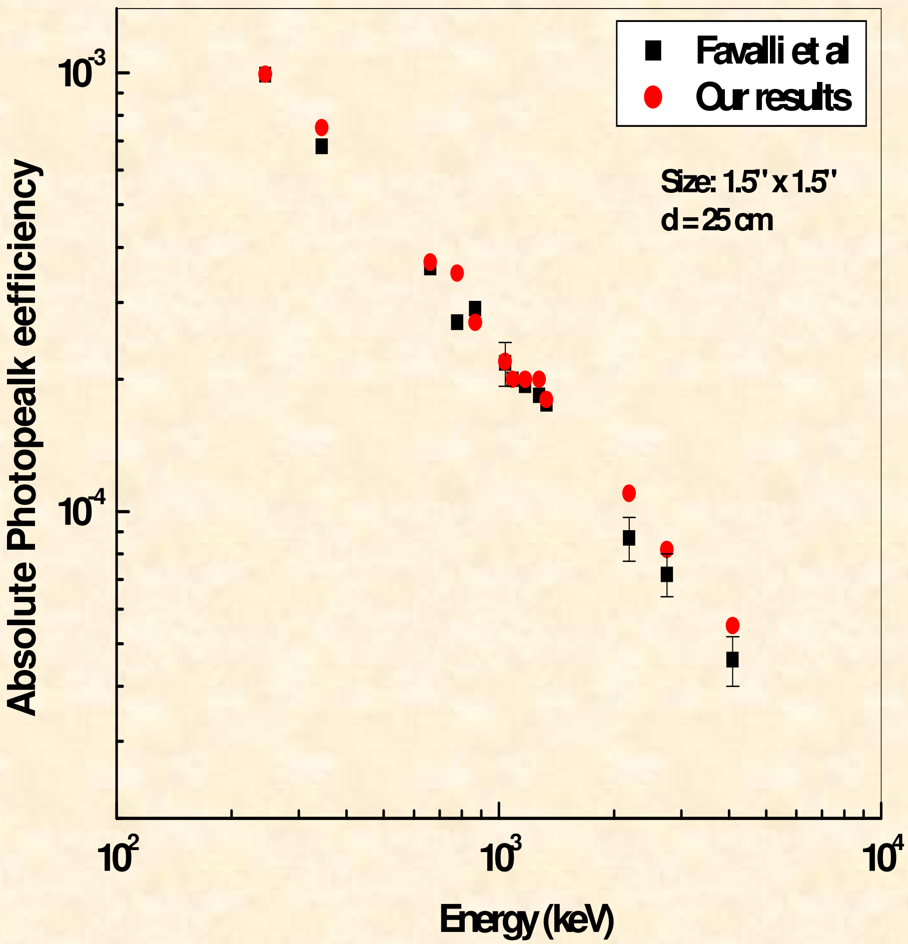
- Extensive simulations have been carried out for calculating the detection efficiencies of the individual detectors and the entire 4π array.
- The total intrinsic and photo peak efficiencies have been measured accurately with calibrated low energy gamma ray sources and are found to be in very good agreement with the simulated results.
- Efficiency measurements and GEANT4 simulations have been carried out for a smaller array of 14 straight NaI(Tl) detectors of hexagonal cross sections packed in castle geometry and the results have been compared with the 4π array.
- The fold distributions have also been calculated for different gamma multiplicities for both the 14 elements and the 4π array.

A comparative study of efficiencies of $LaBr_3$(Ce), NaI(Tl) and BaF_2

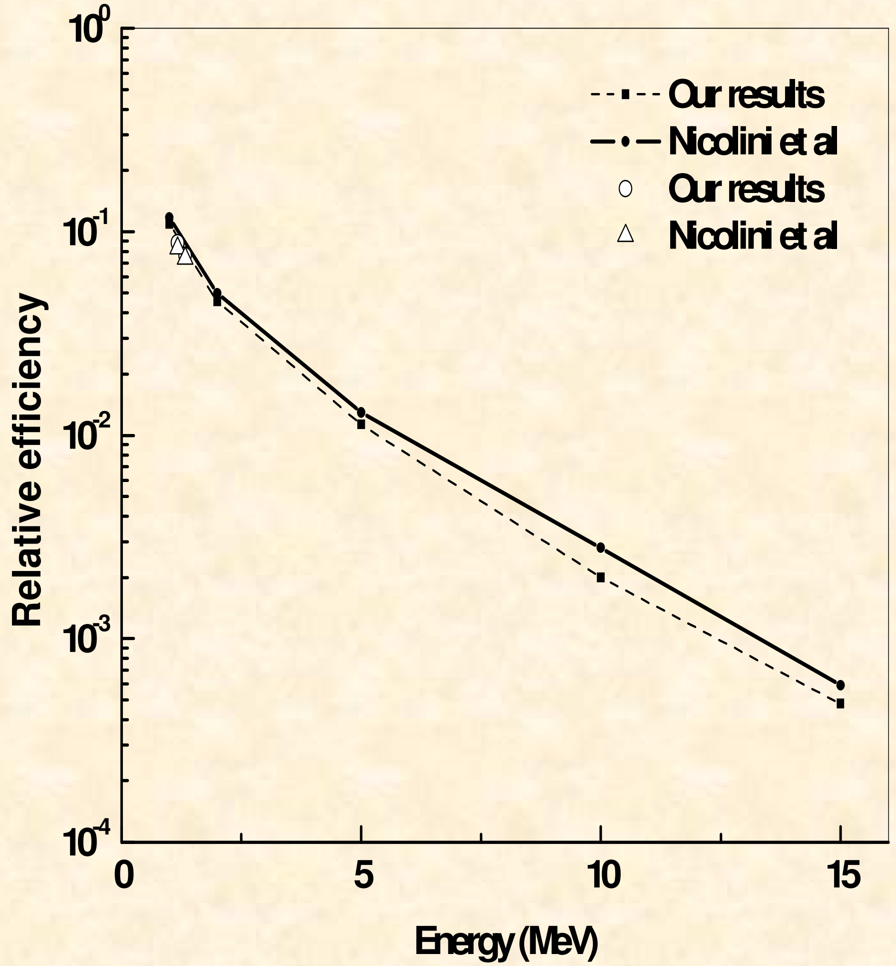


G. Anil Kumar, I. Mazumdar, D.A. Gothe,
Nucl. Instr. and Meth.A,
doi:10.1016/j.nima.2009.08.075

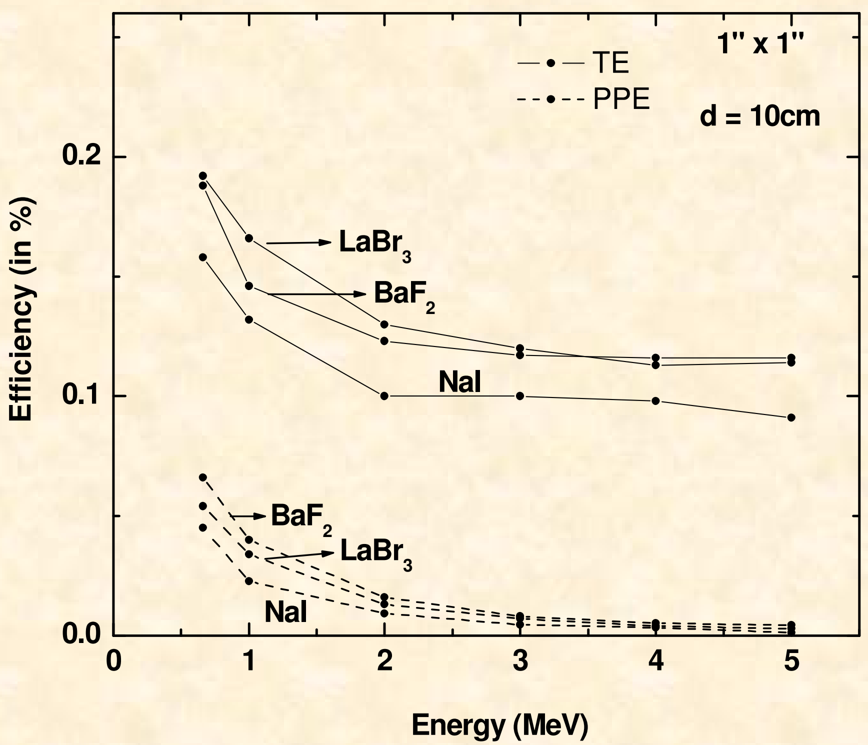
Distance (cm)	ε_{total}		ε_{peak}	
	GEANT4	Exp	GEANT4	Exp
15	0.105 (0.012)	0.114 (0.005)	0.030 (0.004)	0.027 (0.001)
25	0.041 (0.003)	0.044 (0.002)	0.011 (0.001)	0.010 (0.001)



