ISSN: 0067-2904
GIF: 0.851

"Examine the Multi-Scattering Effect on the Detected Backscattering Photons By Cometary Molecules"

Alaa B. Kadhim and Ghosoon N. Ismaeal*
Department of Astronomy and Space, College of Science, University of Baghdad, Baghdad, Iraq

Abstract

The effect of multiple scattering on the detected γ-photons at the surface of Hyakutake comet, which emitted from the radioisotope ^{137}Cs were studied and compared the results with the single scattering case. Also the multiple scattering results were gathered with the single scattering case and investigate the effect. The calculations were conducted to analyze the variation of counts rate with source detector separation and the source of energy. Monte Carlo (MC) method was used to simulate the scattering and absorption of photons in semi-infinite material by developing the program in FORTRAN language (77 - 90) for this purpose. The distance between the source and the detector takes values of 1, 2,….5 cm, the results showed that single scattering gives a maximum counts generally at distances between 3 and 4 cm, while the multiple scattering case appears increasing as the source detector distance increased.

Keywords: Comets, Multi-scattering and Monte Carlo simulation

اختبار تأثير الاستطارة المتعددة على اكتشاف الفوتونات المستطارة خلفيا بواسطة جزيئات المذنبات

علاء باقر كاظم و غصون ناطق اسماعيل*
قسم الفلك والفضاء، كلية العلوم، جامعة بغداد، العراق.

الخلاصة

تاثير الاستطارة المتعددة على اكتشاف فوتونات كاما على سطح مذنب هايكيوتك و المنبعثة من المصدر المشع Cs ^{137}تمت دراستها و مقارنتها مع حالة الاستطارة المفردة. نتائج الاستطارة المتعددة قد جمعت ايضا مع حالة الاستطارة المفردة وتمت دراسة التاثير. الحسابات اوصلت الى تحليل اختلاف نسبة العد مع المسافة بين المصدر و الكاشف و مصدر الطاقة و كثافة المركبات الكيميائية في نواة المذنب. استعملت طريقة مونتي كارلو لمحاكات استطارة و امتصاص الفوتونات في المادة الشبه لا منتهية بواسطة انشاء برنامج بلغة الفورتران (77–90). كما اخذت القيم للمسافة ما بين المصدر و الكاشف: 1، 2، .....،5 سم و اظهرت النتائج بأن الاستطارة المفردة تعطي اعلى نسبة عد عند المسافات 3 و 4 سم، في حين ان حالة الاستطارة المتعددة تظهر تزايد مع تزايد المسافة بين المصدر و الكاشف

1. Introduction

Gamma nuclear instruments are used in a wide astronomical applications. This paper contains the computational results which have been obtained from MC simulation of Compton backscatter densitometer in semi – infinite bulk materials to investigate the variation of backscattered count rate with the design parameters. Backscattering is a phenomenon in which

Photons colliding within the material are scattered backward compared to their original direction. When the material thickness is very thin, the backscattering phenomenon does not occur. The number of single and multiple backscattering photons increases according to the target thickness, eventually reaching the saturation [1]. In the collisions between photons and free electrons, higher orders

E-mail: Ghosoon.natiq@gmail.com

processes occur due to large number of secondary radiation produced in the first encounter and are known as multiply Compton scattered radiation. In gamma ray interaction study, these radiations may also reach the detector along with singly scattered radiation and get counted [2]. MC method was commonly used to predict the distribution of multiple scattering. Uemura 1965 used Single Scattering Model (SSM) of gamma ray from materials of various densities into a surface gauge of the soil density [3]. Felstiner et.al. 1974 used MC technique to calculate the total intensity and spectral distribution of multiple scattered photons in a typical γ – Ray Compton scattering experiment [4]. Pitkanen et. al., 1986 directly measured the spectrum of 662 keV gamma radiation multiply scattered by a nickel sample in a Compton scattering experiment at a scattering angle of 104°. Under these conditions the multiple profile extends well beyond the single, and this affords an opportunity to check the MC simulation commonly used to correct the single line shapes (Compton profiles) [5]. Ball et. al., 1998 used the extension of SSM for gamma backscatter density gauges to describe how the total detected count rate change in response to localized density variations within the material [6]. Singh et. al.,2008 observed the energy , intensity and angular distribution of multiple scattering of 662 keV gamma photons, emerging from targets of pure elements and binary alloys as a function of target thickness in reflection and transmission geometries [7]. Sabharwal et. al., 2014 found that the numbers of multiple backscattering events increase with thickness of cooper target, and saturate for a particular thickness known as saturation thickness [8].

2. Chemical composition of Hyakutake comet

In March 1996, Hyakutake comet, which comes from Oort cloud, passed only 0.1 AU from the earth [9]. The nuclei of comets have for many years been cited as likely repositories for primordial material left over from the formation of the Solar System [10]. The primary driving for activity close to the sun is sublimation, which is the transition of solid to vapor state [11]. In Whipple model a comet nucleus was considered as a conglomerate of ice such as H_2O, NH_3, NH_4, CO_2 and CO these materials and other possible material volatiles combined in conglomerate with some amounts of meteoric materials at low temperature [12]. In addition to the orbital classification, short and long period comets, comets have also been classified according to their dust content based on continuum emission in the visible range of the spectrum, so, there are dust-rich and dust-poor comets. This classification refers to the dust observed in the coma. The abundance of volatiles in the nucleus is not discovered directly by the observed of mixing ratios in the coma, the mixing ratio of species in the nucleus provides the important information about the composition of the solar nebula. Thus, it is important to relate the observed mixing ratios in the coma to those in the nucleus. This is a major goal for modeling comet nuclei [13]. An important recent development is the ability to map the molecules in the coma at radio wavelength, this allows to address the origin, nuclear or not, of a species, and to reveal structures of the coma [14]. Gamma ray spectroscopy is a suitable technique to determine the abundance of the major rock-forming and radioactive elements of a planetary body. The composition of the surface and sub-surface of astronomical objects can be extracted from the measured γ-ray spectra, where the γ-ray spectrum emitted from a planetary surface at ranges between 200 keV and 10 MeV [15]. Table -1 illustrates the chemical composition of hyakutake comet:

Table 1- Molecular abundances of Hyackutake comet [16-17].

Molecules	Abundances	Densities
H_2O	100	0.917
CO	5-30	0.789
CO_2	≤ 7	1.562
CH_4	0.7	0.442
H_2CO	0.2-1	0.815
C_2H_2	0.3-0.9	0.729
C_2H_6	0.4	0.546
NH_3	0.5	0.86
CH_3OH	2	0.791
H_2S	0.6	1.540
HCN	0.15	0.697
CS_2	0.1	1.26
SO_2	0.04	1.458
HNCO	0.07	1.14
CH_3CN	0.01	0.787

3. MC simulation

A MC simulation has been developed to describe the interaction processes of Gamma rays when coming in a medium with semi-infinite volume. It has been used to evaluate several parameters of gamma ray gauges and to reproduce the related experimental calibration curves [18][19]. The photons emitted from a radiation source is followed until they are lost by the photoelectric absorption in the medium or registered by the detector [10, 19]. The MC can be used to duplicate theoretically a statistical process such as the interaction of nuclear particles with materials, and is particularly useful for complex problems that cannot be modelled by computer codes, that use deterministic methods. The individual probabilistic events that comprise a process are simulated sequentially [20]. In the present work MC simulation can be employed to model the backscatter densitometer design. While the attenuation of primary photons is easily calculated analytically, the MC method can also model the scattered radiation. The author developed a FORTRAN Monte Carlo code to examine the absorption and scattering of a large number of photons in bulk material of uniform bulk density. The code does not model the detector response but can provide the basic properties (position, direction and energy) of photons passing through one or more 'virtual detectors' at or above the material's surface [10, 16].

