Simulation of Photons Transportation in Scintillators with Monte Carlo Method

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【Abstract】
The author analyzes the generation and transportation of photons in a scintillator, proposes the consistent model for it and works out the simulation results for several particle detection processes. Several original methods concerned with photons generation and dielectric and diffusive reflection have been presented. This thesis also exhibits the always neglected photons’ distribution on the interface, which contributes to facilitating the continued work of simulation in waveguide or PMT. In addition, the author proposes a new method to collect photons at the interface.

【Key Words】
Scintillator detectors; Collection efficiency; Photons distribution; Monte Carlo;

1. Introduction

A scintillation counter measures ionizing radiation. The sensor, called a scintillator, consists of a transparent crystal, usually phosphor, plastic, or organic liquid that fluoresces when struck by ionizing radiation. A sensitive photomultiplier tube (PMT) measures the light from the crystal. The PMT is attached to an electronic amplifier and other electronic equipment to count and possibly quantify the amplitude of the signals produced by the photomultiplier. In this thesis, symbols like i, ii, and iii indicate footnotes, while symbols like [1],[2] and [3] indicate references.
no sufficient or full-developed theory describing the process of photons transportation in scintillators, which leaves computer simulation one of the reasonable methods to predict the efficiency before fabricating the scintillators. The value of simulation methods consists most in that selecting the scintillators with predicted higher efficiency will save more cost than testing the efficiency of various scintillators one by one.

In this thesis, the author analyzes the photons transportation process in the scintillators first, and then proposes his own simulation model consistent with the physical process with brief proofs about the reasonability of key simulation measurements, at last simulation results like the efficiency data simulating several scintillators of different materials like BGO, NaI, CsI, of different shapes, and of different wrapping ways are presented, as well as the distribution of photons at the outlet surface, namely the interface with the waveguide or PMT.

2. The physical process of photons transportation in scintillators

To be consistent with the following simulation process, it is better to focus on individual photons possible to loss rather than the photons as a whole with decreasing energy here.

When a charged particle strikes the scintillator, some of the phosphor's atoms are excited and emit photons and a flash of light is produced. Each charged particle produces a flash. Once produced, the photons will move randomly in the scintillator: they may move out of the scintillator from the incident surface again, they may collide with other particles in the phosphor and lose the energy so that they stop there, they may arrive the interface with PMT or waveguide at last with or without crashing on the boundaries of the scintillator. Among the photons described above, those of the last category will contribute to the collection and then to the electrical pulse at the anode of PMT. The intensity of the light flash depends on the energy of the charged particles. To determine the collection efficiency with Monte Carlo method, the light flash intensity is substituted by the number of photons in the following simulation.

![Diagram of photons transportation in scintillators](FIG 2.1 the physical process of photons transportation)
In details, the photons will be generated randomly in the scintillator exposing the scintillator in the homogeneous radiation environment. The photons, in fact, are also possible to be generated along a particular trajectory in the phosphor. Each produced photon has to be traced in order to determine whether it is collected at the interface or stops during transportation and describe the photons distribution at the surface. As is shown in FIG 2.1, once generated, the photon is assumed to move randomly, loss part of its kinetic energy until the next boundary. Since in terms of light beam, the intensity remaining after moving along length $L$ will be $e^{-\mu L}$, whether the photon stops can be determined by comparison $e^{-\mu L}$ with a random number in the range of 0 and 1\(^i\). If the photon remains after moving a distance of $L$, it will be redirected on the scintillator boundary by dielectric reflection or diffuse reflection, which is determined by the warp material around the scintillator and is what is concerned with by designers to improve the collection efficiency. No matter how it will be reflected, reflectance $R^i$ can be determined by Fresnel's law. Similarly, by comparing the reflectance $R$ with a random number in the range of 0 and 1, the photon is determined whether to be redirected in a new track or transmit the boundary and so leave the scintillator. The comparison between $e^{-\mu L}$ and a random number and between $R$ and a random number will continue until the photon stops or leaves away or reaches the interface, when the photon is collected and a new photon will be tracked in the same way.

3. The simulation process consistent with the above real one

3.1 Before generating a photon

It is reasonable to determine the number of photons to be generated when the scintillator stricken by particles with particular energy in that despite the fact the absolute number of the photons does not affect the light collection efficiency to be calculated, the different numbers of photons emitted from different particles do affect the distribution to be obtained at the interface. Since it is rather difficult to simulate the process of generating and unworthy to obtain the number of photons with such a work, estimating the number in a rough way before simulation the transportation process is advisable. Average energy loss for a MIP (Minimum Ionizing Particle) to produce a photon in a particular scintillator can be used to estimate the total number of photons. For example, the average loss in BGO is 300eV, then for a proton with kinetic energy 1 MeV, about $\frac{1\text{MeV}}{300\text{eV}} = 3333$ photons will be generated.