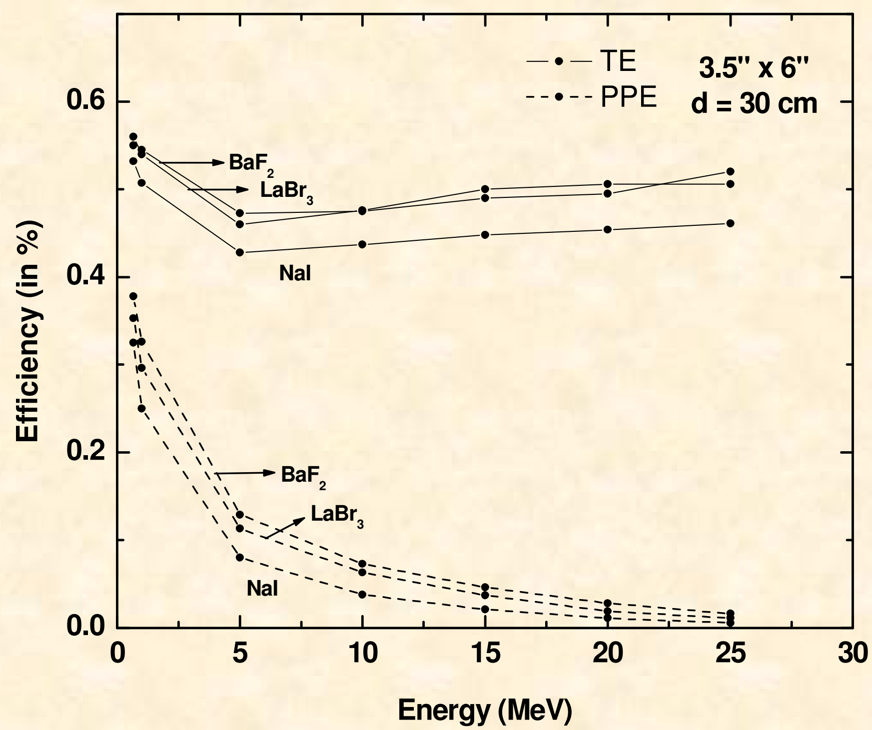
Favalli et al
Our results
Size: 1.5" x 1.5"
d = 25 cm
Absolute Photopealk eefficiency
Energy (keV)



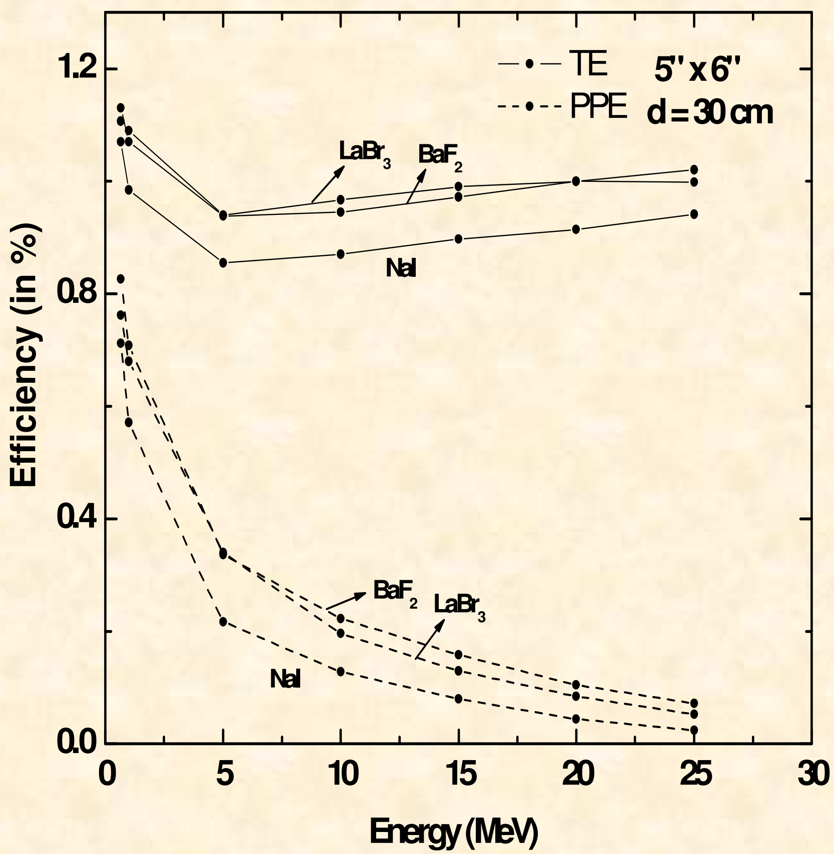
Our results
Nicolini et al
Our results
Nicolini et al
Relative efficiency
Energy (MeV)



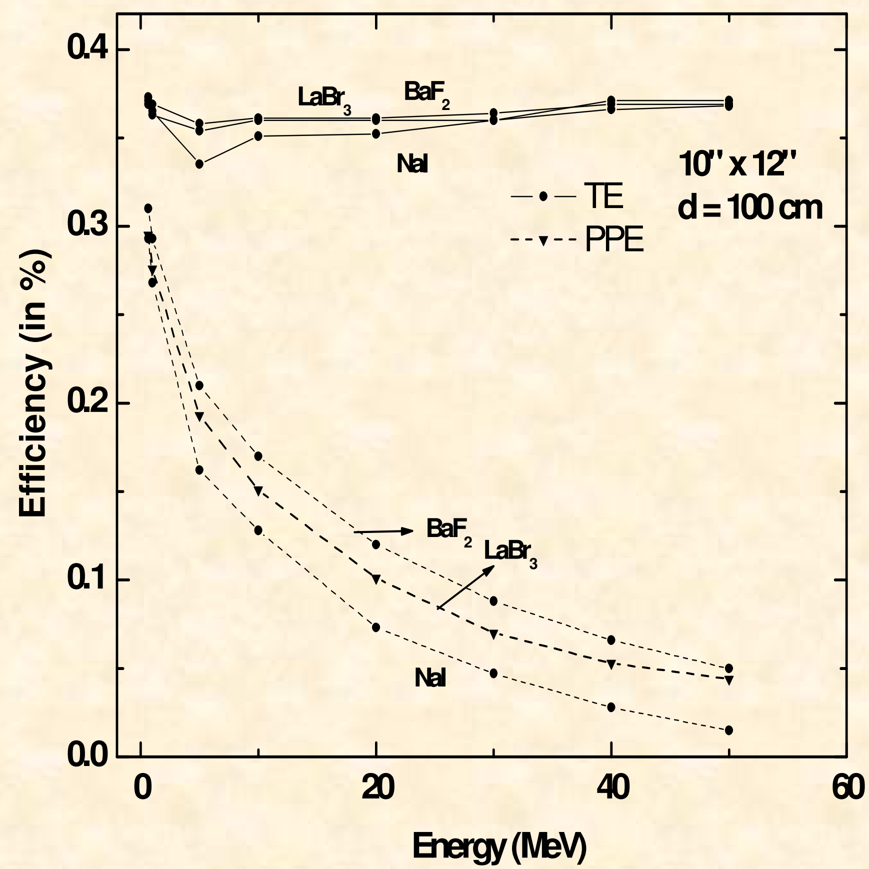
TE
PPE
1'' x 1''
d = 10cm
Efficiency (in %)
0.0
0.1
0.2
LaBr$_3$
BaF$_2$
NaI
BaF$_2$
LaBr$_3$
NaI
0
1
2
3
4
5
Energy (MeV)



