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Efficiency calibration of Whole Body Counter

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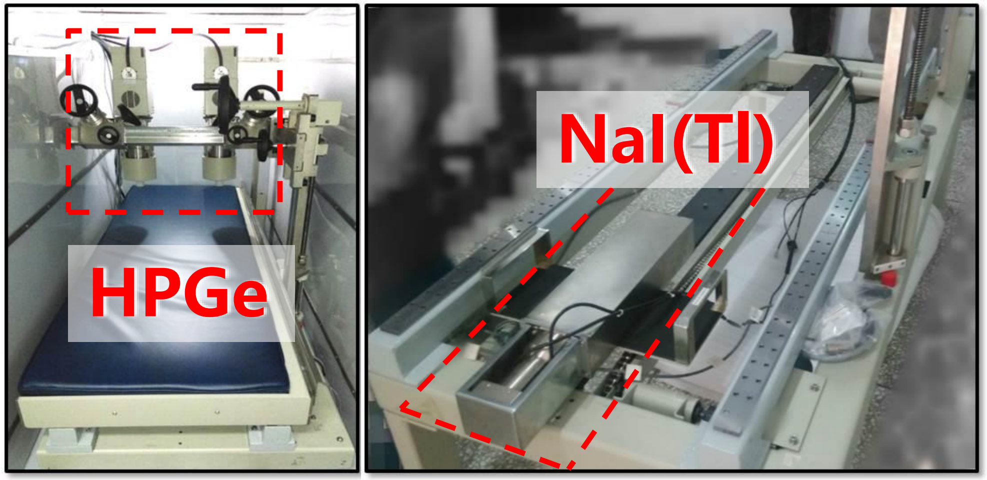
Background

We make personal internal exposure dose monitoring for hundreds of staff in CIAE every year, including lung and whole body counter monitoring.

The whole body counter in our laboratory was established in 1978. The detectors were composed of four φ10×10 NaI crystals， and the shielding room is 2.2×1×1.5m^3 with quartz sand, steel, lead and plastic plates. In 2015, the detectors were replaced with two HPGe detectors model BE6530 and a NaI detector of 2259A from the US Canberra.



During the routine measurement process, The calibration of WBC is necessary. This presentation is mainly about the calibration experiment for WBC in our laboratory.

Content of report

The Whole Body Counter calibration is including two parts::

- ## Experiment part:

Liquid source phantom calibration, uses liquid source and Bottle Manikin Absorber (BOMAB) phantom.

The point source phantom calibration: uses square phantom and solid point radioactive source to measure multi-times by placing it at different locations in the phantom.

- ## MCNP simulation part:

Simulate liquid source calibration experiment with MCNP4. The detection efficiency results of the MCNP simulation can be used to estimate the detection efficiency of other nuclides which haven’t been calibrated in experiment.

Liquid source phantom calibration

Liquid source phantom calibration experiment：

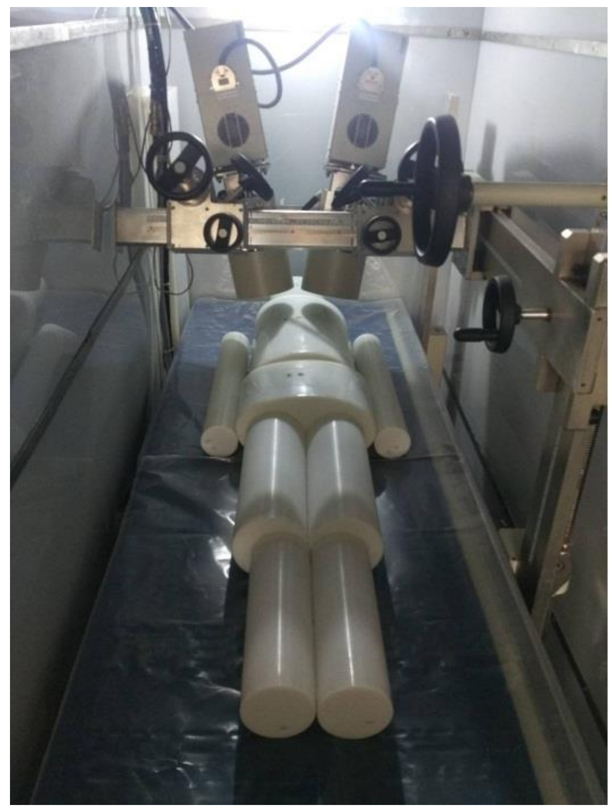
Use the WBC to measure the liquid source phantom and calculate measurement results. The experimental steps are as follows：