4. Geometry of Single and Multi scattering models:

The geometrical arrangement of Compton backscatter process is very important to calculate the bulk density near the surface of comet nucleus and write the computer program. Each primary and secondary photons are tracked through the geometry by the following steps:

Step1: A beam of photons of energy $\mathbf{E_\gamma}$ emitted from a source at **S** point propagate into the semi-infinite material under study which is considered to be of uniform density. The emission direction making an angle $\boldsymbol{\alpha}$ (of value $\mathbf{45^\circ \geq \alpha > 90^o}$) with baseline **SD**. At the source energy (such as the most commonly used radioisotope ^{137}**Cs**, which emits at 662 keV). Compton scattering is the dominant interaction. Primary photons emitted from the mono-energetic source having linear attenuation coefficient ($\boldsymbol{\mu}$).

Step2: Compton scattering is considered to occur at a point **P** in the bulk material. Though some proportion of the photons may not reach P having an undergone absorption, scattering somewhere along the path **SP** of length $\mathbf{r_1}$, or escaping along its path outside the bulk material.

Step3: photons scattered at P towards the detector make an angle $\boldsymbol{\beta}$ with baseline. Those photons may of course be lost along the path **PD** of length $\mathbf{r_2}$, or escaping along its path outside the bulk material. Figure -1 explain Kan method which was used to calculate the energy of scattered photons.

Mass attenuation coefficient ($\boldsymbol{\mu_2}$) for the scattered photons will depending on the scattering angle (θ), the following relationship related the energy of gamma photons, energy of scattered photons and the scattering angle (θ):

$$E_{\gamma'} = \frac{E_\gamma}{1+(1-cos\theta)E_\gamma/m_e c^2} \text{...........(1)}$$

$E_{\gamma'}$ and $m_e c^2$ is the energy of scattered photons and electron rest mass energy respectively.

Inside the bulk material it is possible that photons undergo multi-scattering before it reaches the detector at the surface. A photon detector of sensitive area is placed on the surface at distance **d.** Both of the source and detector are considered to be point like in order to simplify the geometry and subsequent analysis. Figure (2) illustrate the basic geometry of the backscatter technique. Because of the random nature of the radiation emission Kahn method would have been chosen, which is not an approximation and works for any incident photon energy. The method requires generating and analysis of at least one set of these random numbers (υ_1, υ_2, υ_3) in the range ($0 \leq \upsilon_1 \leq 1$) Using simple trigonometry one can obtain the basic relations between the angular and linear parameters in the diagram. These are useful when transforming between angular and Cartesian co-ordinate systems and when writing computer codes for the SSM and MSM [10]:

$r_1^2 = x^2 + y^2 + z^2$ ....(2)

$r_2^2 = (x-d)^2 + y^2 + z^2$.................................(3)

$r_3^2 = y^2+z^2$..(4)

$\boldsymbol{\theta} = \alpha + \beta$..(5)

$\boldsymbol{\alpha} = \tan^{-1}\frac{\sqrt{y^2+z^2}}{x}$, $\boldsymbol{\beta} = \tan^{-1}\frac{\sqrt{y^2+z^2}}{d-x}$ ....(6)

where,X,Y,Z are the coordinates of emitter point.

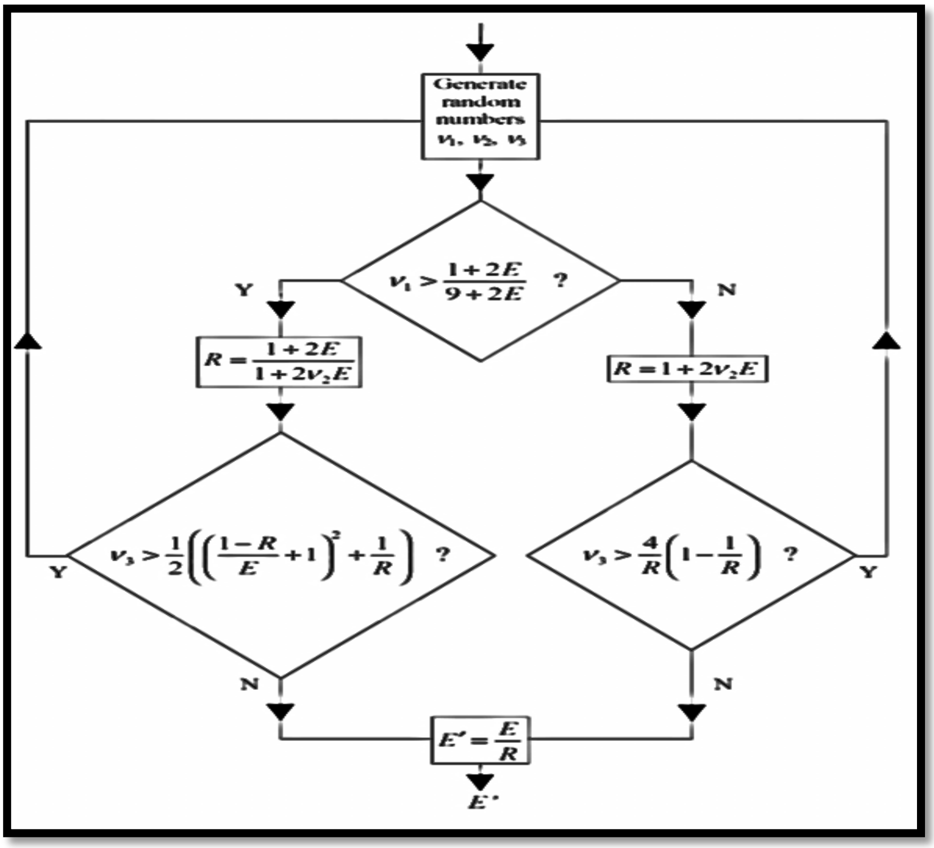


Figure 1- Method for random sampling of the Klein-Nishina distribution by the Kahn method **[10].**

5. Results and discussion

Measurements of the scattered photons are carried out as a function of source detector separation and source of energy in the cases of single scattering and the mixed case (single + multiple scattering). The effect of these parameters had been studied for $3*10^4$ photons subtracted by extremely 10% from the scattered photons in the case of multiple scattering as escaping photons.

