

## The Monte Carlo Simulation of the Neutron Array Detector

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**Abstract.** A neutron array detector aiming the investigation of halo neutron pair pre-emission in Si ( $^{11}\text{Li}$ , fusion) has been experimented. To test the true n-n coincidences against cross talk a Monte Carlo simulation with MENATE program was used to generate neutrons incident on the central detector and to obtain their interactions in the array detector. To construct the denominator in the correlation function the program MENATE was used to generate neutrons incident on the whole area of the array detector. Some results were analyzed with PAW program.

**Key words:** neutron halo nuclei, neutron array detector, Monte Carlo simulation

The neutron halo nuclei were discovered by I.Tanihata and co-workers [1]. These nuclei are characterized by a very large matter radii, small separation energy and small internal momenta of valence neutrons (Fig.1). Due to the very large dimension of  $^{11}\text{Li}$  it was predicted that in the fusion process on a light target the valence neutrons may not be absorbed

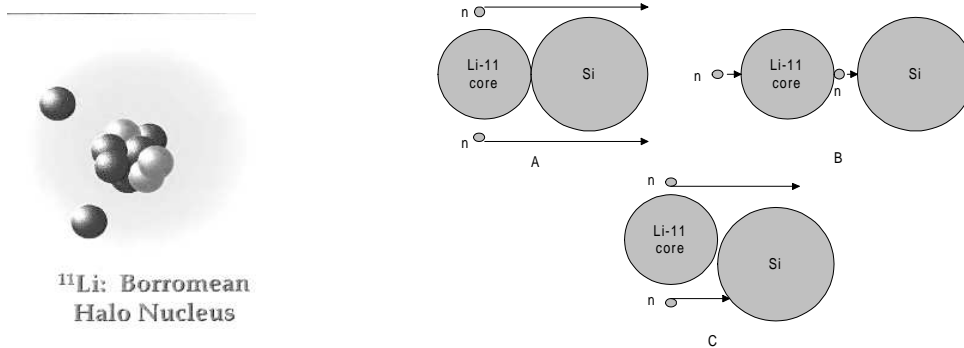
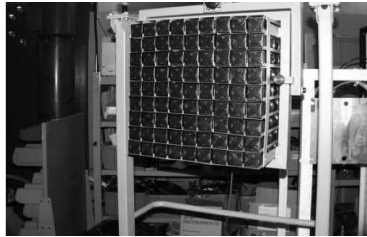


Fig.1 Schematic representation for a) the Borromean Halo Nucleus  $^{11}\text{Li}$  b) The halo neutron pre-emission in the Si ( $^{11}\text{Li}$ , fusion)

together with the  $^{11}\text{Li}$  core ( which is  $^9\text{Li}$  ), but may be emitted in the early stage of the reaction [2]. Experimental investigations of neutron pre-emission in the fusion of  $^{11}\text{Li}$  halo nuclei with Si targets [3] have shown that a fair amount of fusions,  $(40\pm 12)\%$  are preceded by one or two halo neutron pre-emission.

A very narrow peak in the transverse momentum distribution of the pre-emitted neutrons has been found and there have been some indications on the presence of neutron pairs within this correlation peak. In the light of this indication, the narrow neutron distribution could be caused by final state interaction [4] between the two pre-emitted neutrons. A new experiment, which confirmed the existence of the n-n coincidences, has been performed at the RIKEN-RIPS facility by means a neutron array detector (Fig.2) specially developed [5]. This neutron array detector consists of 81 detectors made of  $4\times 4\times 12\text{ cm}^3$  BC-400 crystals, mounted on XP2972 phototubes. This detector, placed in forward direction at

138 cm from the target, was used for neutron energy determination by time of flight technique and for neutron position determination. The distance between adjacent detectors was 0.8 cm. The array components were aligned to a threshold of 0.3 MeV-equivalent electron (MeVee), using the cosmic ray peak at 12 MeV (8 MeVee).



54	53	52	51	50	81	80	79	78
55	29	28	27	26	49	48	47	77
56	30	12	11	10	25	24	46	76
57	31	13	3	2	9	23	45	75
58	32	14	4	1	8	22	44	74
59	33	15	5	6	7	21	43	73
60	34	16	17	18	19	20	42	72
61	35	36	37	38	39	40	41	71
62	63	64	65	66	67	68	69	70

Fig.2 - The neutron array detector a) general view b) the numbering scheme

In this scheme first order coincidences are considered coincidences between adjacent detectors, second order coincidences are considered coincidences between 2 detectors separated by one detector, and so on.