In fact, it is neither necessary nor sufficient to track the photons of the same number as that is estimated. If not so many photons would be produced, tracking more photons than that will present a simulation result closer to the real result. And if too many photons would be produced, tracking fewer photons than that will present the simulation result costing less time without disturbing the simulation effect.

3.2 Generating a photon

Where the phosphor's atomic excited, photons are emitted randomly. Any emitted photon is determined by its original location and the initial moving direction.

\(^{\text{i}}\)A brief proof is provided in Appendix A. 1.

\(^{\text{ii}}\)The fraction of the incident power that is reflected from the interface is given by the reflectance $R$ and the fraction that is refracted is given by the transmittance $T$. 


As for the original location, different methods are applied to different detecting manners. In the situation where the scintillator is exposed to homogeneous radiation environment, a new particle will be generated randomly in a new location after the former one is determined to stop or leave or reach the interface. If the scintillator is stricken by a beam of particles, a new particle will be generated randomly along the expected trajectory of the particles in the scintillator. For example, if a scintillator as shown in FIG. 2 is exposed to homogeneous radiation environment, the original location of a new photon is determined as:

\[
\begin{align*}
  x &= \zeta_1 X \\
  y &= \zeta_2 Y \\
  z &= \zeta_3 Z
\end{align*}
\]  

(3.2.1)

where \( \zeta_i \) (i=1,2,3) indicates a random number between 0 and 1.

As for the initial direction of the produced photon, assuming the isotropy of its emission, it is reasonable to determine the direction vector by homogenously distributed spin angle \( \phi \) and homogenously distributed conifer angle \( \theta \). So the unit velocity vector can be simulated as:

\[
\begin{align*}
  u &= \sin \theta \cos \phi = \sin(\pi \zeta_5)\cos(2\pi \zeta_4) \\
  v &= \sin \theta \sin \phi = \sin(\pi \zeta_5)\sin(2\pi \zeta_4) \\
  w &= \cos \theta = \cos(\pi \zeta_5)
\end{align*}
\]  

(3.2.2)

where \( \zeta_i \) (i=4,5) indicates a random number between 0 and 1.

### 3.3 The reflection of the photons

For simplicity, the thesis dealing with the reflection at surfaces as the wrapping materials are immediately adjacent to the scintillator boundary.

#### 3.3.1 Determine the incident surface

Before the following work on obtaining the reflection mode and new velocity vector of the photon, that which surface of the scintillator the photon will reach first should be determined.

With the shape and geometry parameters of the scintillator input into the simulation program, the functions of determining whether a point is located in a surface is created in the program. The functions will be based on the equations of the surfaces as shown in the coordinate in FIG. 2.1.

For example, as for a photon with current location \( \vec{r}_0 = (x_0, y_0, z_0) \) and velocity \( \vec{v}_0 = (u, v, w) \), the equation of the potential trajectory of the photon is described as:

\[
\begin{align*}
  x &= x_0 + ut \\
  y &= y_0 + vt \\
  z &= z_0 + wt
\end{align*}
\]  

(3.3.0)

Then substituting the equation into the equations of the surfaces like \( \{ F_i(x, y, z) = 0 \} \) will show the value of \( t \) and whether \( (x, y, z) \in D \) is satisfied. If \( t \) is minus, it is certain the next incident surface is not the one of equation \( F_i(x, y, z) = 0 \). If \( t \) is positive but \( (x, y, z) \in D \) cannot be satisfied, it is also certain \( S_i \) is not the one. After obtaining values of \( t \) for all the surfaces, the minimum value of the ‘t’s (at least one) solved from the equations will be acquired, the new point given by (3.3.0) is the incident point and the surface with whose equation the minimum \( t \) is acquired is the incident surface. Once the next reached surface is determined, its normal vector, its reflection parameters will be so. Then whether the photon will stop or leave and the new velocity direction after reflection can be determined as follows in section 3.3.2 and (3.3.3).