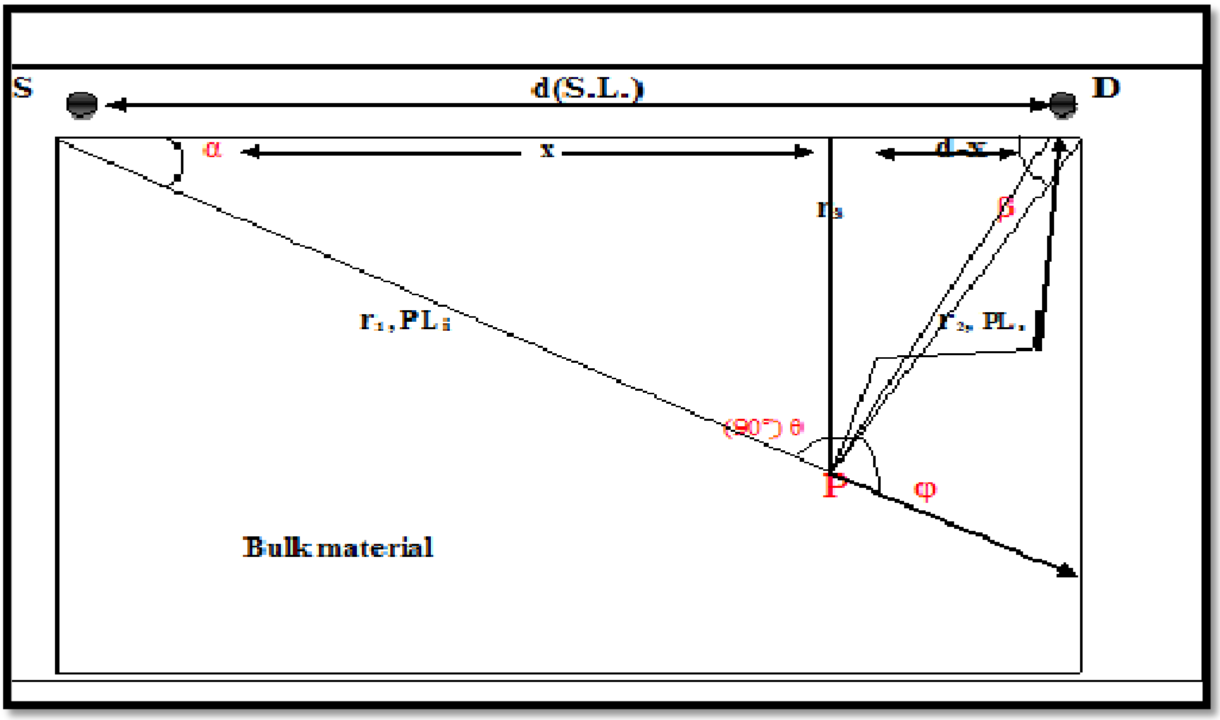


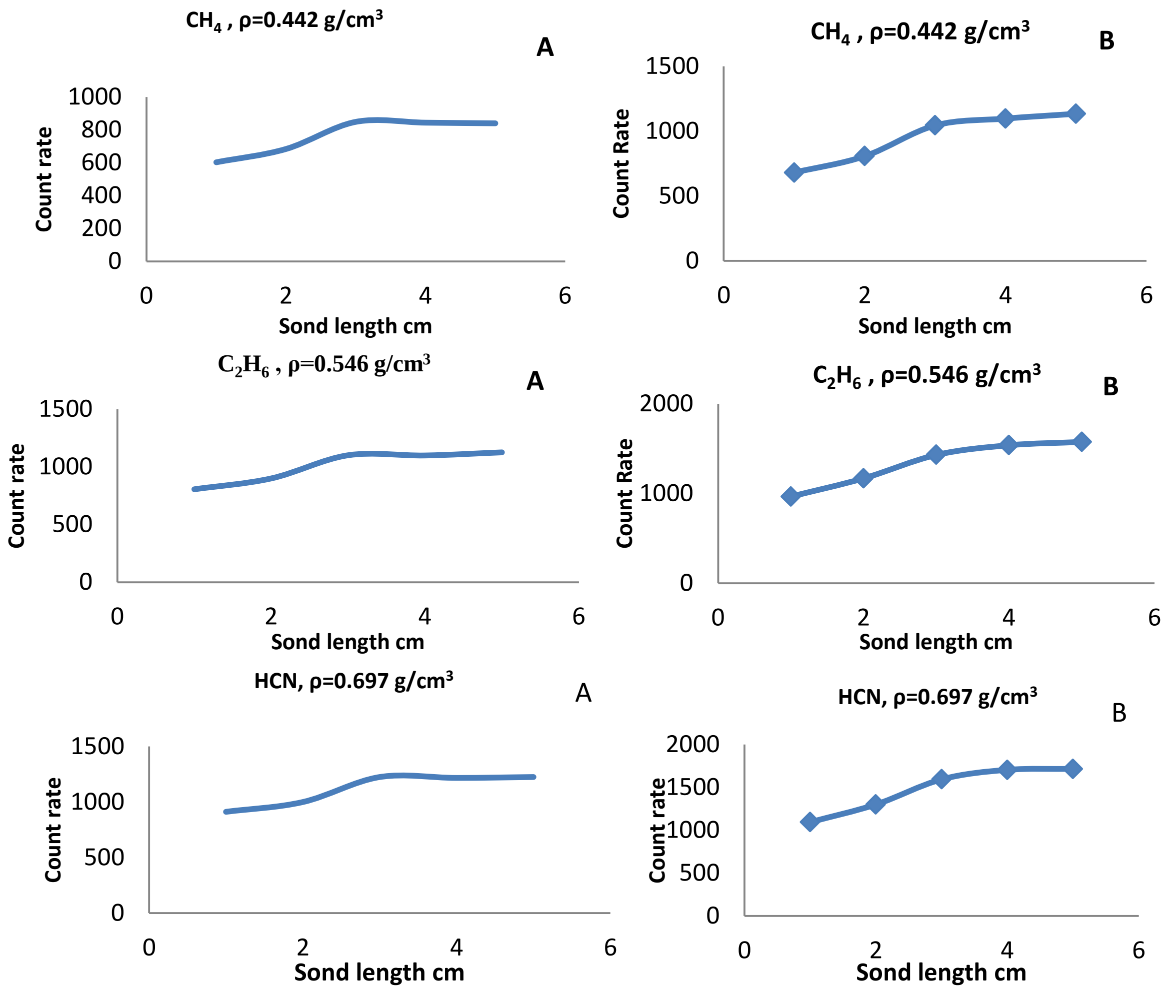
Figure 2- Basic geometry of Compton backscatter technique