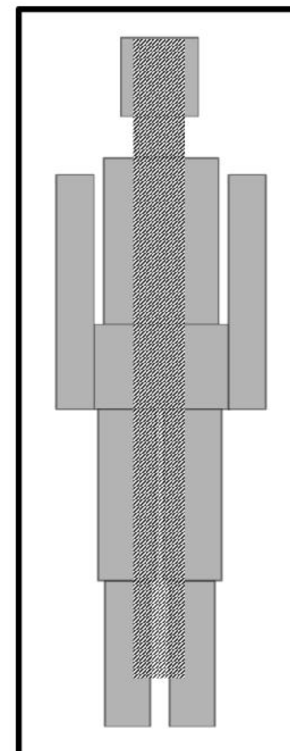
1. Design and make the BOMAB phantom, measure its background;
2. Select the species of liquid radioactive sources;
3. Fill the phantom with liquid radioactive sources;
4. Measure the phantom;
5. Data processing.

Design and make the phantom

We designed the BOMAB phantom based on the human body parameters of the Chinese reference person. The phantom height is 170cm, the weight is 63kg after filling with water. The phantom is made of polyethylene with a wall thickness of 4mm and a bottom thickness of 6mm.

Part	Dimensions (cm)	Hight (cm)	Quality (kg)	Volume (cm^3)
Head	16×19	20	4.72	4761
Neck	ϕ11.8	10	1.07	1089
Chest	21×28.5	41	19.14	19260
Abdomen	18.2×33.2	21	9.86	9946
Thigh	ϕ14.4	42	6.79	6840
Calf	ϕ11.2	36	3.51	3547
Arm	ϕ9.2	58	3.81	3856
Total	–	170	63	63542





Nuclides selection

The selection of the nuclides needs to consider the following tips:

- The nuclides' energy should cover the detector's detectable energy range (80keV~2000keV) as much as possible;
- The photon emission rate at the characteristic energy peak of the nuclide should be high enough to be detected;
- Disposition of the source after experiment.

Nuclide	Cd-109	Ce-139	Sn-113	Mn-54	Zn-65	Y-88
Energy(keV)	88/0.037	165.9/0.804	391.0/0.650	834.8/0.999	1115.5/0.508	1836.0/0.994
Half-life(D)	464.0D	137.7D	115.1D	312.7D	244.4D	106.6D
Activity（Bq）	8.00E+05	4.00E+04	5.00E+04	3.00E+04	5.00E+04	3.00E+04

Fill the phantom with radioactive sources

First, the phantom was filled with water. After its background measurement, fill the phantom with radioactive sources.