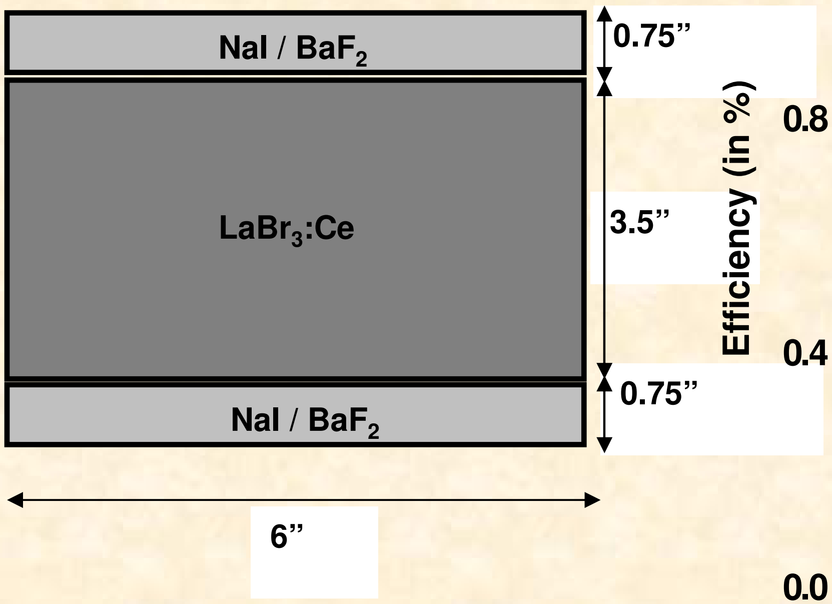
TE
PPE
3.5'' x 6''
d = 30 cm
Efficiency (in %)
0.0
0.2
0.4
0.6
BaF$_2$
LaBr$_3$
NaI
BaF$_2$
LaBr$_3$
NaI
0
5
10
15
20
25
30
Energy (MeV)

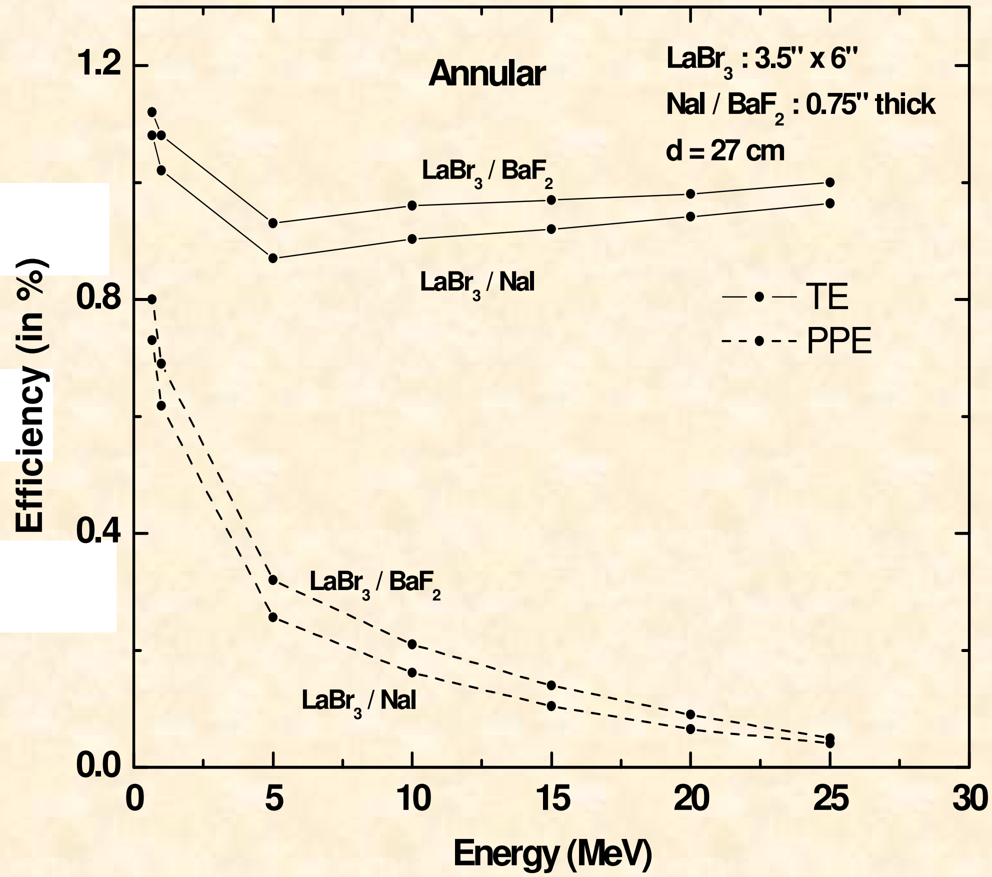


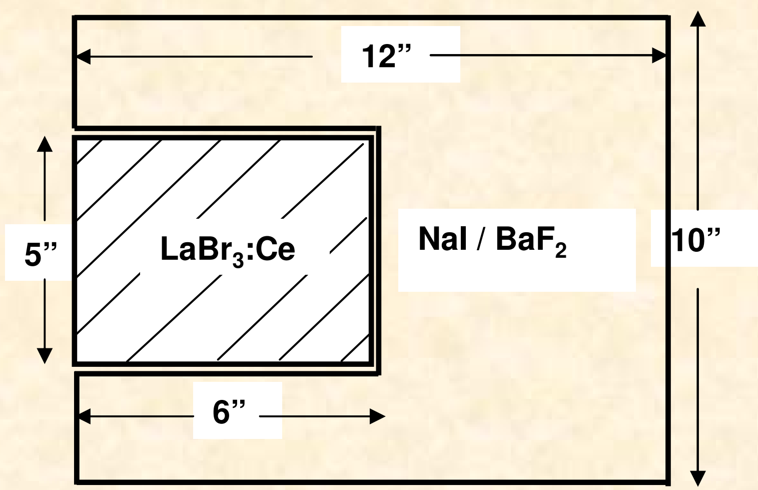
TE
PPE
5" x 6"
d = 30 cm
LaBr3
BaF2
NaI
BaF2
LaBr3
NaI
Efficiency (in %)
Energy (MeV)



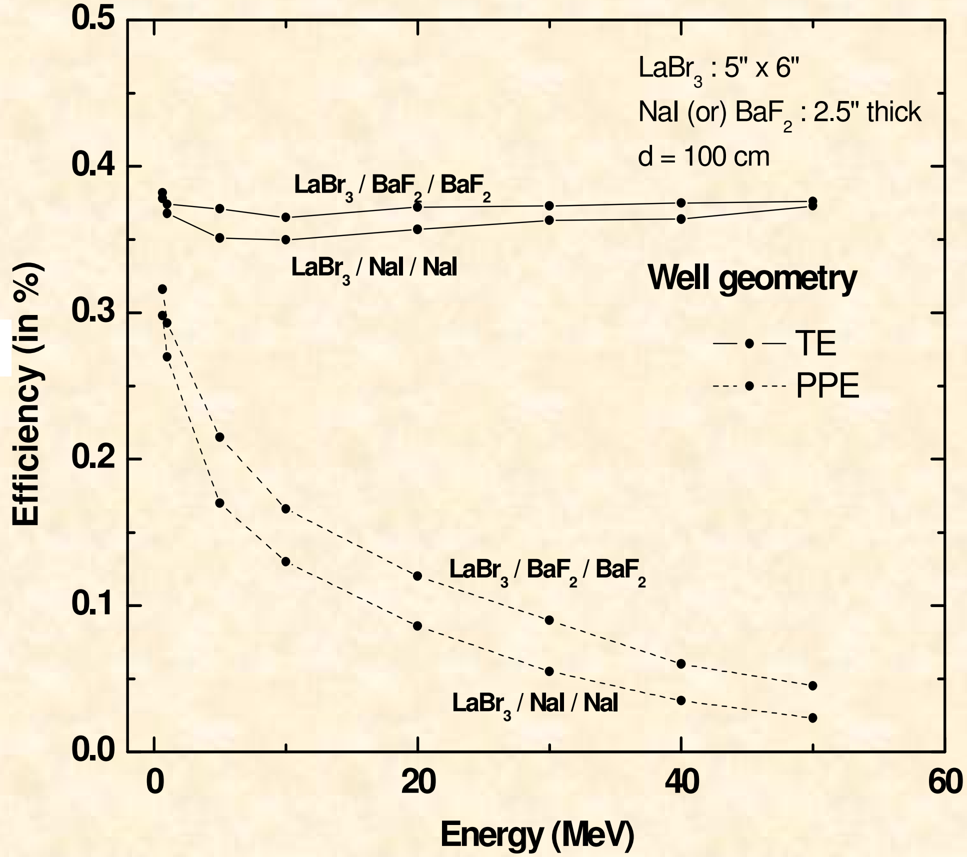
LaBr3
BaF2
NaI
TE
PPE
10" x 12"
d = 100 cm
BaF2
LaBr3
NaI
Efficiency (in %)
Energy (MeV)


NaI / BaF2
LaBr3:Ce
NaI / BaF2
0.75"
3.5"
0.75"
6"


Annular
LaBr3 : 3.5" x 6"
NaI / BaF2 : 0.75" thick
d = 27 cm
LaBr3 / BaF2
LaBr3 / NaI
TE
PPE
LaBr3 / BaF2
LaBr3 / NaI
Efficiency (in %)
Energy (MeV)
0.0
0.4
0.8
1.2
0
5
10
15
20
25
30



12”
5”
LaBr3:Ce
NaI / BaF2
10”
6”



LaBr3 : 5" x 6"
NaI (or) BaF2 : 2.5" thick
d = 100 cm
LaBr3 / BaF2 / BaF2
LaBr3 / NaI / NaI
Well geometry
TE
PPE
LaBr3 / BaF2 / BaF2
LaBr3 / NaI / NaI
Efficiency (in %)
Energy (MeV)
0.0
0.1
0.2
0.3
0.4
0.5
0
20
40
60

Summary

The simulation results are compared with recent measurements reported by other authors for 1" x 1" and for 1.5" x 1.5" detectors. A good agreement between simulations and measurements has been achieved

Simulation results are presented in connection with a proposition for high energy gamma detection using combination of $LaBr_3(Ce)$ with $NaI(Tl)/BaF_2$.