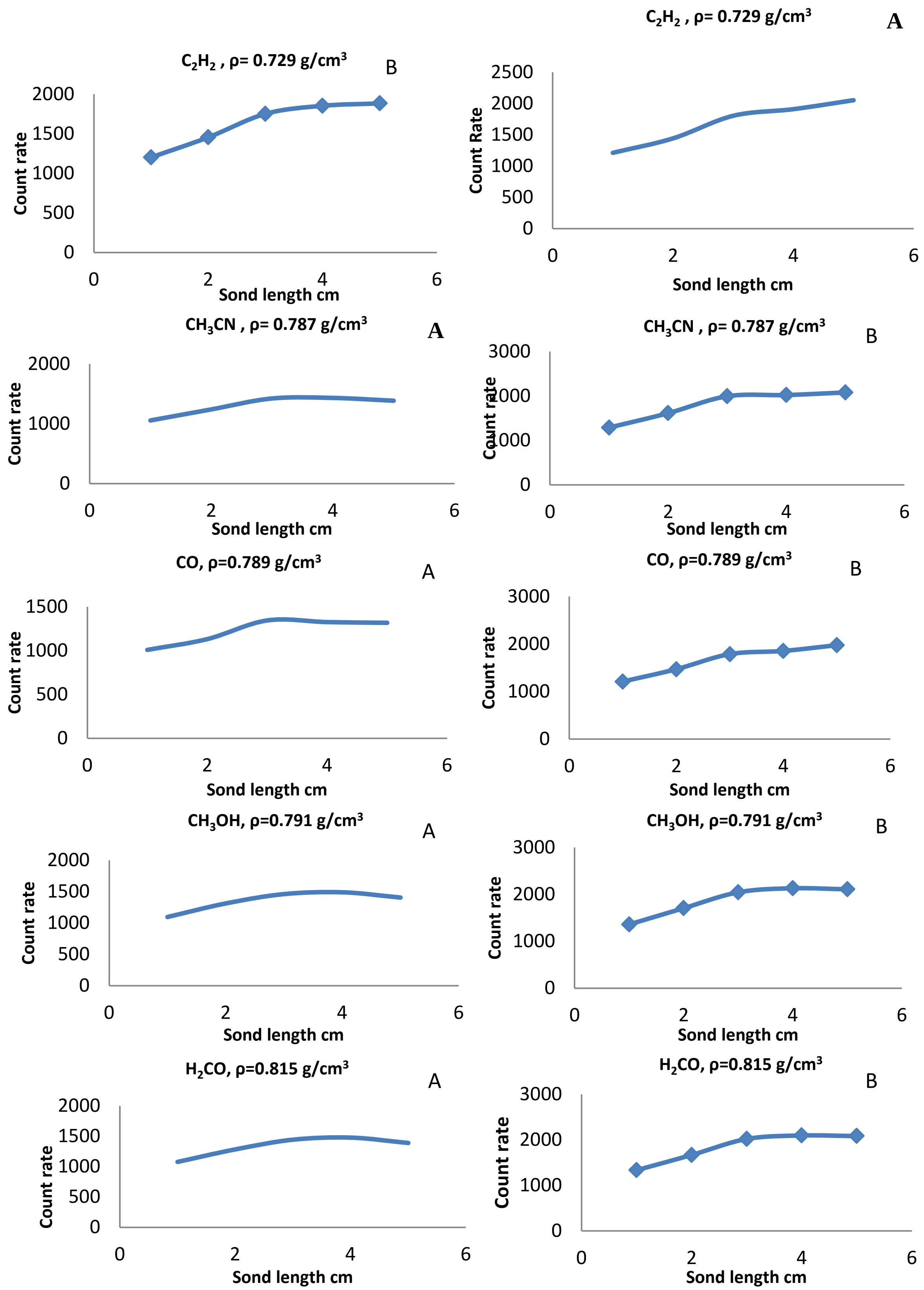
Source - detector separation (sond length SL)

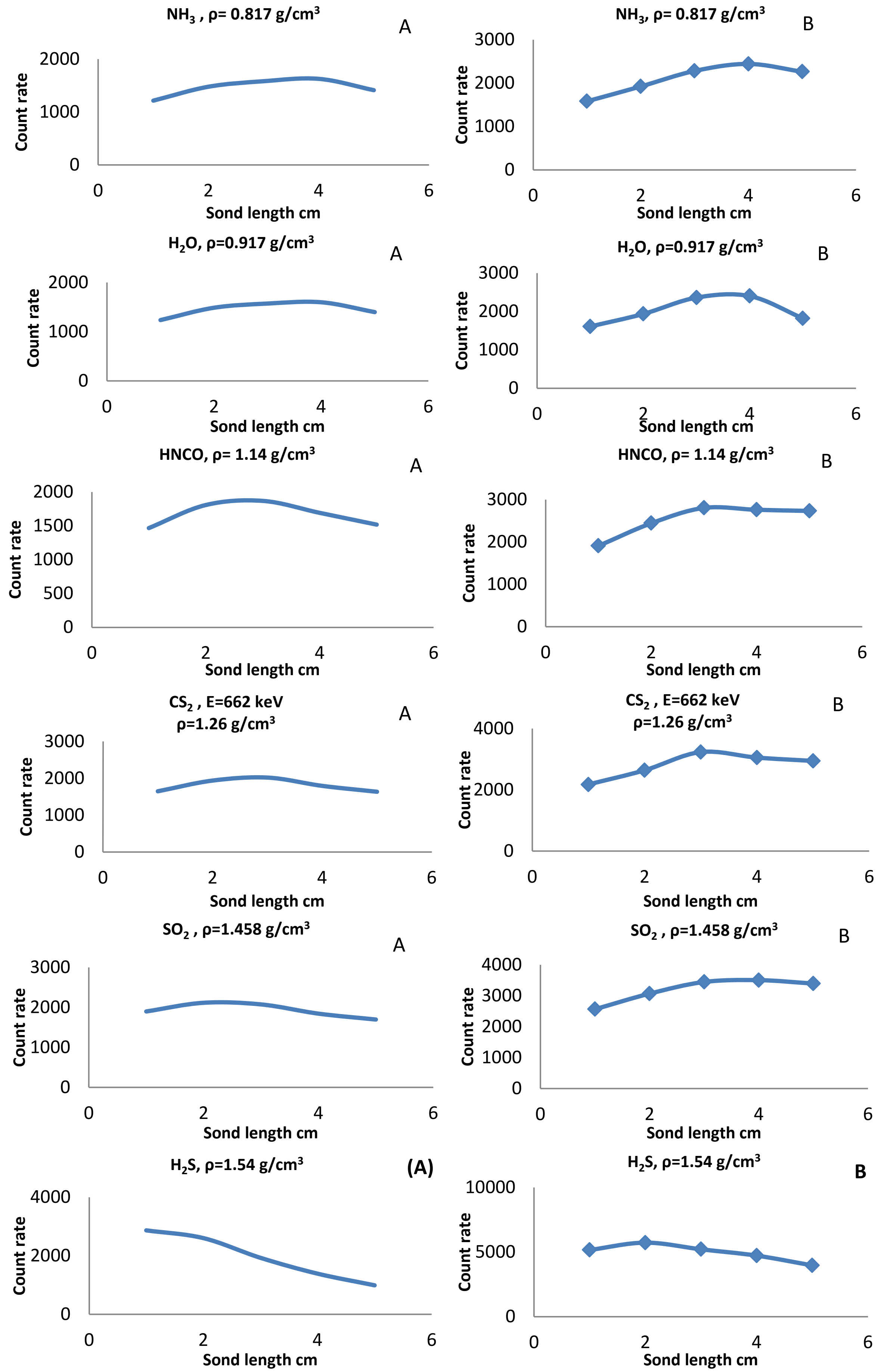
To investigate the sond length effect on the detected count rate, several runs of MC calculation for $3*10^4$ photons for the energy 662 keV for comet materials and the detector of radius 12.5 cm placed at 1,2,3,4 and 5 cm from the source. The results reveal that more suitable distance for the detector was between 3 and 4 cm from the source, where the counts of photons reach the maximum values at these distances.