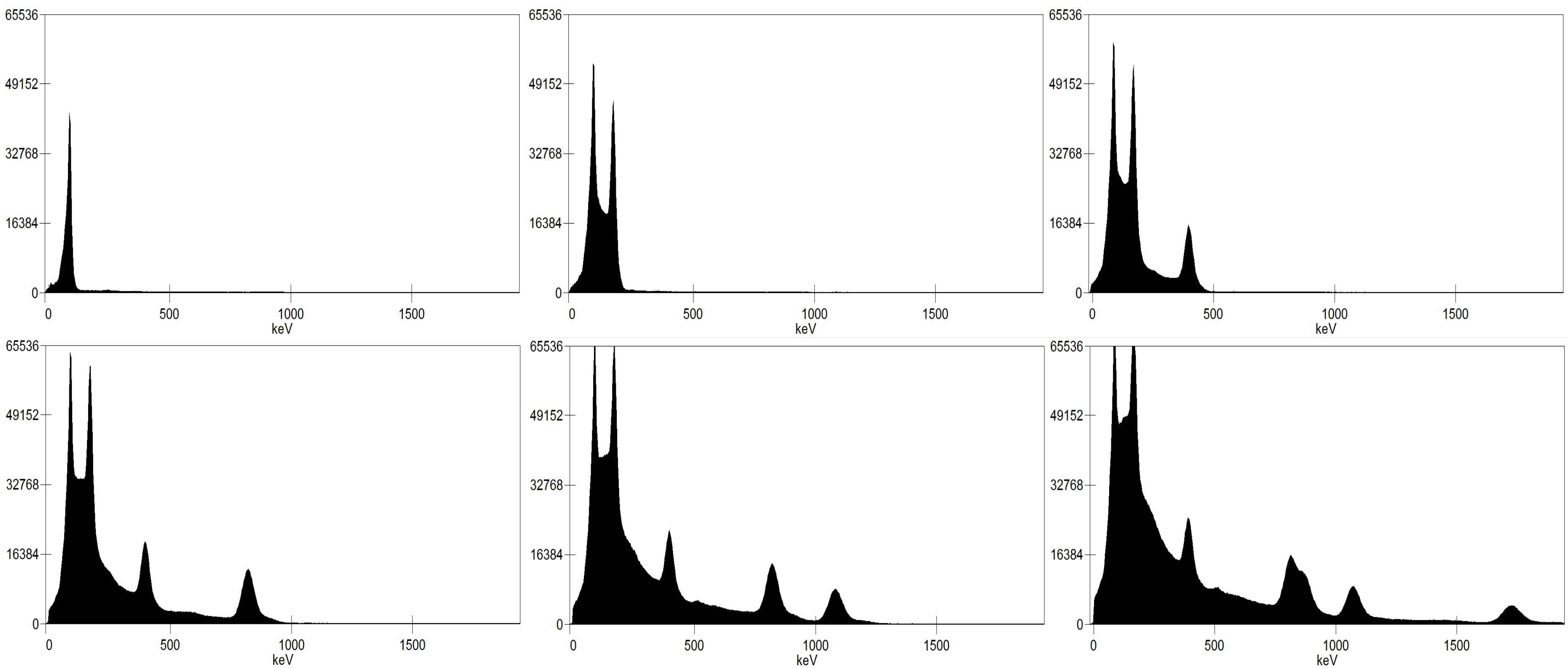
0.1 mol/L Hydrochloric acid was added into the phantom to keep the source evenly distributed in the phantom and prevent the wall-attaching effect.

The liquid sources are filled according to the γ ray energy of the liquid source from low to high, and each filling of sources is used for a set of measurements. And then fill next source.

The energy spectrum is acquired after WBC measuring, by striping the spectrum of the previous measurement from the spectrum of the last measurement. By analogy, all six nuclides are filled and the spectrum was got.

Measurement result

The following pictures are the measurement spectrum of the nuclide. We can see after the new source is filled. The new spectrum increase new energy peak, and the total peak count increases because of the impact of Compton scattering .



Integral region

After the integral region (ROI) is selected. The detection efficiency of the detector can be calculated according to the Formula:

$$\eta = \frac{N}{\gamma \cdot A \cdot t}$$

η -- NaI(Tl) detector's detection efficiency (count / Bq·s);

N--the net count rate of characteristic peaks (cps);

γ--probability of nucleus γ ray;

t--measurement time (s).

Result

Finally, the efficiency factors of each nuclide is obtained:

Nuclide	Energy (keV)	Probability	Activity (Bq)	Net count rate (cps)	Efficiency (counts/Bq·s)
Cd-109	88.03	0.037	8.56E+05	1.49E+02	4.70E-03
Ce-139	165.85	0.804	3.27E+04	1.24E+02	4.72E-03
Sn-113	391.69	0.649	2.71E+04	8.76E+01	4.98E-03
Mn-54	834.83	0.999	2.57E+04	1.13E+02	4.38E-03
Zn-65	1115.50	0.508	4.28E+04	7.69E+01	3.54E-03
Y-88	1836.00	0.994	1.90E+04	5.19E+01	2.74E-03