Close-geometry efficiency calibration and true coincidence summing correction

Calculation of coincidence summing correction factors

Assumptions:

1) Point source
2) β-radiation absorbed in the detector window

Count rate resulting from full absorption of γ-rays of energy E_1 and E_2 are given by

$$N_1 = A\, p_1\, \varepsilon_{p1}$$

$$N_2 = A\, p_2\, \varepsilon_{p2}$$

where

p_1 is emission probability of γ-rays with energy E_1

p_2 is emission probability of γ-rays with energy E_2

ε_{p1} is photo peak efficiency for gamma rays with energy E_1

ε_{p2} is photo peak efficiency for gamma rays with energy E_2

(T. Vidmar et al., NIM-A 508 (2003) 404)

The count rate in recorded full energy peak in the spectrum, however, is smaller. Since each γ_1 is followed by a γ_2 in coincidence, it may happen that both γ-rays are detected, thus leading to a single count. If the energy of γ_1 is totally absorbed, this sum pulse is recorded at an energy between E_1 and $E_1 + E_2$ and the event is lost from the full energy peak of γ_1

$$N'_1 = A\, p_1\, \varepsilon_{p1} - A\, p_1\, \varepsilon_{p1} \varepsilon_{t2} = A\, p_1\, \varepsilon_{p1} (1 - w\varepsilon_{t2})$$

where ε_{t2} is total detection efficiency of γ_2

Similarly,

$$N'_2 = A\, p_2\, \varepsilon_{p2} (1 - w\varepsilon_{t1})$$

$$N'_{12} = A\, p_1\, p_2\, w\, \varepsilon_{p1}\, \varepsilon_{p2}$$

Three equations and four unknowns if the source is calibrated

If the source is non-calibrated point source,

$$A = N_{total} + \frac{N'_1 N'_2}{w N'_{12}}$$

Finally,

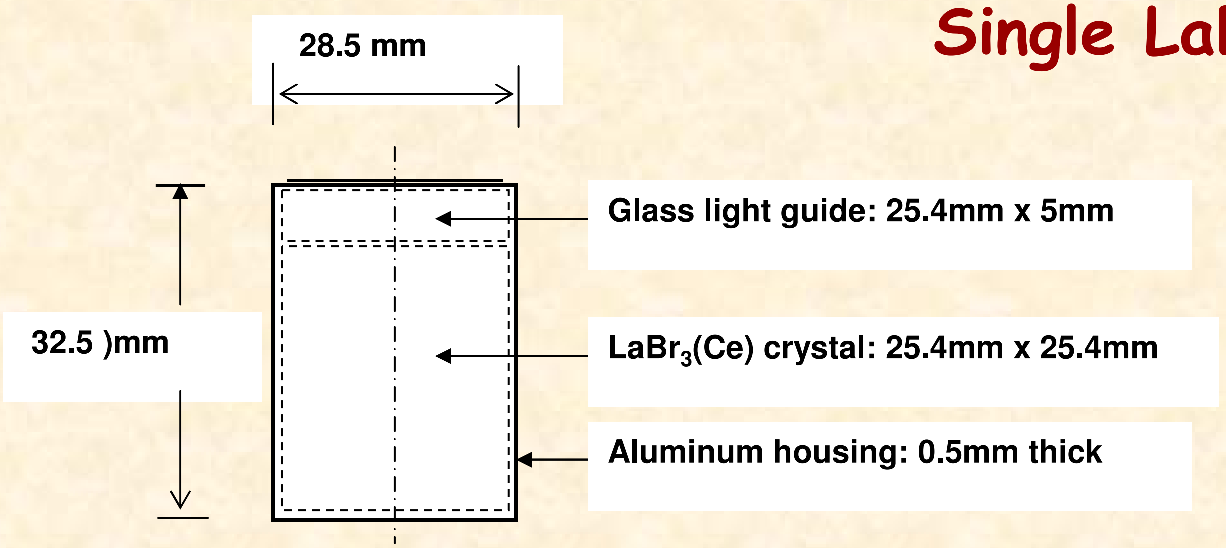
$$\varepsilon_{p1} = \frac{\left(\frac{(N'_1 - N'_2) + \sqrt{(N'_1 - N'_2)^2 + 4AN'_{12}}}{2A} + \sqrt{\frac{N'_1 N'_{12}}{AN'_2}} \right)}{2}$$

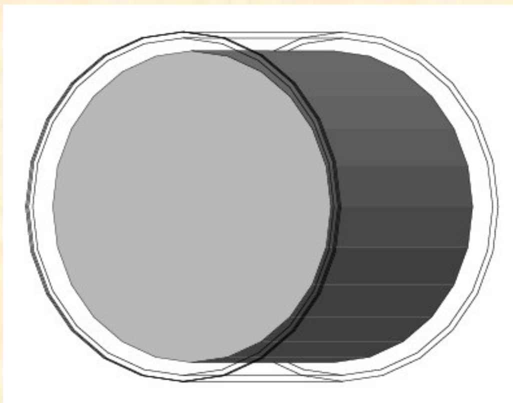
$$\varepsilon_{p2} = \frac{N'_{12}}{A\,\varepsilon_{p1}}$$

$$\varepsilon_{t1} = 1 - \frac{\varepsilon_{p1} N'_2}{N'_{12}}$$

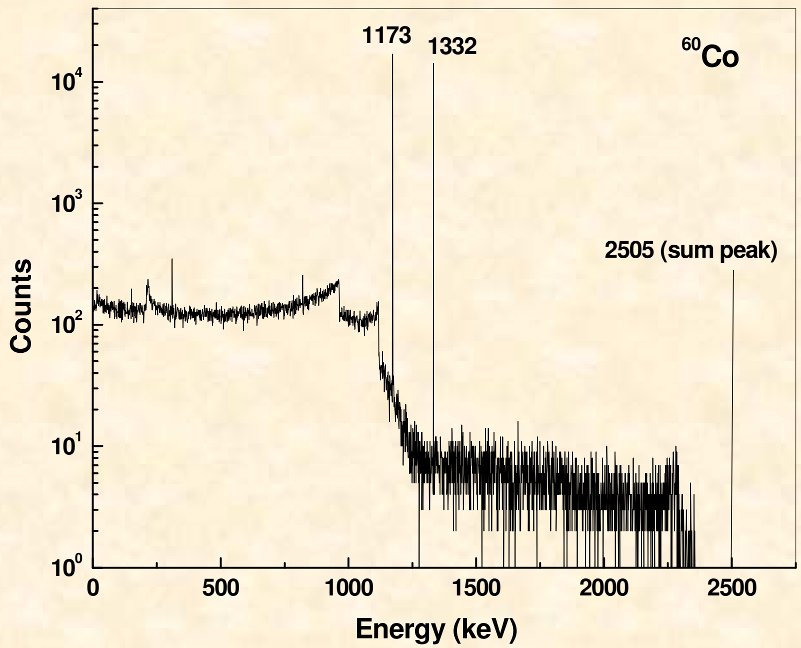
$$\varepsilon_{t2} = 1 - \frac{N'_1}{A\,\varepsilon_{p1}}$$