From figure -3 it's appear that in the molecules of CH_4, C_2H_6, HCN, C_2H_2, CH_3CN, and CO respectively the number of counts reach its maximum value at S.L. = 3 cm in the single scattering case. For CH_3OH molecule, in first case, number of counts reaches the maximum value extremely at 3 and 4 cm and decreasing at 5 cm. Generally in the mixed case (single scattering + multi scattering) single scattering almost causes a decreasing in the multi scattering case, so the curves show saturation instead of continuous increasing and the highest count rate recorded at 3 cm too. The count rate was saturated at H_2CO in the first case, NH_3 and H_2O appear increasing at 2 and 4 cm (more than 3 cm) in the first case. The mixed case gives the same behavior but the degradation is sharper at H_2O than NH_3.

At HNCO and CS_2, the first sond lengths (2 and 3 cm) recorded the highest count rate and decreased after these distances. The mixed case indicate that number of counts increases in HNCO to 3 cm and then decreases, in CS_2 number of detected photons decreases below and above 3 cm. After 3 cm the counts at SO_2 decreases in the first case. While the mixed case shows a saturation between 3 and 5 cm.




C2H2 , ρ= 0.729 g/cm3
B
Count rate
Sond length cm
C2H2 , ρ= 0.729 g/cm3
A
Count Rate
Sond length cm
CH3CN , ρ= 0.787 g/cm3
A
Count rate
Sond length cm
CH3CN , ρ= 0.787 g/cm3
B
Count rate
Sond length cm
CO, ρ=0.789 g/cm3
A
Count rate
Sond length cm
CO, ρ=0.789 g/cm3
B
Count rate
Sond length cm
CH3OH, ρ=0.791 g/cm3
A
Count rate
Sond length cm
CH3OH, ρ=0.791 g/cm3
B
Count rate
Sond length cm
H2CO, ρ=0.815 g/cm3
A
Count rate
Sond length cm
H2CO, ρ=0.815 g/cm3
B
Count rate
Sond length cm


NH3 , ρ= 0.817 g/cm3
A
Count rate
Sond length cm
NH3, ρ= 0.817 g/cm3
B
Count rate
Sond length cm
H2O, ρ=0.917 g/cm3
A
Count rate
Sond length cm
H2O, ρ=0.917 g/cm3
B
Count rate
Sond length cm
HNCO, ρ= 1.14 g/cm3
A
Count rate
Sond length cm
HNCO, ρ= 1.14 g/cm3
B
Count rate
Sond length cm
CS2 , E=662 keV
ρ=1.26 g/cm3
A
Count rate
Sond length cm
CS2 , E=662 keV
ρ=1.26 g/cm3
B
Count rate
Sond length cm
SO2 , ρ=1.458 g/cm3
A
Count rate
Sond length cm
SO2 , ρ=1.458 g/cm3
B
Count rate
Sond length cm
H2S, ρ=1.54 g/cm3
(A)
Count rate
Sond length cm
H2S, ρ=1.54 g/cm3
B
Count rate
Sond length cm

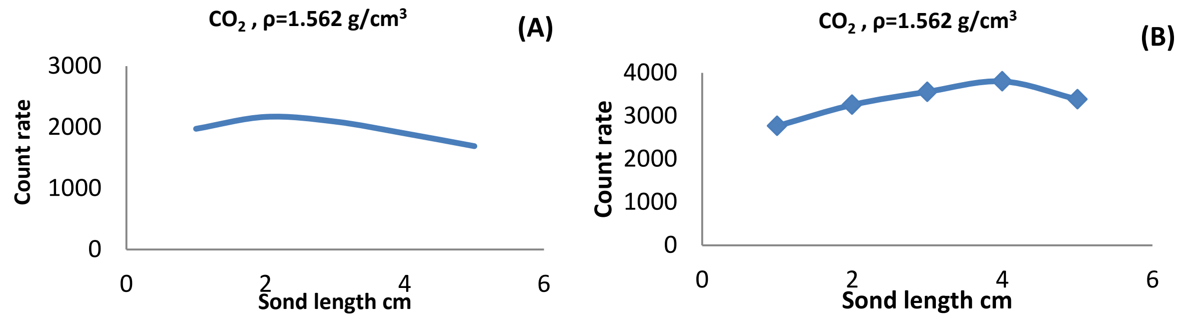


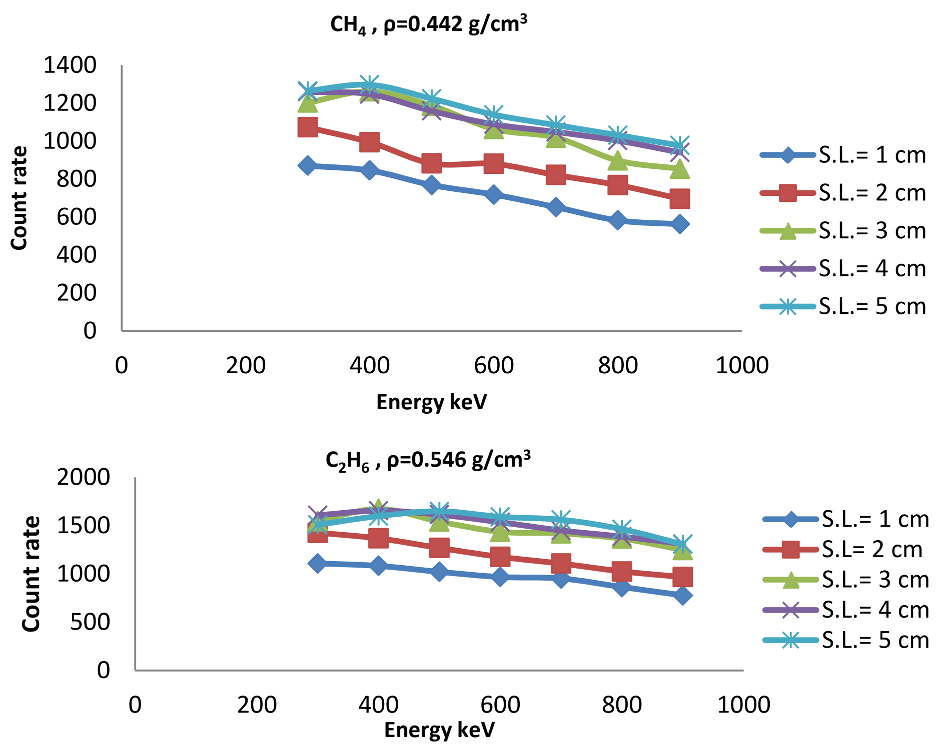
Figure 3 - variation of count rate with the sond length E=662 keV, A): single scattering case, B): mixed case.