#### 3.3.2 Dielectric reflection
When the photon reaches the surface where dielectric reflection occurs, reflection direction and reflectance R can be obtained from Snell’s Law and Fresnel’s Law respectively. The reflection and refraction of light from a perfect dielectric interface can be described by the laws of geometrical optics if the scintillation photons are unpolarized. If the angles between the directions of the incident, reflected and transmitted photon with respect to the surface normal are denoted with i, r, and t, respectively, the law of reflection states that $\theta_i = \theta_r$, while the law of refraction on the other hand requires that $n_i \sin \theta_i = n_t \sin \theta_t$ where $n_i$ and $n_t$ are the indices of refraction of the media.

So with the surface normal vector $\vec{n}$ predetermined by setting shape and parameter of the scintillator, the incident direction vector as shown in (3.2.2), namely $\vec{v}_i = (u, v, w)$, the reflected direction vector can be obtained from Snell’s Law that

$$\vec{v}_r = 2 \frac{\vec{v}_i \cdot \vec{n}}{\|\vec{n}\|^2} \vec{n} + \vec{v}_i. \quad (3.3.1)$$

The reflection and transmission phenomena for unpolarized light would then be described by the Fresnel formulas:

The reflection coefficient is $R = \frac{R_s + R_p}{2} = \frac{1}{2} \left[ \sin^2(\theta_i - \theta_r) + \frac{\tan^2(\theta_i - \theta_r)}{\tan^2(\theta_i + \theta_r)} \right]. \quad (3.3.2)$

Then by comparing a random number between 0 and 1 with $R$, the photon is determined to reflect in $\vec{v}_r$ or transmit the surface and lose. In the former case, the photon will move until reach the next surface and perform the same operation; in the latter case, a new photon will produced as described in section 3.2.

### 3.3.3 Diffuse reflection

For most inorganic scintillators, it is optimized to collect light with scintillators wrapped in diffusive reflection materials like MgO, Al$_2$O$_3$ powders, Teflon films and Tyvek papers. $^2$

Before the following arduous work on determining the velocity direction, it is also required to compare the reflectance R of the wrapping material with a random number between 0 and 1 to determine whether the photon will be reflected or transmitted.

When the photon reaches such surfaces, the angular distribution of the scattered radiation is isotropic since the perfectly diffuse reflector is defined by the uniform scattering probability $P(\theta)$ into a unit solid angle $d\omega$. As for the cases of diffused by plane surfaces of scintillators, the energy distribution of the reflected light will be

$$I(\theta) = \begin{cases} I_0 \cos \theta, & 0 \leq \theta \leq \frac{\pi}{2} \\ 0, & \frac{\pi}{2} \leq \theta \leq \pi \end{cases}. \quad (3.3.3)$$

And consequently, the reflected direction of the photon will not be randomly longer. Obviously, the reflected direction should be derived from the new coordinate $X'Y'Z'$. The unit vectors of $X'Y'Z'$ can be expressed as

---

$^1$The proof will present itself in section 3.3.3.

$^2$If the light is polarized with the electric field of the light perpendicular to the plane (s-polarised), the reflection coefficient is given by $R_s = \left( \frac{n_t \cos \theta_t - n_i \cos \theta_i}{n_t \cos \theta_t + n_i \cos \theta_i} \right)^2$. If the incident light is polarized in the plane (p-polarized), the $R$ is given by $R_p = \left( \frac{n_t \cos \theta_t - n_i \cos \theta_i}{n_t \cos \theta_t + n_i \cos \theta_i} \right)^2$. 
Besides, since the energy distribution is described as (3.3.3), the reflected direction will be different from (3.2.2) not only in the new $X'Y'Z'$ coordinate but also in the distribution in $\theta$ direction. The reflected photon is distributed as

$$f(\zeta_0) = \cos(\zeta_0) \ (0 \leq \zeta_0 \leq \pi/2).$$

So the new direction can be determined like:

$$\vec{v}_r = \sin(\zeta_0) \cos(2\pi \zeta_1) \vec{e}_{x'x''} + \sin(\zeta_0) \sin(2\pi \zeta_1) \vec{e}_{y'y''} + \cos(\zeta_0) \vec{e}_{z'}$$

$$= \begin{bmatrix} \sin(\arcsin(\zeta_2)) \cos(2\pi \zeta_1) \\ \sin(\arcsin(\zeta_2)) \sin(2\pi \zeta_1) \\ \cos(\arcsin(\zeta_2)) \end{bmatrix} \begin{bmatrix} \zeta_2 \cos(2\pi \zeta_1) \\ \zeta_2 \sin(2\pi \zeta_1) \\ \cos(\arcsin(\zeta_2)) \end{bmatrix} = \begin{bmatrix} \zeta_2 \cos(2\pi \zeta_1) \\ \zeta_2 \sin(2\pi \zeta_1) \\ \cos(\arcsin(\zeta_2)) \end{bmatrix}$$

where $\zeta_1$ and $\zeta_2$ are uniformly distributed random numbers between 0 and 1.$^i$

### 3.4 The collection of the photons

Within several processes of determining a new incident location and a new velocity direction as shown above, the photon will at last be determined reach the interface with waveguide or PMT if not stopping or leaving.