Single $LaBr_3(Ce)$ detector

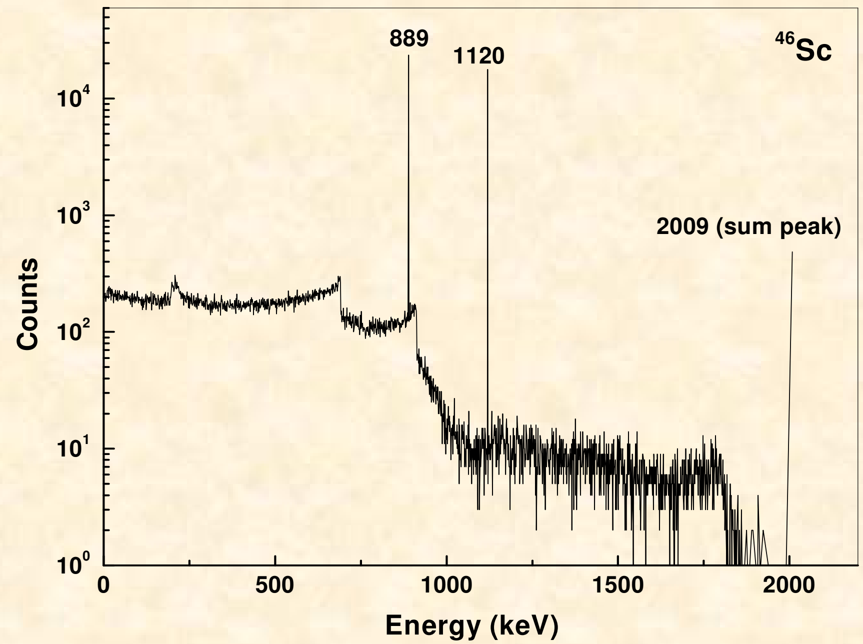




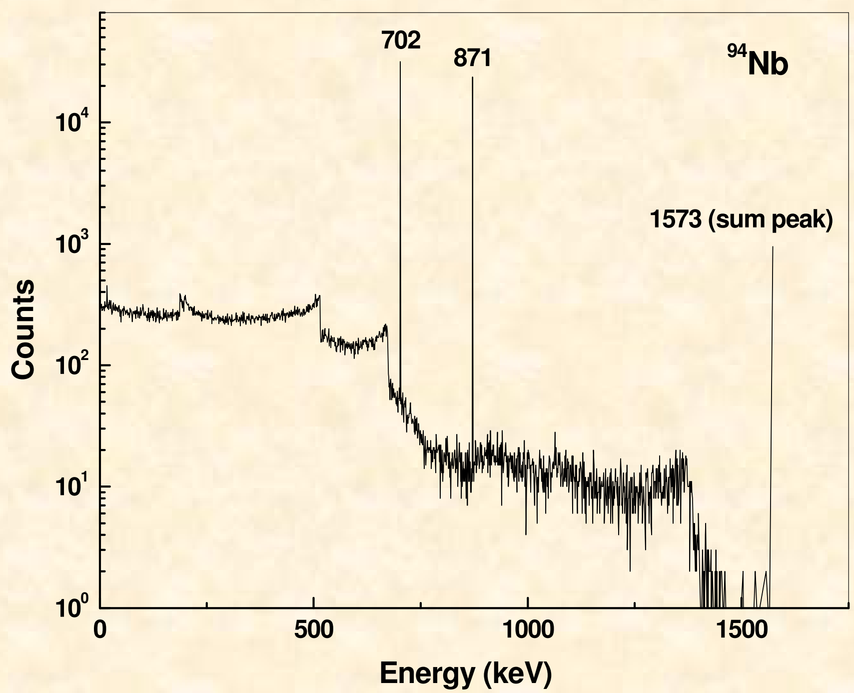
Nuclide	E_1(keV)	E_2(keV)	b_1(%)	b_2(%)
^{60}Co	1173.23	1332.50	99.85	99.98
^{46}Sc	889.27	1120.54	99.98	99.98
^{94}Nb	702.64	871.11	99.79	99.86
^{24}Na	1368.63	2754.03	99.99	99.85



1173
1332
60Co
2505 (sum peak)
Counts
Energy (keV)

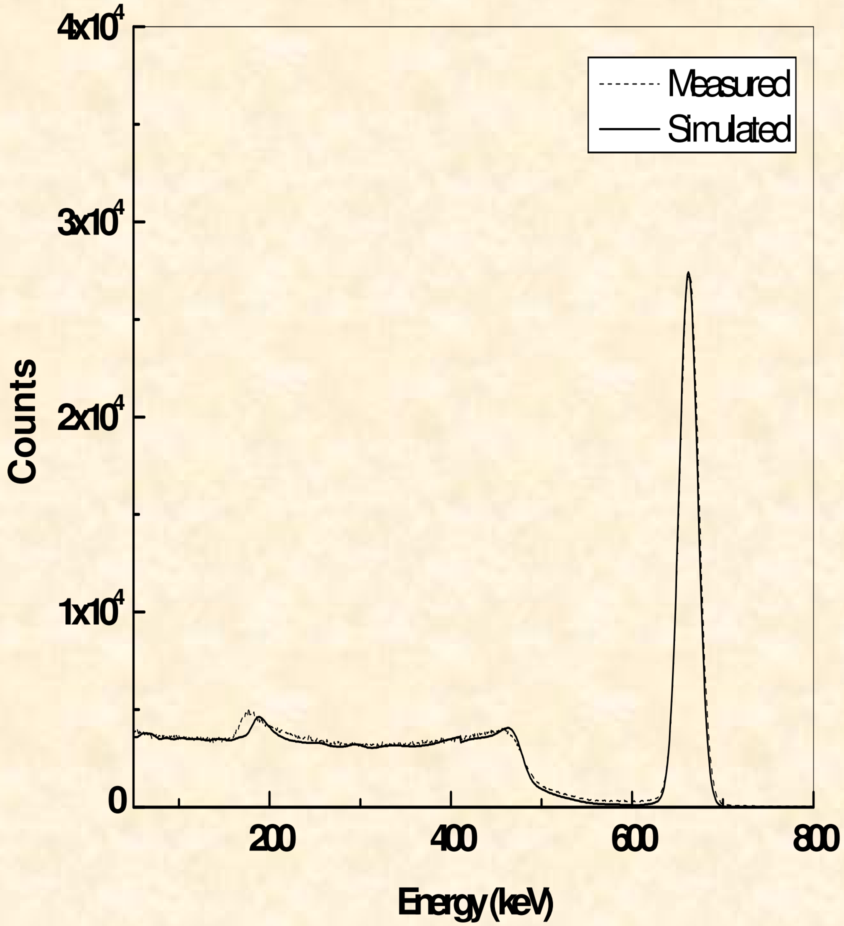


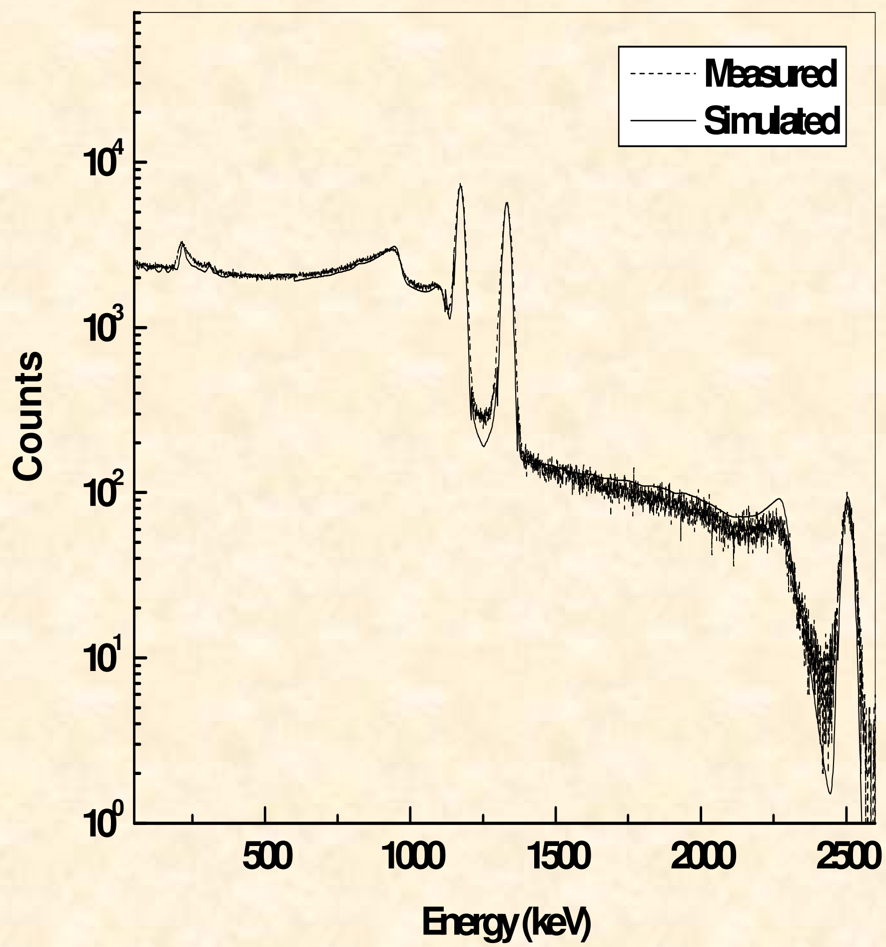
889
1120
46Sc
2009 (sum peak)
Counts
Energy (keV)