Original fitting

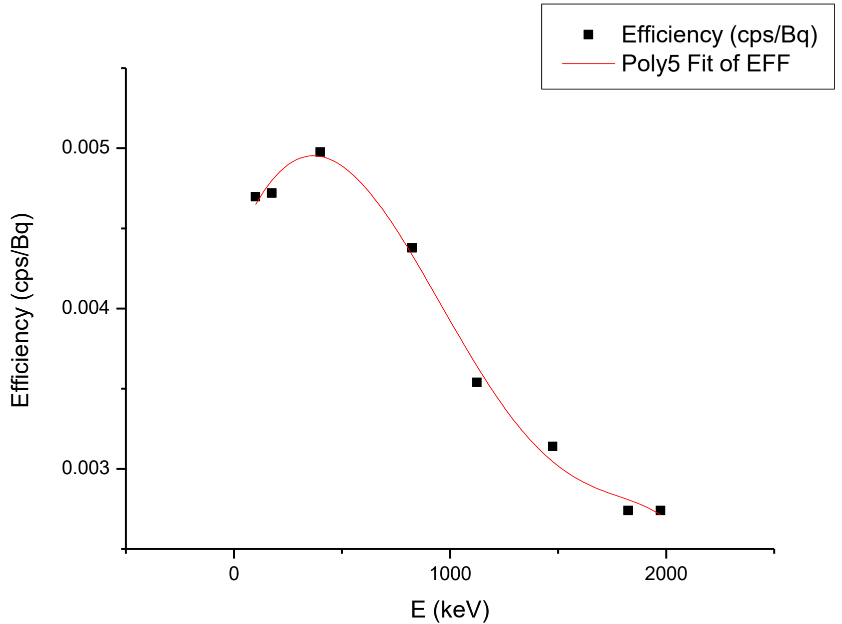
According to the efficiency factors, efficiency fitting Formula (2) is obtained:

$$y = (4.37E-03) + (3.30E-06)x + (-4.68-09)x^2 + (-4.65E-13)x^3 + (1.93E-15)x^4 + (-5.24E-19)x^5$$

y —detection efficiency factors of NaI(Tl) detector for the corresponding liquid source (count / Bq·s);

x—γ energy (keV).

The experimental efficiency fitting curve is shown as follow:



Point source calibration

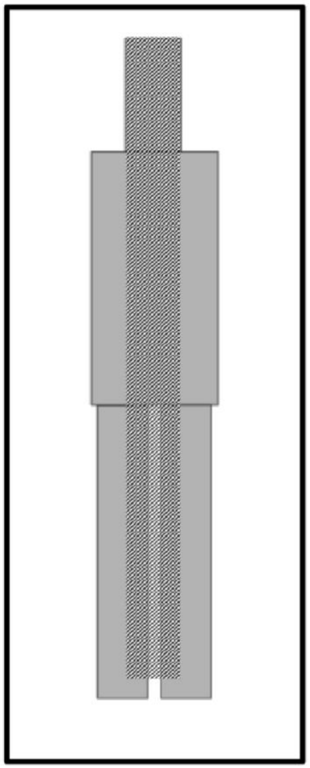
The point source phantom calibration uses a square box phantom to simulate the human body. The phantom consists of four different sizes of polyethylene square boxes filled with water, which are representing head, neck, torso, arms and legs.

Φ25mm plexiglass tubes sealed in each box at different position, and the point source can be placed on any part in the plexiglass tube for calibration.

Parameter	Length /cm	Width /cm	Height /cm	Vertical tube spacing	Horizontal tube spacing	Number of tubes
Head and neck	28	13	18	5	-	2
Torso arms	62	30	22	5	8	3×3
Leg (single)	72	12	18	5	-	2

Experiment design

Fill the phantom with water, place it at the fixed position same as the person in routine monitoring, and then put a point source into phantom in plexiglass tube. Take a point every 10cm and measure 88 points from head to toe. Each point is measured once a time, and the time of each measurement is 5min。



Nuclide selection

The selection of the point source is similar as the liquid source selection .The following nuclides were selected as the point source for calibration：

Nuclide	Energy(keV)	Probability	Half life
Cd-109	88.0/0.037	464.0D	8.00E+05
Ce-139	165.9/0.804	137.7D	8.00E+05
Sn-113	391.0/0.650	115.1D	8.00E+05
Ba-133	356.0/0.605	10.5Y	8.00E+05
Mn-54	834.8/0.999	312.7D	8.00E+05
Zn-65	1115.5/0.508	244.4D	8.00E+05
Co-60	1173.2/1.000	5.271Y	8.00E+04
Y-88	1836.0/0.994	106.6D	8.00E+05

Result

The energy spectrum is analyzed after measurement, and the energy peak count rates of average values of 88 points were obtained. The detection efficiency factors are as follows:

Nuclide	Probability	Activity(Bq)	Net count rate (count/s)	Efficiency （count/Bq·s）
Cd-109	0.037	6.56E+05	8.92E+01	3.66E-03
Ce-139	0.804	3.28E+05	9.76E+02	3.71E-03
Ba-133	0.939 （mix）	6.97E+05	2.66E+03	4.06E-03
Mn-54	0.999	5.19E+05	2.09E+03	4.04E-03
Co-60	1	6.87E+04	1.84E+02	2.68E-03
Y-88	0.994	3.02E+05	7.91E+02	2.63E-03

Original fitting

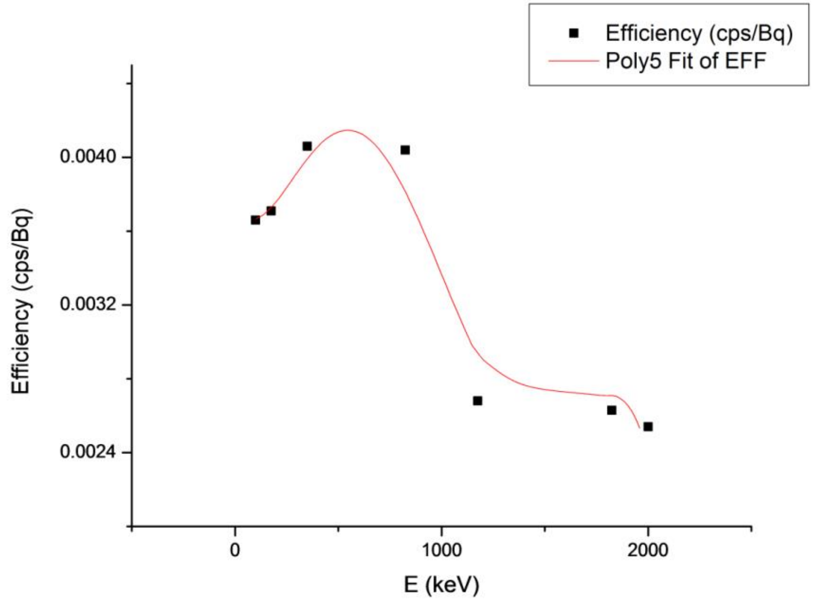
According to the efficiency factors, efficiency fitting Formula (2) is obtained：

$$y = (3.74E-03) + (-1.59E-06)x + (1.50-08)x^2 + (-2.62E-11)x^3 + (1.60E-14)x^4 + (-3.26E-18)x^5$$

y—detection efficiency of the NaI(Tl) detector for the corresponding energy nuclide of the point source (count / Bq·s);

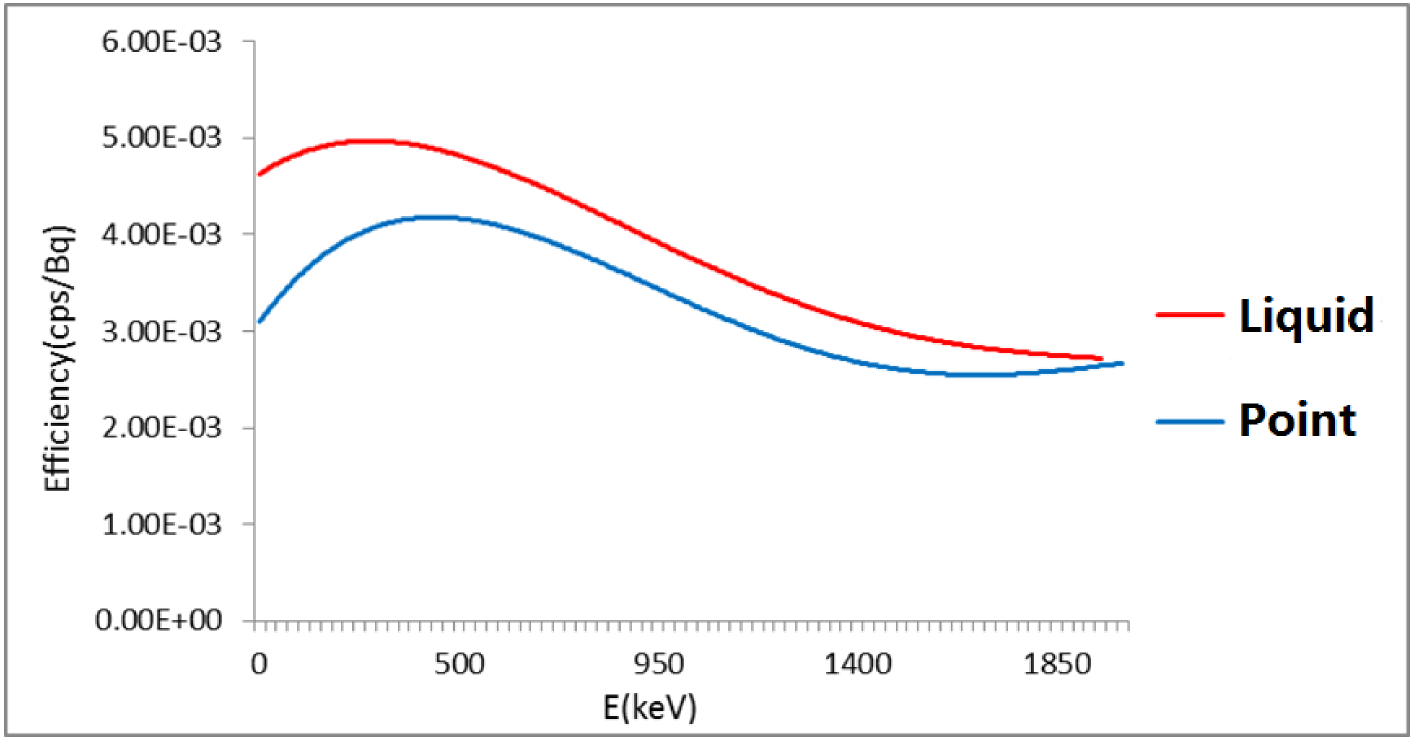
x—nuclide energy (keV).