The two-neutron correlation function [6] is given by

$$C(\mathbf{q}) = k N_c(\mathbf{q}) / N_{nc}(\mathbf{q}) \quad (1)$$

where  $N_c(\mathbf{q})$  represents the yield of coincidences events and  $N_{nc}(\mathbf{q})$  represents the yield of uncorrelated events. The normalization constant  $k$  is obtained from the condition  $C(\mathbf{q})=1$  at large relative momenta. The relative momentum  $\mathbf{q}$  is given by  $\mathbf{q} = |\mathbf{p}_1 - \mathbf{p}_2| / 2$ ,  $\mathbf{p}_1$  and  $\mathbf{p}_2$  being the momenta of the two coincident neutrons. In order to get the correlation function two problems have been investigated: the selection of the true coincidences against cross talk and the construction of the denominator consisting in single neutron products. The cross talk is a spurious effect in which the same neutron is registered by two or more detectors. The significance of the obtained data [7] was tested through a complete Monte Carlo simulation [8] of the neutron array detector performances using MENATE program [9].

We get information about cross-talk by firing the central, #1, detector by neutrons of given energy and by extracting the information about their interactions in #2-#9 detectors (first order), in #10-#25 detectors (second order) and so on. Adjoining a code fragment written in the main.f by the user of MENATE code is reproduced ( $z\_front\_face(1)=138$  cm,  $cylinder\_radius=2$  cm). The coordinate system has the origin in the center of the detector #1, the X-axis goes through detectors #2, #10, #26, #50, the Y-axis goes through detectors #8, #22, #44, #74, Z-axis is normal on XY-plane The neutrons are uniformly generated in the cone with an aperture of arc ( $\cos\_theta\_min$ ) around the forward direction (z-axis) (first part). If the number of fired detectors is greater than 2 then we select the 'first order' cross-talk, 'second order' cross-talk and so on by the number of the detector in the second interaction. If the number of detector is in the field #2-#9 then there is a 'first order' cross talk, if it is in the field #10-#25 there is a 'second order' cross talk and so on. The information about the characteristics of the interaction is written only if the total light deposit due to the interaction is greater than 0.3 MeVee (second part)

```
.....
      cos_theta_min = z_front_face(1) /
&          dsqrt(z_front_face(1)**2 +
cylinder_radius(1)**2)
```

```

        call random_number(xrand)
        cos_theta = cos_theta_min + (1.-
cos_theta_min)*xrand
        sin_theta = sqrt(1-cos_theta**2)

        call random_number(xrand)
        phi = 2*pi*xrand
        wx(1) = sin_theta*cos(phi)
        wy(1) = sin_theta*sin(phi)
        wz(1) = cos_theta
.....
        if (nb_of_fired_detectors.GE.2) then
        do iint=2,nb_of_interactions
        if(interactions(iint,8).GE.0.3D0) then
            inbdet=interactions(iint,5)
            select case(inbdet)
                case(2:9) ! or 10:25 or 26:49 or 50:81
                    goto 919
            end select
        end if
        end do
        goto 920
919      write(65,'(I10,2I5)')
num_particle,nb_of_interactions,
      &  nb_of_fired_detectors
      do iint = 1, nb_of_interactions
          if(interactions(iint,8).GE.0.3D0)
      &  write(65,'(I5,4D12.3/4D16.7/3D16.7)')iint,
      &
interactions(iint,1),interactions(iint,2),interactions(iint,3)
      ,
      &  interactions(iint,5),
      &
interactions(iint,4),interactions(iint,6),interactions(iint,7)
      ,
      &  interactions(iint,8),
      &
interactions(iint,9),interactions(iint,10),interactions(iint,1
1)
          end do
          end if
920      continue

```

We have investigated the cross-talk distribution as a function of  $t_2-t_1$  ( $t_1$ ,  $t_2$  are neutron-arrival time in ns) for different coincidence (1<sup>st</sup> to 4<sup>th</sup>) orders.