702
871
94Nb
1573 (sum peak)
Counts
Energy (keV)

G. Anil Kumar, I. Mazumdar, D.A. Gothe, Nucl. Instr. and Meth. A 609 (2009) 183





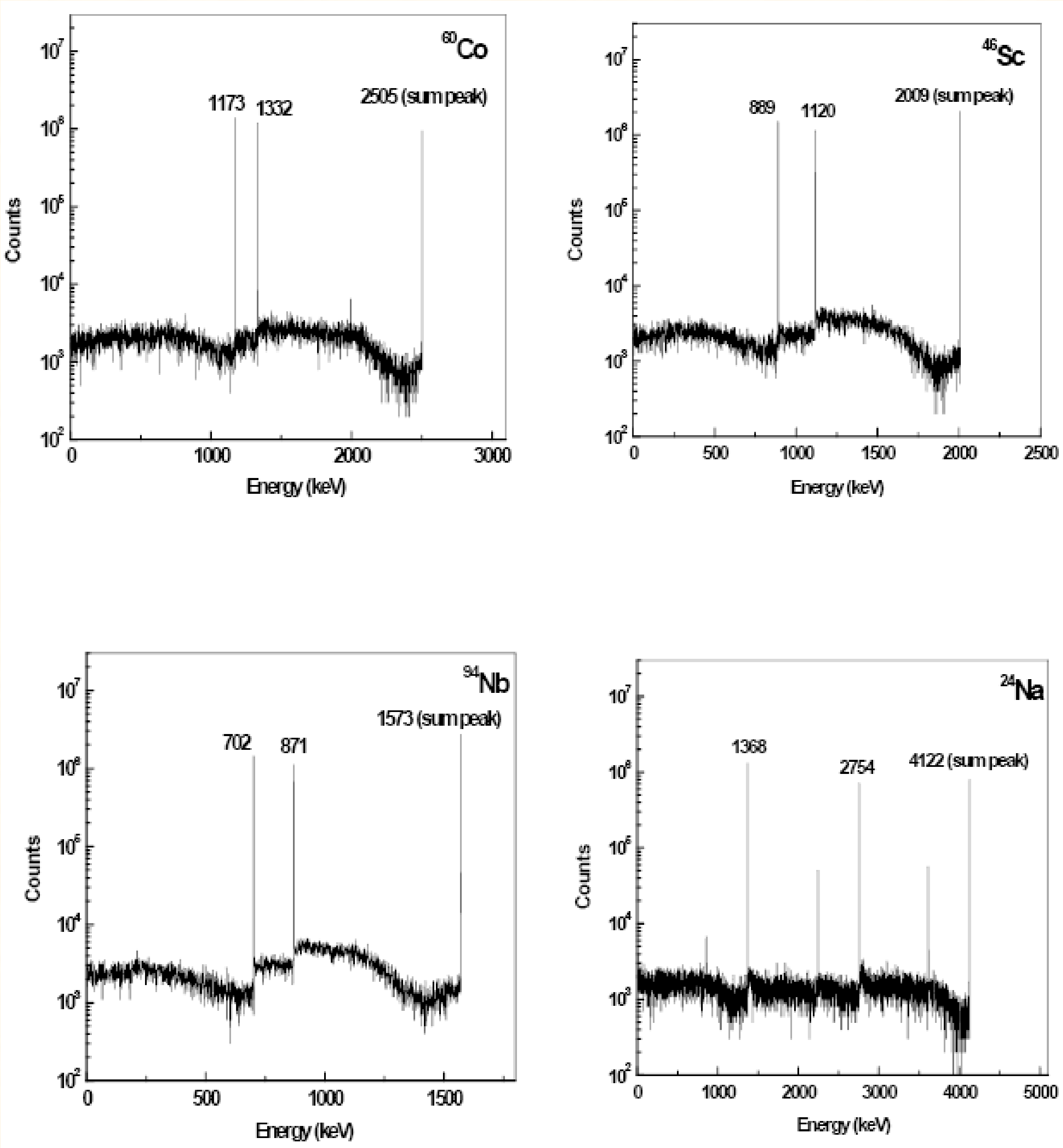
Simulated true efficiencies for double photon emitters (^{60}Co, ^{46}Sc and ^{94}Nb) and for mono-energetic gamma sources of similar energies

Source	ε_{t1} (%)	ε_{t2} (%)	ε_{p1} (%)	ε_{p2} (%)
^{60}Co	12.63 (1.10)	11.75 (1.14)	1.87 (0.11)	1.60 (0.10)
Mono energetic	10.80 (0.77)	9.74 (1.00)	1.84 (0.16)	1.56 (0.14)
^{46}Sc	12.67 (0.40)	11.75 (0.46)	2.67 (0.10)	1.97 (0.07)
Mono energetic	11.40 (0.87)	10.40 (0.79)	2.60 (0.23)	1.94 (0.17)
^{94}Nb	12.67 (0.46)	11.00 (0.40)	3.61 (0.09)	2.74 (0.07)
Mono energetic	12.58 (0.95)	11.47 (0.90)	3.64 (0.30)	2.71 (0.24)

Nuclide	Energy (keV)	Coincidence summing correction factor
^{60}Co	1173.23	0.882 (0.075)
	1332.50	0.873 (0.077)
^{46}Sc	889.27	0.889 (0.076)
	1120.54	0.873 (0.077)
^{94}Nb	702.62	0.877 (0.037)
	871.1	0.860 (0.041)

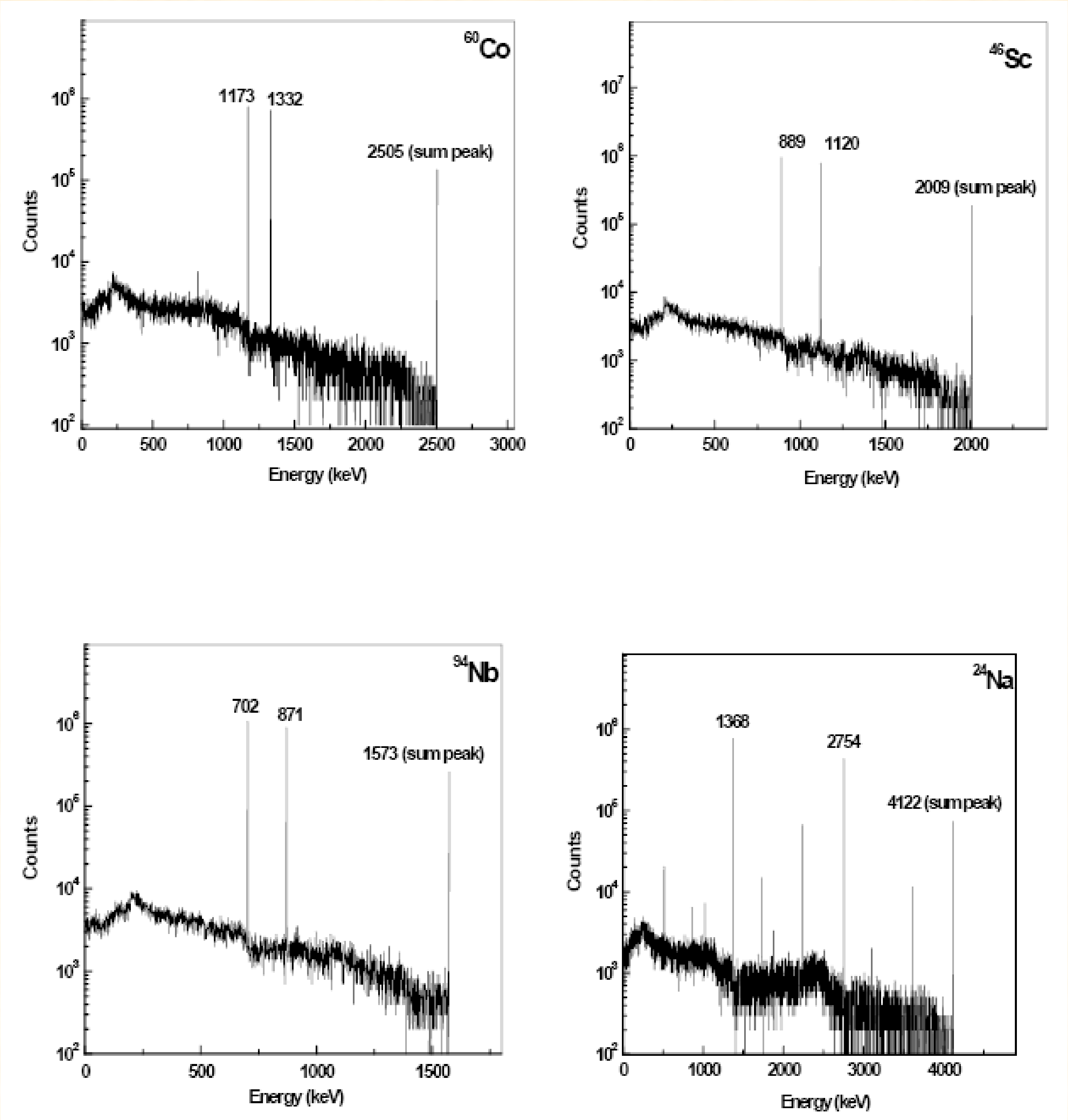
Nuclide	Energy (keV)	Total efficiency (%)		Photo-peak efficiency (%)	
		Measured	Simulated	Measured	Simulated
^{137}Cs	661.6	12.01 (0.60)	12.90 (1.00)	3.41 (0.17)	3.93 (0.34)
^{60}Co	1173.23	14.39 (2.19)	12.63 (1.10)	1.65 (0.09)	1.87 (0.11)
	1332.50	13.94 (2.20)	11.75 (1.14)	1.51 (0.08)	1.60 (0.10)