The experimental efficiency fitting curve is shown in Figure as follows:



Difference between the two

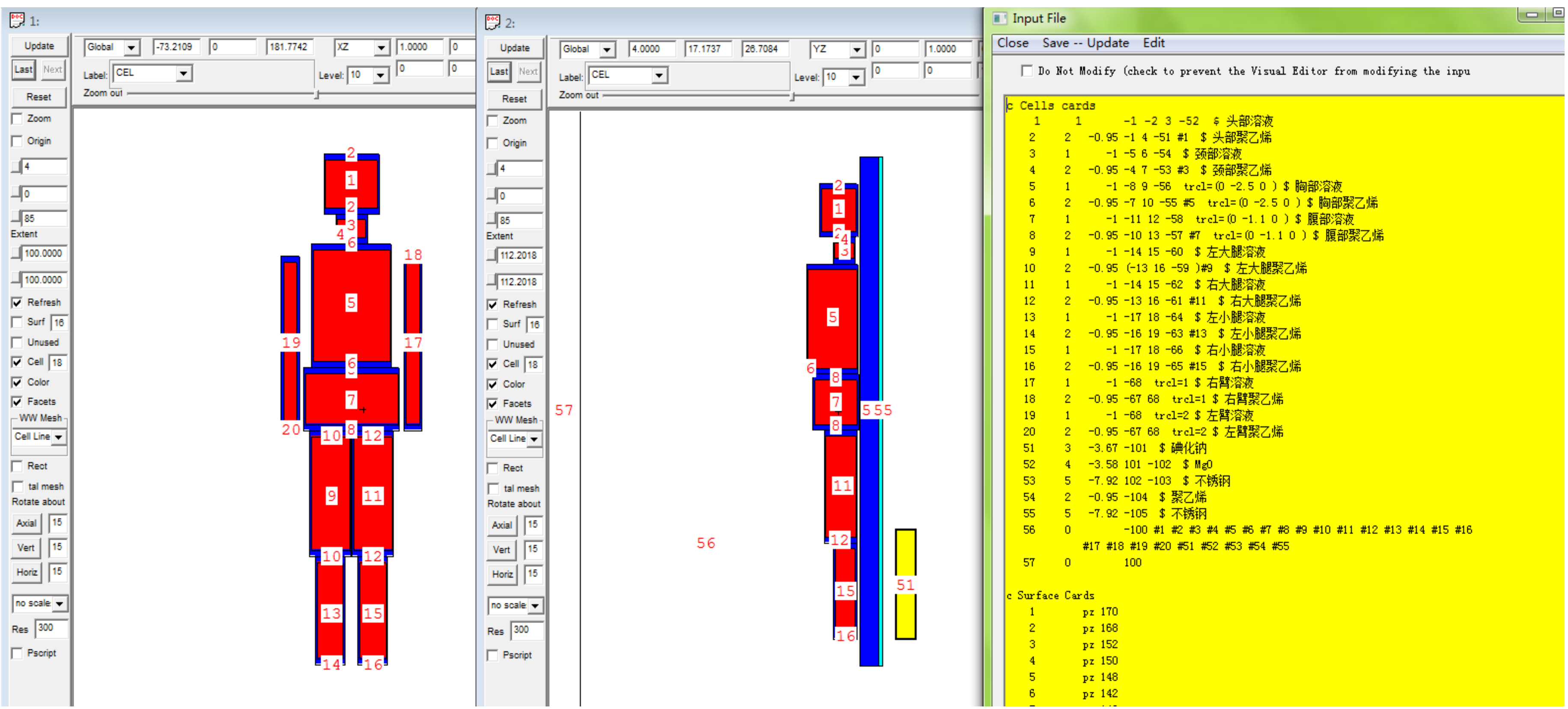
The following figure is a comparison of the liquid source scale and the point source scale. We can analyze that the detection efficiency of them is basically the same as the energy increase. As the nuclide energy increases, the γ-ray is gradually less affected by the measurement environment. The deviation between them is gradually reduced. Overall, the detection efficiency of the liquid source scale is about 20% higher than the point source detection efficiency, mainly caused by the phantom size difference.