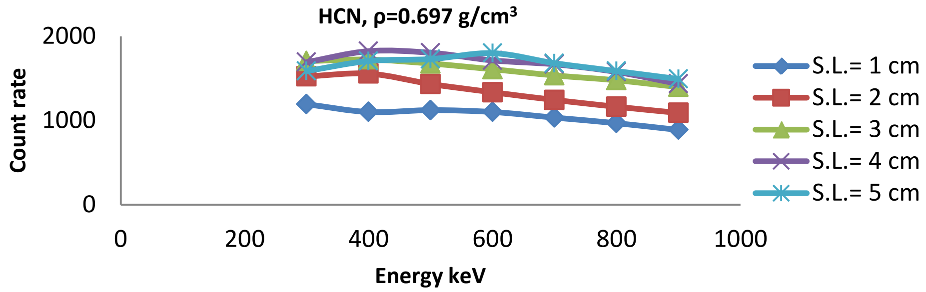
At H_2S the counts rapidly degradation after 2 cm in the first case. The depreciation beyond 2 cm distance is clear in the mixed case. The continuous smooth depression in the first state appears in CO_2 molecule. In mixed case the detected photons slightly increasing with sond length to about 4 cm and fall at 5 cm.

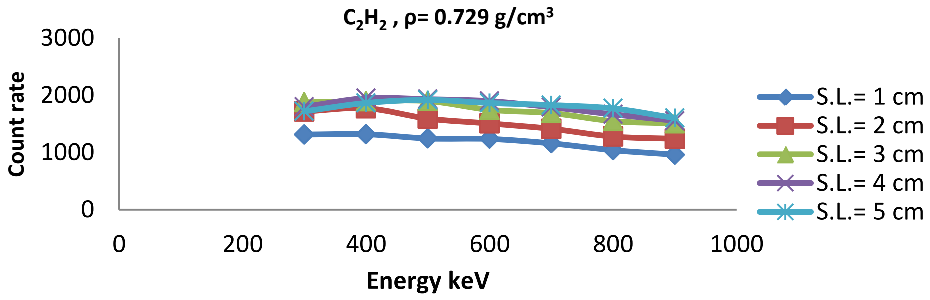
Source of energy (E)

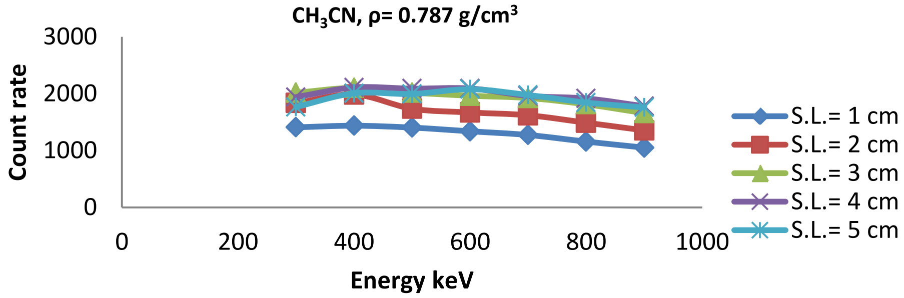
The nature of backscattering or reflection gamma photons incident on the surface of a scattering medium depends on the energy of the primary gamma flux [18]. To calculate the optimal source energy for $3*10^4$ photons, fixed detector radius 12.5 cm, different densities and source – detector separation 1,2,3,4 and 5 cm, were considered taking range of energies from 300, 400, ……..to 900 keV.

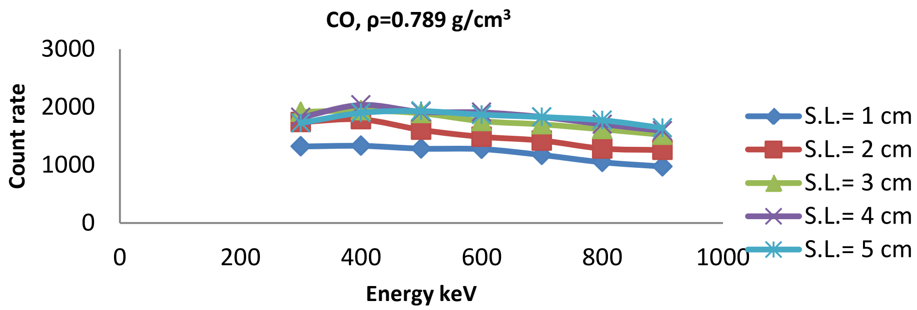
From figure (3) we notice that the count rate depression with the increasing of energies and the maximum counts recorded between 300 and 400 keV where the probability of photons interaction at low energies is more than at higher energies. At higher densities 1.26 to 1.56 g/cm^3 (at molecules CS_2, SO_2, H_2S and CO_2 respectively) the count rate appears extremely saturation instead of depression.

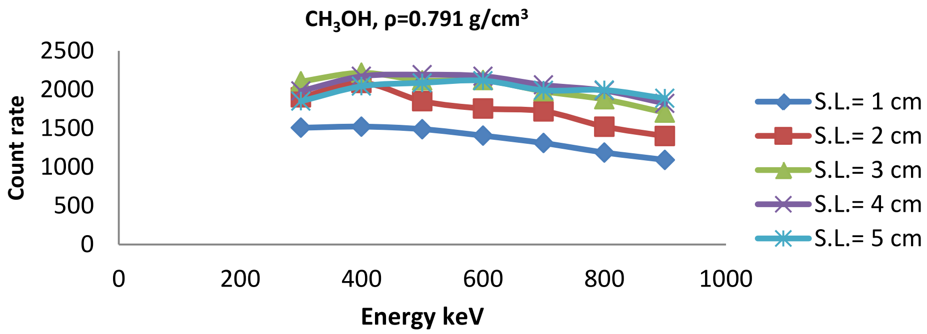


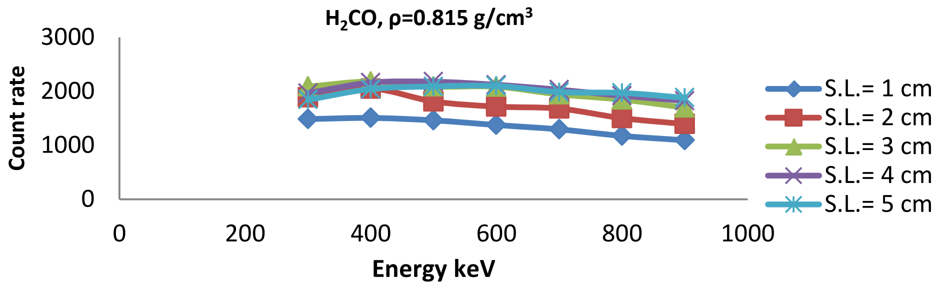

HCN, ρ=0.697 g/cm³
Count rate
2000
1000
0
0
200
400
600
800
1000
Energy keV
S.L.= 1 cm
S.L.= 2 cm
S.L.= 3 cm
S.L.= 4 cm
S.L.= 5 cm