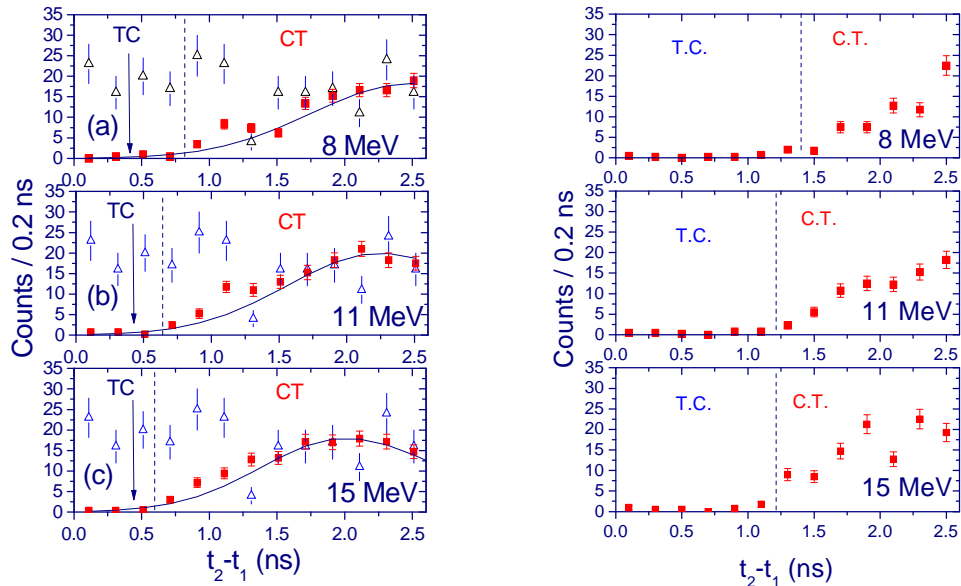


Fig. 3 - The Monte Carlo simulation of the first order cross-talk (CT) for the distance between adjacent detectors of 0.8 cm (on the left) and for 2 cm (on the right), for various energies of the incident neutrons.

In the figure 3 one can see an extension of the windows for true coincidences (TC) by increasing the distance between the adjacent detectors from 0.8 cm to 2 cm.

The  $z_1$ -coordinate and  $z_2$ -coordinate distributions for 8 MeV (up) and 15 MeV (down) incident neutron energies,  $z_1$  and  $z_2$  being the  $z$ -coordinates of the first and the second interactions, give an indication that the first interaction occurs mainly in the first half of the detectors, while the second interaction occurs mainly in the second half.

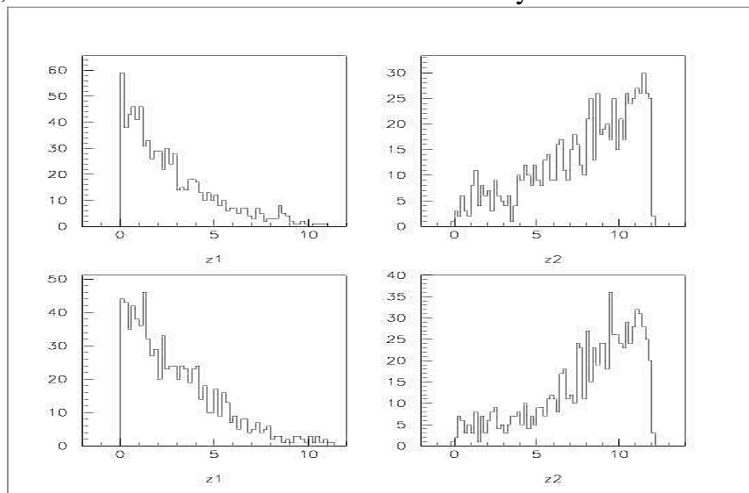


Fig.4 -  $z$ -distributions for the first ( $z_1$  in cm) and the second ( $z_2$  in cm) interactions at different incident neutron energies for the 4-th order cross talk.