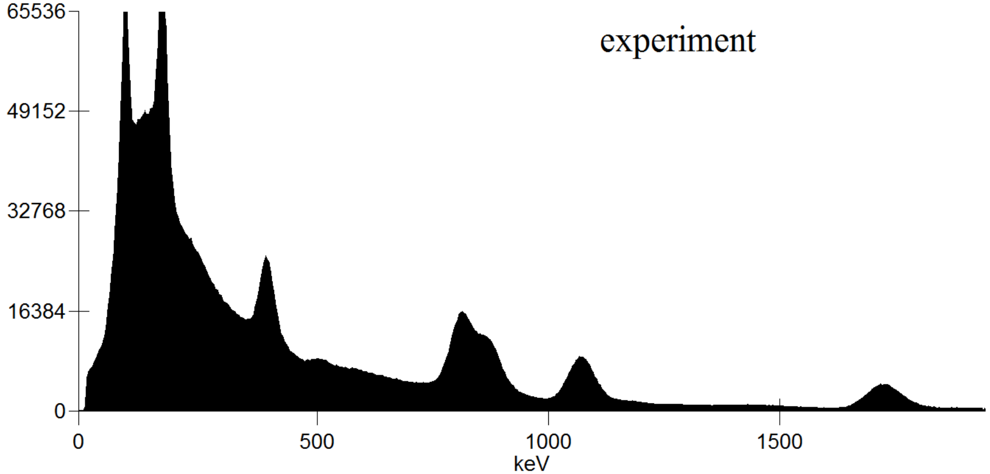
Use MCNP4 simulate liquid source calibration experiment：

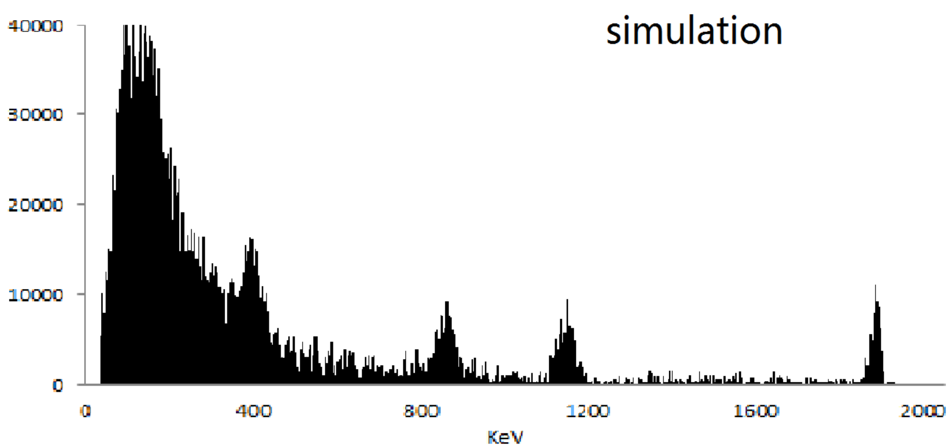
MCNP simulation steps: model building, solving Gaussian functions, program running, debugging, and result analysis.