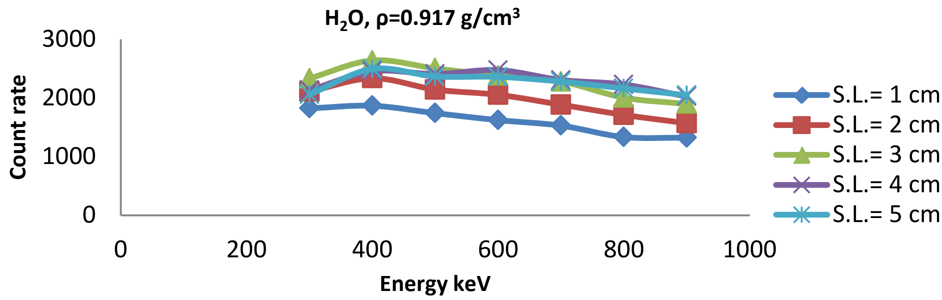

C₂H₂ , ρ= 0.729 g/cm³
Count rate
3000
2000
1000
0
0
200
400
600
800
1000
Energy keV
S.L.= 1 cm
S.L.= 2 cm
S.L.= 3 cm
S.L.= 4 cm
S.L.= 5 cm

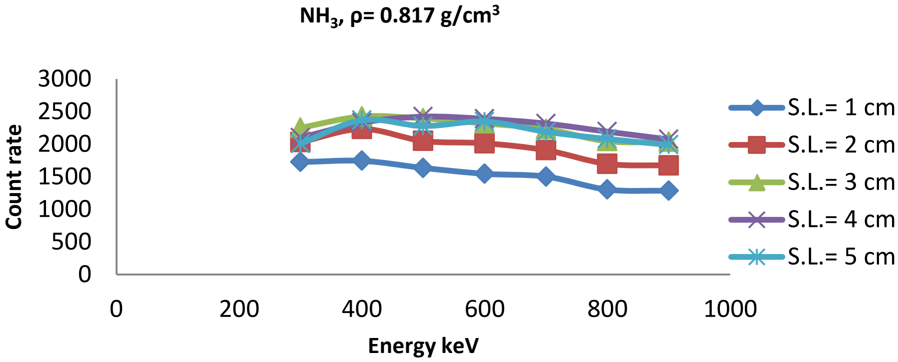

CH₃CN, ρ= 0.787 g/cm³
Count rate
3000
2000
1000
0
0
200
400
600
800
1000
Energy keV
S.L.= 1 cm
S.L.= 2 cm
S.L.= 3 cm
S.L.= 4 cm
S.L.= 5 cm

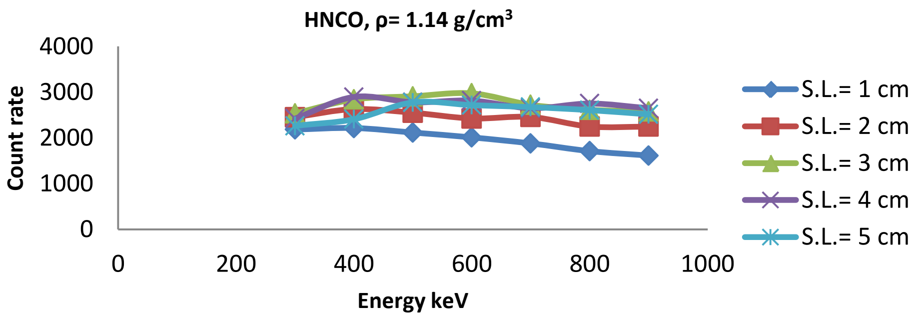

CO, ρ=0.789 g/cm³
Count rate
3000
2000
1000
0
0
200
400
600
800
1000
Energy keV
S.L.= 1 cm
S.L.= 2 cm
S.L.= 3 cm
S.L.= 4 cm
S.L.= 5 cm

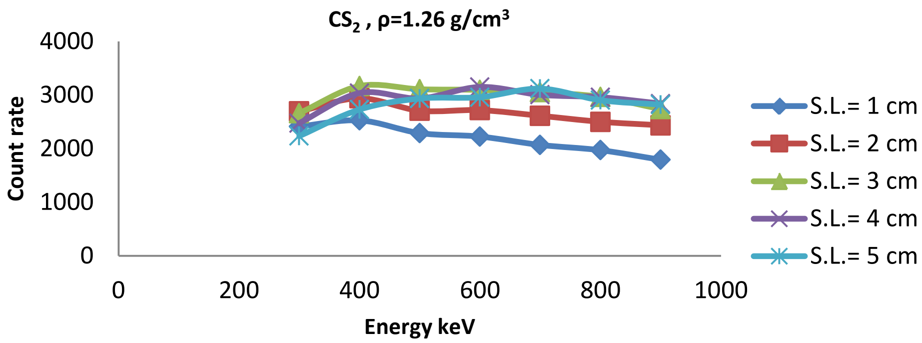

CH₃OH, ρ=0.791 g/cm³
Count rate
2500
2000
1500
1000
500
0
0
200
400
600
800
1000
Energy keV
S.L.= 1 cm
S.L.= 2 cm
S.L.= 3 cm
S.L.= 4 cm
S.L.= 5 cm


H2CO, ρ=0.815 g/cm3
Count rate
Energy keV
S.L.= 1 cm
S.L.= 2 cm
S.L.= 3 cm
S.L.= 4 cm
S.L.= 5 cm


H2O, ρ=0.917 g/cm3
Count rate
Energy keV
S.L.= 1 cm
S.L.= 2 cm
S.L.= 3 cm
S.L.= 4 cm
S.L.= 5 cm


NH3, ρ= 0.817 g/cm3
Count rate
Energy keV
S.L.= 1 cm
S.L.= 2 cm
S.L.= 3 cm
S.L.= 4 cm
S.L.= 5 cm


HNCO, ρ= 1.14 g/cm3
Count rate
Energy keV
S.L.= 1 cm
S.L.= 2 cm
S.L.= 3 cm
S.L.= 4 cm
S.L.= 5 cm


CS2 , ρ=1.26 g/cm3
Count rate
Energy keV
S.L.= 1 cm
S.L.= 2 cm
S.L.= 3 cm
S.L.= 4 cm
S.L.= 5 cm