If a photon is determined to reach the interface, in order to present the distribution of photons there, the collected numbers will not only be counted in total but also for arrayed unit areas like uniform squares.

In conclusion, the simulation process can be sketched in FIG 3.2.

---

$i$ The expression of $\vec{e}_{x''}$ also implies the proof of formula (3.3.1). If the vectors of incident, reflected and normal direction are placed in one triangle, it is obvious that $\vec{v}_r = \vec{n} + \vec{v}_i = \vec{v}_x + \frac{[\vec{v}_r \cdot \vec{n}]}{|\vec{n}|^2} \vec{n} = \frac{[\vec{v}_r \cdot \vec{n}]}{|\vec{n}|^2} \vec{n} + \vec{v}_i$

$^i$ (3.3.6) is proved in Appendix A.2
i. "Stop or Leave" judgment be performed both before the reflection by calculating $e^{-\mu|\vec{\nu}_0|}$ and after the reflection by reflectance $R$.

ii. For general prisms, once $\vec{r} = \vec{v}_0 t + \vec{r}_0 \subset S$ is satisfied, the photon is determined to reach Surface $i$.

**FIG. 3.2 Flowchart of simulation logic**
4. Results and discussion

Since the simulation process is quite a rough one in comparison with more advanced ones, the following result from it will just be used to substantiate acknowledged facts and no further complex simulation will be performed with it.

4.1 Collection efficiency of different wrapping materials

For general polygons, the surface equations can be established easily with the simulation software. After setting the shapes of the scintillator as shown in FIG. 4.1, particular parameters like the length, width and thickness should be set in the appearing dialog after clicking “Set” button shown in FIG.4.1. Numerical data should be input for irregular blocks.

![FIG. 4.1 selecting the scintillator shape](image)

Select a cuboid for example, with X × Y × Z, and set the wrapping materials by setting the reflectance R for a diffusive reflection side and refraction index for the immediate coupling materials. The bulk attenuation length D, the index of refraction n_i are also needed to calculate P(L) and reflectance R later.

The simulation results for different wrapping materials are shown in TABLE 4.1.

<table>
<thead>
<tr>
<th>Surfaces wrapped by Teflon</th>
<th>None</th>
<th>001 and 00_1</th>
<th>100 and _100</th>
<th>All except incident plane and interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collection Efficiency %</td>
<td>14.56</td>
<td>16.42</td>
<td>16.28</td>
<td>17.48</td>
</tr>
</tbody>
</table>

So the conclusion that the diffusive reflection resulting from wrapping materials can improve the light collection efficiency has been substantiated.

---

\(^1\) The key codes are presented in Appendix. B.

\(^a\)001 indicates the normal of a plate as shown in FIG. 2.1.
4.2 Collection efficiency of different scintillator parameters

Obviously, the collection efficiency will decrease with the shorter attenuation length, which is shown in FIG.4.2.

![Efficiency and attenuation length](image)

FIG. 4.2 Efficiency and attenuation length

\[ X \times Y \times Z = 0.6 \times 0.6 \times 0.9m^3; n = 2.15; \]

Surface 100, _100_ are wrapped with Teflon;

Surfaces without Teflon are exposed to media of refractive index 1.8;

4.3 Photons distribution and incident manners

The distribution of photons can be easily obtained by counting at different areas in the interface with waveguide or PMT. For the scintillator described as in FIG.4.2 with D=150cm, the distribution diagram is shown in FIG.4.3.

![Distribution of homogeneously generated photons](image)

FIG. 4.3 Distribution of homogeneously generated photons at the interface with waveguide or PMT
To show the number of photons, the total photons generated should be determined as illustrated in section 3.1. For BGO scintillator with average energy loss per photon, 1MeV radiation will produce 3333 photons. Multiply the counters of each area by \( \frac{3333}{N_{\text{tot}} \text{ for simulation}} \) will give the absolute rather than relative distribution, which contributes to compare the distribution of different incident charged particles.