The picture below is a model picture of MCMP simulation.



Comparative analysis

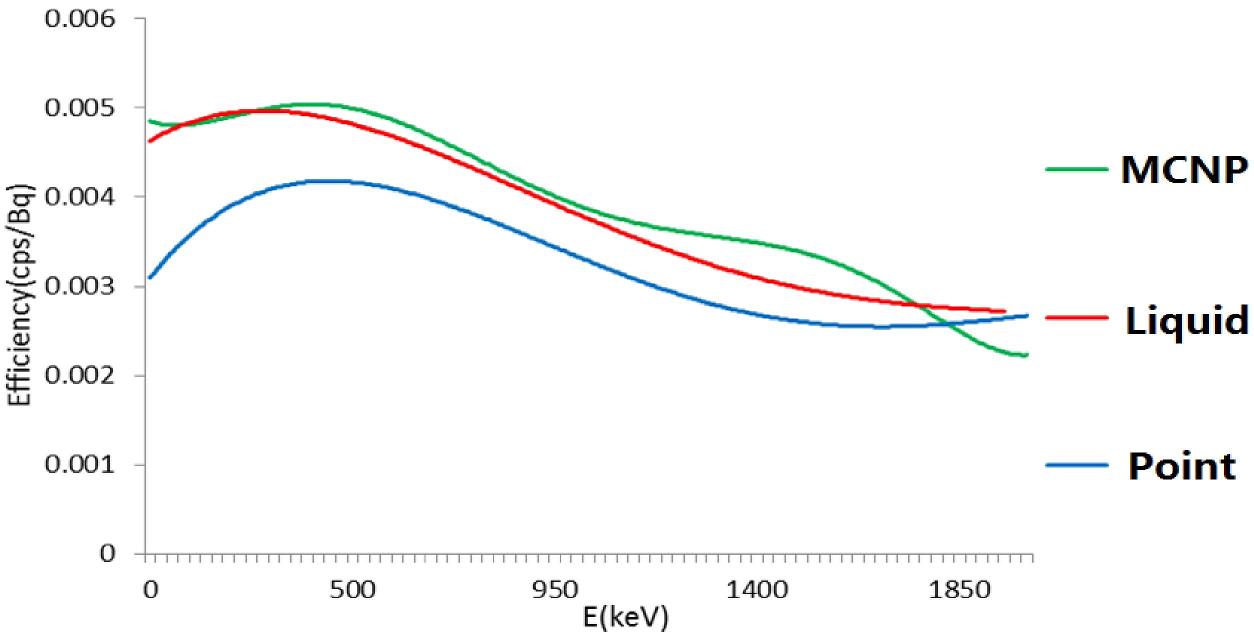




1. **The actual Gaussian broadening parameter selects ^{113}Sn, ^{54}Mn, and ^{65}Zn in the middle;**
2. **Sodium iodide has many factors affecting the measurement of low-energy data, so it is difficult to simulate;**
3. **In addition to the 1836 keV ray (branch ratio 99.38%), ^{88}Y also has ray (branch ratio 93.42%) at 898 keV, which overlaps with ^{54}Mn in the measurement spectrum and is not included in the simulation plan.**

Result

Nuclide	Energy (keV)	Liquid source efficiency (counts /Bq·s)	Point source efficiency (counts /Bq·s)	MCNP efficiency (counts /Bq·s)	Efficiency deviation between liquid source and MCNP
Cd-109	88.03	4.70E-03	3.66E-03	5.13E-03	-9.19%
Ce-139	165.85	4.72E-03	3.71E-03	4.57E-03	3.28%
Sn-113	391.69	4.98E-03	4.06E-03(Ba-133)	4.88E-03	2.06%
Mn-54	834.83	4.38E-03	4.04E-03	4.41E-03	-0.76%
Zn-65	1115.5	3.54E-03	2.68E-03(Co-60)	3.42E-03	3.32%
Y-88	1836	2.74E-03	2.63E-03	2.65E-03	3.23%



Summary

We do two calibration experiments: the liquid source calibration and the point source calibration. And the efficiency result is basically the same. We build liquid source calibration model of MCNP simulation.

Finally we use the liquid source calibration efficiency and its efficiency fitting formula in routine measurement calculation.

Thank you very much

Welcome to visit CIAE tomorrow

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