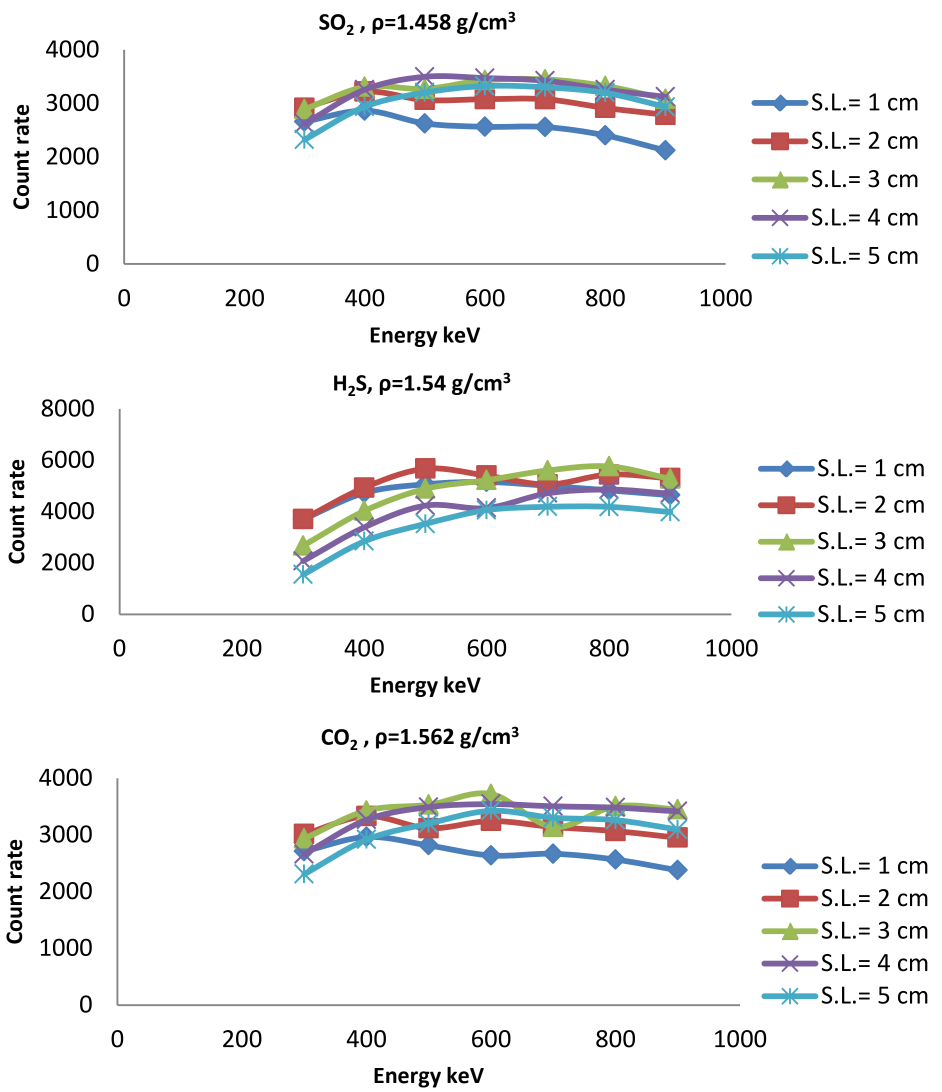


Figure 4-Variation of count rate as a function of energy for 15 compounds.

6. Conclusions

The main conclusions could be summarize as follows:

1. The simulation results can help to improve the conditions and the accuracy of the experimental measurements.
2. The optimal radioisotopes source at Compton window ^{137}Cs of energy 662 keV is useful to reduce the chemical composition effect.
3. From the chosen sond lengths, it was found that the optimal sond lengths is about 3 cm for singly scattered photons.
4. The count rate in the single and mixed cases increasing with the increasing of material density.
5. At the critical density of H_2S 1.54 g/cm^3 the counts reach its maximum values while, above and below this density the counts is reduced.
6. Smaller source _ detector separations are better for higher densities.
7. In Compton scattering, the probability of scattering is decreasing with the increasing of energy.

Reference

1. Hoang S. T., Yoo S., and Sun G. M. **2011** "Experimental Validation of The Backscattering Gamma-Ray Spectra With The Monte Carlo Code "PP. 13-18, Nuclear, *Engineering and Technology*, Vol.43 No.1.
2. Singh G., Singh M., Sandhu B. S. and Singh B. **2007** "Experimental investigation of saturation depth of 0.662 MeV gamma rays in copper" PP. 111-115, Indian *Journal of Pure* & Applied Physics Vol.45.

3. Uemura, T. ; **1965** "Observations of Backscatter Gamma Rays in a surface Density Gauge" pp. 667, Japanese *Journal of Applied physics*, volume 4.

4. Felstiner, J. ; Pattison P. and Cooper, M. ; **1974** "Effect of multiple scattering on experimental Compton profiles: a Monte Carlo calculation" PP. 537-548, *Philosophical Magazine,* Vol. 30.

5. Pitkanen, T. ; Laundy, D. ; Holt, R. S. and Cooper, M. J ; **1986**"The multiple scattering profile in gamma-ray Compton studies" pp.536-544, *Elsevier,* Vol. 251.

6. Ball, A. J. ; Solomon, C. J. and Zarnecki, J. C. ; **1998** "The response of gamma backscatter density gauges to spatial inhomogeneity-An extension of the single scattering model" pp.449-462, *ELSEVIER*, Vol. 140.

7. Gurvinderjit, S. ; Manpreet, S. ; Sandhu, B. S. and Bhajan, S. ; **2008** "Experimental investigations of multiple scattering of 662 KeV gamma photons in elements and binary alloys" PP.1151-1159, *Elsevier 66*.

8. Sabharwal A. D., Singh B. and Sandhu B. S. **2014** "Energy Dependance of Parameters Characterizing Multiply Backscattering of Gamma Photons" *Journal of Nuclear Physics Material Sciences, Radiation and Applications*, Vol. 1, No. 2, PP. 239-246.

9. Crovisier J. **1998** "Physics and chemistry of comets: recent results from comets Hyakutake and Hale-Bopp" *Faraday Discuss* Vol.109, PP. 437-452.

10. Ball, A. J. ; **1997**, "Measuring Physical Properties at the surface of a Comet Nucleus" ph.D thesis. Unit for Space Sciences and Astrophysics University of Kent Canterbury, UK.

11. Festou, M.C. ; Keller, H. U. and Weaver, H. A. ; **2004** "*COMETS II*" , the university of Arezona Press.

12. Heidarzadeh, T. ; **2008**, "*A History of Physical Theories of Comets, From Aristotle to Whipple*" Springer, University of California.

13. Huebner W. F. Benkhoff J. ; Coradini, M-T. A. ; De Sanctis, C. ; Orosei, R. and Prialnik D. ; *2006* "Heat and Gas Diffusion in Comet Nuclei" International Space Science Institute, Southwest Research Institute, USA.

14. Despois, D. ; Biver, N. ; Bockelee – Morvan D. and Crovisier J. ; **2005**" Observations of molecules in comets" PP.119-128, International Astronomical Union, No. 231.

15. Skidmore M. S., **2009** "A Geophysical Package for In-sit Planetary Science" ph.D thesis. Space Projects and Instrumentation Group, Department of Physics and Astronomy University of Leicester.

16. Ball, A. J. ; Stanislaw, G. ; Marek, B. ; Tilman, S. ; Thomas, J. A. ; Mattew, W. and John, C. Z. ; 2001 "An instrument for in situ comet nucleus surface density profile measurement by gamma ray attenuation", pp.961-961, *Planetary and Space Science,* Vol. 49.

17. Lide D. R., **2002** "CRC Handbook of Chemistry and Physics", pp. 4 –1771, CRC Press LLC.

18. Rani E. K., **2014** "Multiple Scattering in Various Sources Using Scalar and Vector Transport Equations-A comparative Study" PP. 2319-8753, *International Journal of Technology,* Vol. 3, Issue 2.

19. X-5 Monte Carlo Team, **2003** "MCNP — A General Monte Carlo N-Particle Transport Code, Version 5" Vol. 1.

20. Hulber T., **2012** "Transmission, emission and excitation Gamma tomoghraphy" MASTER Thesis. Department of physics, Budapest University of Technology and Economics.