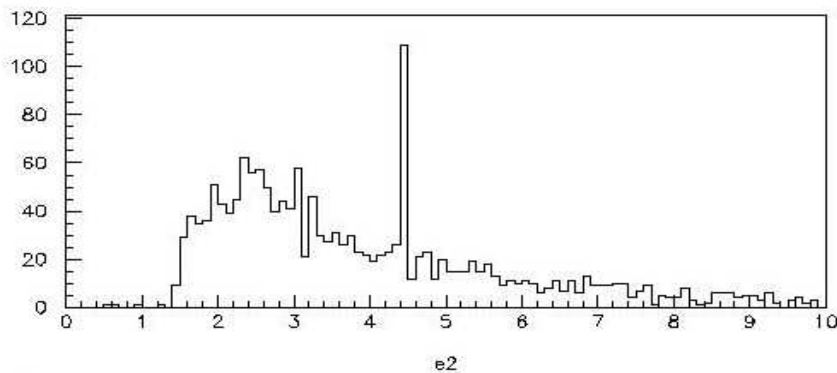


Fig. 5 - Incident energy-distribution (e2 in MeV) in the second interaction.  
One can see the peak at 4.4 MeV, the first resonance in Carbon.

To construct the denominator we generated the incident neutrons on the array detector with the following fragment code in the main.f (29.98 cm is the radius of the circle which contains the whole area of the array detector, so now the neutrons are uniformly generated in a cone with this circle aperture, first part of the code). This time we select the incident neutrons, which fire only one of the array detectors and give the greatest total light deposit (the second part of the code).

```

cos_theta_min=z_front_face(1)/
&      dsqrt(z_front_face(1)**2+29.98D0**2)

      call random_number(xrand)
cos_theta=cos_theta_min+(1.-cos_theta_min)*xrand
      sin_theta = sqrt(1-cos_theta**2)

      call random_number(xrand)
      phi = 2*pi*xrand
      wx(1) = sin_theta*cos(phi)
      wy(1) = sin_theta*sin(phi)
      wz(1) = cos_theta
.....
      if (nb_of_fired_detectors.EQ.1)then
        kdep=0
        do iint=1,nb_of_interactions
          if(interactions(iint,8) .GE. 0.3) kdep=1
        end do

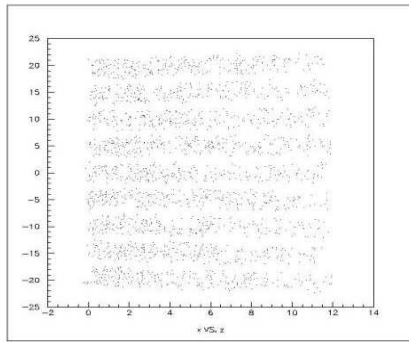
        if(kdep .EQ. 1) then
          iint=1
          do iint1=2,nb_of_interactions

```

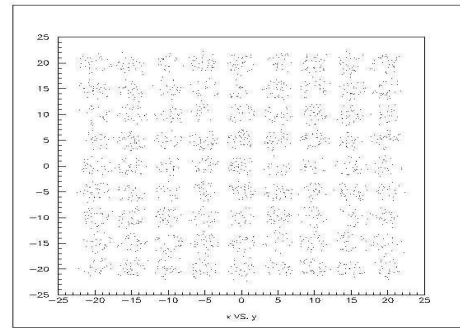
```

        if(interactions(iint1,8) .GT. interactions(iint,8)
iint=iint1
    end do
    write(65,'(I10,2I5)')num_particle,nb_of_interactions
    write(65,'(I5,4D12.3/4D16.7/3D16.7)')iint,
    &    interactions(iint,1),interactions(iint,2),
    &    interactions(iint,3),interactions(iint,5),
    &    interactions(iint,4),interactions(iint,6),
    &    interactions(iint,7),interactions(iint,8),
    &    interactions(iint,9),interactions(iint,10),
    &    interactions(iint,11)
    end if
end if

```



(a)



(b)

Fig.6 - The x-z coordinate (a) and the x-y coordinate (b) distributions (x, y, z in cm) of the neutron interactions on the array detector.