As referred to in section 3.2, a photon can be generated randomly in the scintillator or randomly along the initial direction. FIG.4.3 presents the distribution of photons for a scintillator exposed to homogeneous radiation environment. If the charged particles strike the scintillator along the symmetrical axis of the scintillator as showing in FIG.2.1, the distribution of photons is shown in FIG.4.4.

\[
\begin{align*}
\text{FIG.4.4. Distribution of photons generated along the incident direction at the interface with waveguide or PMT}
\end{align*}
\]

In comparison with FIG.4.3, the photons are distributed more converged in the center as expected. In addition to the minor increase of collection efficiency from 67.43% to 67.94%, more collecting surface can be saved for this incident manner.

Besides, the simulation method describing photons generated from a particle beam by generating them uniformly randomly along the direction needs improving in that the method fails to take into consideration whether the particles stop just at the point where the incident velocity reaches the interface or whether the incident particle beam can be precisely described as a line.

4.4 Photons distribution, collection efficiency and collecting surface selection
As for the photons generated by homogeneous radiation, that which interface is selected as interface is less responsible for collection efficiency than as for photons generated by particles beam. The author is also interested in how the collection efficiency will alter if not collecting photons at the opposite surface of incident one. So a scintillator like FIG.4.5 is designed with the 011 surface adjacent to PMT or waveguide.
The scintillator in FIG. 4.5 is assumed to be fabricated by cutting away the triangular prism from the scintillator simulated above in FIG. 4.4 and so on. After altering the equations and normal directions of the surfaces, the simulated distribution is similar to that of FIG. 4.4 with the expected converged one. And the collection efficiency has grown from 67.94% to 84.32%. The hypothesis of changing interface for higher collection efficiency proves reasonable in this simulation method. However, the feasibility needs substantiating from other considerations.

In fact, cutting part away from the original scintillator also expurgates some space for generating photons. As for the incident particles beam in this case, the efficiency of scintillator is different from that of collection in that not all the energy of the beam will be used to generate photons before it travels out of the scintillator. With less space for generating photons, despite higher collection efficiency, the total efficiency of the scintillator may not increase to the same degree.

5. Conclusion and prospective of promising future

In this thesis, the author analyzes the generation and transportation of photons in a scintillator, proposes the consistent model for it and works out the simulation results for several particle detection processes.

Based on the fundamentals of photon transportation and reasonable hypotheses, this thesis presents several original methods dealing with the physical processes including photons generation in determined distribution and dielectric and diffusive reflection.

In the rough simulation, some acknowledged facts prove consistent with the results, which substantiate the simulation work to some degree. So far, simulation on scintillators has progressed to a very advanced level. Though performing simulation in a rough way, the author proposes several methods different from those extant ones. This thesis presents photons distribution on the interface, which have been neglected by others. The distribution may not only imply the potential lower cost of smaller scintillators as analyzed in section 4.3 but also facilitate the continued work of simulation in waveguide or PMT. With the given determination, it may not be necessary to deal with individual photons in the next processes. Manipulating photons as a group with conceptions like intensity tends to save more work than simulating...
individual photons with probability and random numbers. In addition, the author proposes a new method to collect photons at the interface proves his hypothesis and presents some rudimentary discussions.

Introduced to the world of detectors for not long, the author cannot have been similar with the customs of this field. So it is not advisable to establish too advanced models. Chances are that, the more advanced the simulation work is, the more it will deviate from the common method.

6. Acknowledgments

The author wishes to thank Mr. SUN Yong jie for leading me to the world of detectors and making me obtain the opportunity of working on the interesting simulation by requiring of the thesis. The author also would like to acknowledge Mr. GAO Chen at NSRL for inviting us to his group and giving me the chance of evoking my programming skills.

7. References

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8. Appendix

A. Brief proofs
A.1
For a beam of light transportation in the media, intensity will decrease to e^{ul} of the initial. So as for an individual photon, the probability of its remaining after moving the distance of L will be P(L)=e^{ul}. Comparing the random number ζ(uniformly distributed) between 0 and 1 to determine whether the photon will remain is consistent with the physical process in that

\[ P (L) = P \text{(remaining after travelling for L)} = P (\zeta < e^{-ul}) = \int_{0}^{e^{-ul}} 1 \, dx = e^{-ul}. \]

Similarly comparing the reflectance R with ζ is also qualified to determine whether a photon will be reflected or transmit the boundary.