Energy (keV)	Coincidence summing correction factor	
	Experimental	Simulated
1173.23	0.860 (0.048)	0.882 (0.075)
1332.50	0.856 (0.048)	0.883 (0.077)



Soccer-ball geometry

Castle geometry

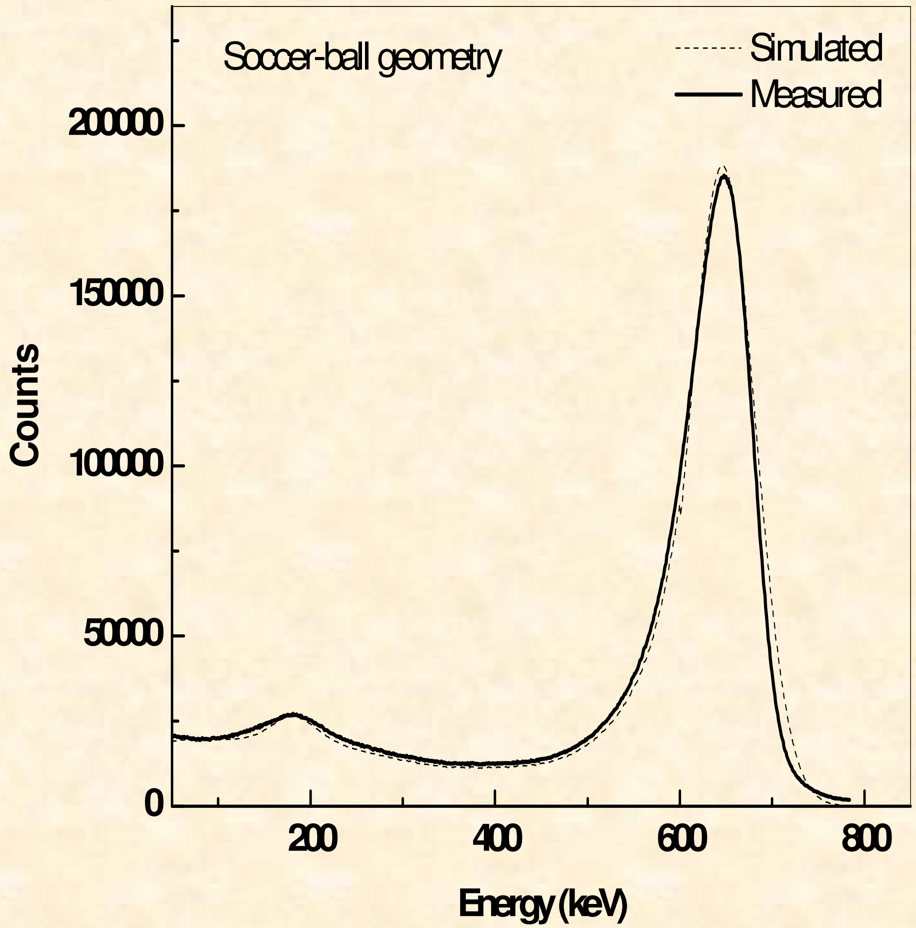


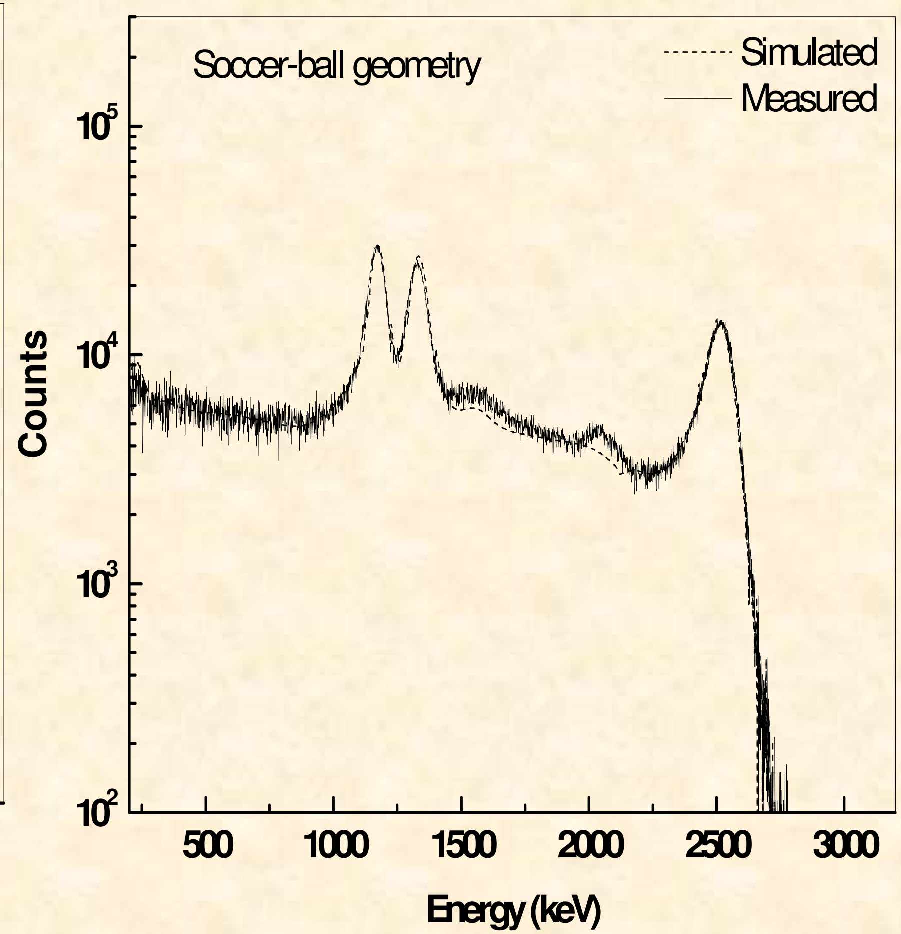
Soccer-ball geometry

Source	ε_{t1} (%)	ε_{t2} (%)	ε_{p1} (%)	ε_{p2} (%)
^{60}Co	68.2 (1.1)	66.7 (1.2)	41.2 (1.4)	37.7 (1.3)
Mono energetic	68.5 (1.3)	66.2 (1.1)	41.0 (1.3)	38.1 (1.0)
^{46}Sc	72.6 (1.1)	70.0 (1.2)	49.5 (2.0)	41.5 (1.6)
Mono energetic	73.1 (1.5)	69.2 (1.3)	48.4 (1.5)	42.2 (1.3)
^{94}Nb	76.2 (1.1)	73.9 (1.3)	56.2 (2.7)	48.1 (2.3)
Mono energetic	76.9 (1.2)	73.6 (1.2)	55.5 (1.3)	49.2 (1.4)
^{24}Na	68.4 (2.0)	61.9 (2.4)	35.0 (2.2)	23.0 (1.4)
Mono energetic	66.0 (1.2)	57.4 (1.0)	37.5 (1.2)	25.7 (0.8)