Some of these results were analysed with PAW program [10] using N-topples and macros. An example is this one in which are created 2 N-tuples ('det1' and 'det2'), each of them with 10 components: np=number of the incident particle, ndet=number of the detector fired in the interaction, t1=time (in ns) of the first interaction, t2=time (in ns) of the second interaction, dd=sqrt((x2-x1)<sup>2</sup>+(y2-y1)<sup>2</sup>+(z2-z1)<sup>2</sup>) where x1, y1, z1 and x2, y2, z2 are the coordinates (in cm) of the first, respectively, the second interaction, e2=incident energy (in MeV) in the second interaction, dep1, dep2 are the total light deposit (in MeVee) due to the first, respectively, the second interaction; a1, a2, a5 and b1 are parameters, values of which are given in the file or in the command line in PAW. The input data are in the files 'g8.txt' and 'h8.txt' for 0.8 cm and, respectively, 2 cm distance between adjacent detectors, 8 MeV energy of the incident neutrons, first order cross talk. The output is given in the file 'dep.ps' (Fig.7).

```

macro nov22 a5='dep.ps' a3=t1 a2=t2 b1=14
ntuple/cre 1 'det1' 10 '' 3100 np ndet t1 t2 dd e2 z1 z2 dep1 dep2
ntuple/cre 2 'det2' 10 '' 3100 np ndet t1 t2 dd e2 z1 z2 dep1 dep2
nt/read 1 g8.txt
nt/read 2 h8.txt

```

```

zone 1 2
pic/switch
pic/cre 'pic1'
nt/pl 1.[a2]-[a3] ([a2]-[a3])<[b1]
nt/pl 2.[a2]-[a3] ([a2]-[a3])<[b1]
pic/print [a5]
pic/de *
return

```

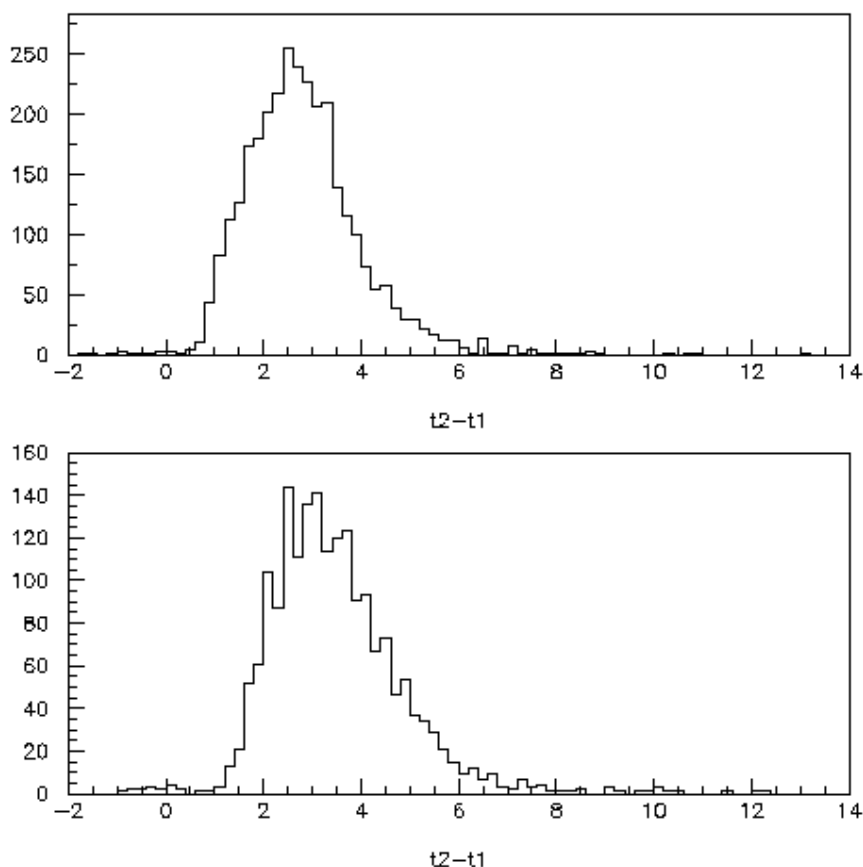


Fig.7 -  $t_2-t_1$  (in ns) distributions for 0.8 cm (up) and 2 cm (down) distance between two adjacent detectors.

As a result of the Monte Carlo simulation the neutron array detector was optimised, by choosing a 2 cm distance between two adjacent detectors. Therefore a new experiment is in preparation aiming to obtain a precise measurement of the intrinsic n-n correlation function.

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