A.2
The random number ζ_0 distributed as:

\[ f(\zeta_0) = \cos(\zeta_0) \quad (0 \leq \zeta_0 \leq \pi/2) \]

(3.3.5)
can be sampled from a uniformly distributed number ζ_2 between 0 and 1 by setting \( \zeta_0 = \arcsin(\zeta_2) \) in that
\[ P(\zeta_0 \leq x) = P(\arcsin(\zeta_2) \leq x) = P(\zeta_2 \leq \sin x) = \int_0^{\sin x} 1 \, ds = \sin(x), \]
and it indicates
\[ f(\zeta_0) = \frac{d}{dx} \sin x \big|_{x=\zeta_0} = \cos(\zeta_0) \ (0 \leq \zeta_0 \leq \frac{\pi}{2}). \]
So (3.3.5) proves right.

B. Key codes.

```c
void main()
{
    int N=1000000,nn=0;
    int i,j;
    bool nco=true,nrea=true;
    double X=0.6,Y=0.6,Z=0.9;
    double ni=2.15,miu=1.0/1.5,R=0,L=0;
    double SP[6][2]={{1,2},{1,2},{1,2},{1,2},{0,0.8},{0,0.8}};
    double r0[3]={5,12,0};
    double s[3]={0};
    double v0[3]={1,-1,-1};
    double n[6][3]={{0,0,-1},{0,0,1},{0,-1,0},{0,1,0},{-1,0,0},{1,0,0}};
    double vr[3]={0};
    double ex[3]={0};
    double ey[3]={0};
    double ez[3]={0};
    double tm;
    int sur=0,cx,cy,cnt=0;
    int col[BB][BB]={0};
    srand((unsigned)time( NULL ));
    double ran1,ran2;
    while(nn<N)
    {
        //
        // for(i=0;i<3;i++)
        //
        r0[0]=rand()/32767.0*X;
        r0[2]=rand()/32767.0*X;
        r0[1]=Y*0.5;
        r0[0]=X*0.5;
        ran1=rand()/32767.0;
        ran2=rand()/32767.0;
        v0[0]=sin(PI*ran2)*cos(2*PI*ran1);
        v0[1]=sin(PI*ran2)*sin(2*PI*ran1);
        v0[2]=cos(PI*ran2);
        nco=true;nrea=true;
        while(nco)
        {
            while(nrea)
            {
                whes001(r0,v0,X,Y,Z,&tm,&sur,&cx,&cy);
                if(1==sur) break;
                whes00_1(r0,v0,X,Y,&tm,&sur);
            }
        }
    }
}
```
if(2==sur) break;
whes010(r0,v0,X,Z,Y,&tm,&sur);
if(3==sur) break;
whes0_10(r0,v0,X,Z,&tm,&sur);
if(4==sur) break;
whes100(r0,v0,Y,Z,X,&tm,&sur);
if(5==sur) break;
whes_100(r0,v0,Y,Z,&tm,&sur);
if(6==sur) break;
}
//
printf("________________"\n);
for(i=0;i<3;i++)
{
    s[i]=v0[i]*tm;
    r0[i]+=s[i];
}
L=model(s);
if(exp(-L*miu)<rand()/32767.0) break;

if(SP[sur-1][0]=0) R=SP[sur-1][1];
else R=ref(v0,n[sur-1],ni,SP[sur-1][1]);
if(  (1!=sur)  &  (R< (rand()/32767.0) )  )
break;

switch (sur)
{
case 1:
    cnt++;
    col[cx][cy]=col[cx][cy]+1;
    nco=false;
    break;
default:
    if(SP[sur-1][0]) deref(n[sur-1],v0,vr);
    else
    {
        ran1=rand()/32767.0;
        ran2=rand()/32767.0;
        dfref(n[sur-1],v0,ran1,ran2,vr);
    }
    break;
}

if(1!=sur)
for(i=0;i<3;i++)
v0[i]=vr[i];
/*
for(i=0;i<BB;i++)
{
    for(j=0;j<BB;j++)
*/}
printf("%d ",col[i][j]);
    printf("\n");
*/
    nn++;
//
    printf("%.2lf\n",nn*100.0/N);
}

double eff=100.0*cnt/N;
printf("%d\n",cnt);
printf("%.2lf\n",eff);

ofstream out("distribution.xls",ios::binary);
if(!out)
{
    cerr<<"Error!Cannot open file!"
    exit(1);
}
for(i=0;i<BB;i++)
{
    for(j=0;j<BB;j++)
        out<<col[i][j]<<"\t";
    out<<"\n";
}