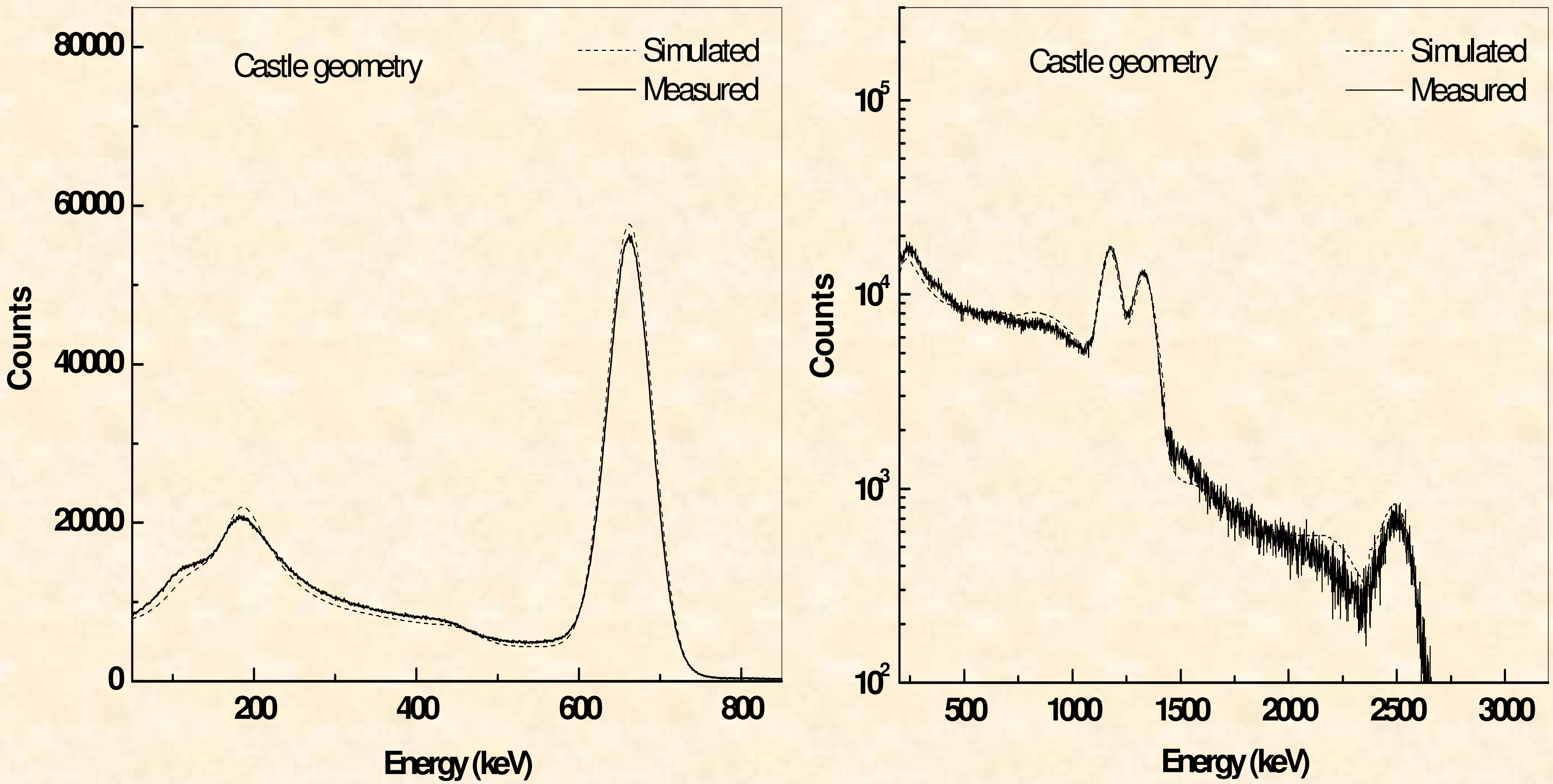
Castle geometry

Source	ε_{t1} (%)	ε_{t2} (%)	ε_{p1} (%)	ε_{p2} (%)
^{60}Co	36.6 (1.9)	35.2 (1.9)	12.4 (0.8)	11.3 (0.7)
Mono energetic	35.7 (1.9)	34.4 (1.7)	12.2 (1.1)	11.1 (1.0)
^{46}Sc	38.8 (1.9)	36.8 (1.1)	14.7 (0.9)	12.8 (0.8)
Mono energetic	38.2 (1.8)	36.0 (1.9)	14.6 (1.2)	12.6 (1.1)
^{94}Nb	40.5 (1.9)	38.4 (2.0)	17.2 (0.8)	14.9 (0.7)
Mono energetic	40.6 (1.0)	38.7 (1.8)	17.3 (1.4)	15.0 (1.1)
^{24}Na	36.3 (1.6)	30.4 (2.0)	10.9 (0.6)	6.9 (0.4)
Mono energetic	34.2 (1.9)	30.3 (1.6)	11.0 (1.0)	6.7 (0.6)





G. Anil Kumar, I. Mazumdar, D.A. Gothe, Nucl. Instr. and Meth.A,
doi:10.1016/j.nima.2009.09.005



Castle geometry
Simulated
Measured
Counts
Energy (keV)
Castle geometry
Simulated
Measured
Counts
Energy (keV)

Soccer-ball geometry

Nuclide	Energy (keV)	Total efficiency (%)		Photo-peak efficiency (%)	
		Measured	Simulated	Measured	Simulated
^{137}Cs	661.6	77.7 (3.9)	78.2 (1.1)	55.3 (2.4)	57.7 (1.3)
^{60}Co	1173.23	71.2 (1.3)	68.2 (1.1)	38.4 (1.6)	40.2 (1.5)
	1332.50	68.3 (1.4)	66.7 (1.2)	35.9 (1.3)	37.7 (1.3)

Castle geometry

Nuclide	Energy (keV)	Total efficiency (%)		Photo-peak efficiency (%)	
		Measured	Simulated	Measured	Simulated
^{137}Cs	661.6	40.0 (2.0)	40.9 (1.9)	16.4 (0.8)	17.2 (1.3)
^{60}Co	1173.23	38.4 (1.9)	36.6 (1.9)	11.8 (1.6)	12.4 (0.8)
	1332.50	37.1 (2.0)	35.2 (1.9)	10.9 (1.8)	11.3 (0.7)

Experimental and simulated coincidence summing correction factors for both the arrays for ^{60}Co

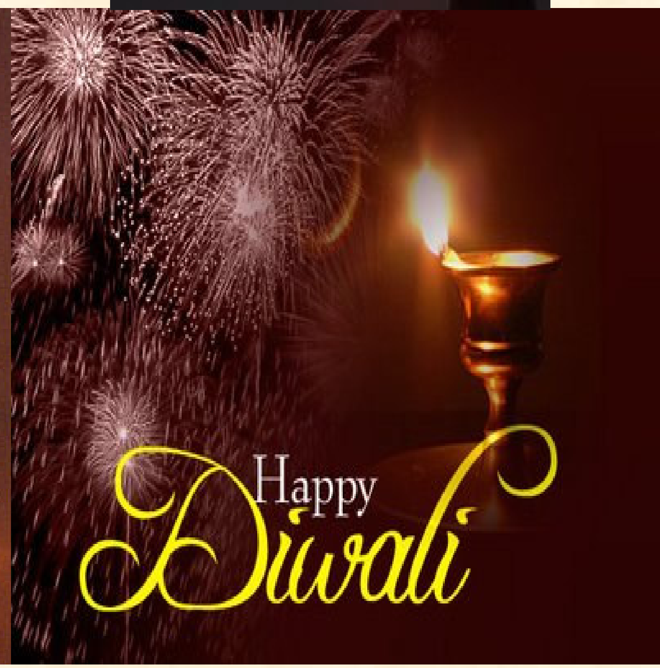
Configuration	Energy (keV)	Coincidence summing correction factor	
		Experimental	Simulated
Soccer-ball	1173.23	0.32 (0.02)	0.33 (0.01)
	1332.50	0.28 (0.02)	0.32 (0.01)
Castle	1173.23	0.63 (0.02)	0.65 (0.06)
	1332.50	0.62 (0.02)	0.63 (0.05)

Summary

Close geometry efficiency calibration and coincidence summing correction have been performed for a single $LaBr_3$(Ce) cylindrical detector, an array of 32 conical NaI(Tl) detectors in soccer-ball geometry and an array of 14 straight hexagonal NaI(Tl) detectors in castle geometry

A good agreement between simulations and measurements has been achieved

The present work demonstrates the reliability of the coincidence summing correction method for efficiency calibration of 3 very different configurations.



"Tamasoma Jyotirgamaya"- From darkness, lead me to light