ENERGY AND TIME SPREADS OF A PARTICLE BEAM USED IN APH TECHNIQUE

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# ENERGY AND TIME SPREADS OF A PARTICLE BEAM USED IN APM TECHNIOUE 

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#### Abstract

A Monte Carlo code has been developed to simulate neutron and alpha production in the time correlated associated particle method (TCAPM). The atomic and molecular composition of the deuterium beam, tritium ratio in the target, slowing - down and straggling of deuterons as well as the angular dependence of emitted neutrons and alpha particles are both taken into account in these calculations. The following physical characteristics are obtained: mean energy of detected alpha particles and their spread, mean time of flight and its spread values for alpha particles, alpha and associated neutron spectra as well as neutron spatial cone distribution.


## INTRODUCTION

The exact knowledge of the physical characteristics of D-T neutron beam is especially needed for high accuracy cross-section measurements in 14 MeV region. The time--correlated associated particle method (TCAPM) is an important technique for the measurements of neutron induced double differential as well as fission crosssections. In the TCAPM, the alpha particle emitted in the $T(d, n)^{4}$ He reaction is detected to fix the neutron beam characteristics. This technique has been implemented in our Laboratory in the frame of the IAEA project [1 ] related to neutron nuclear data measurements at around 14 MeV. Absolute fission cross-section measurements based
on a fission chamber and an alpha particle absolute neutron flux monitor [2] are also planned in the near future. For this reason, it is especially important to know the characteristics of the associated neutron cone by the detection of the alpha particles.

The present paper shows the results of a Monte Carlo simulation of neutron generation - including alpha particle detection. Our purpose is to obtain the energy and spatial characteristics of the neutron cone in dependence of the alpha detector and the deuteron beam characteristics. The code reproduces also the energy and time characteristics of the alpha channel.

In sections $I$ and II, the theoretical formalism as well as the discussion of the results, respectively, are presented.

## I. THEORETICAL FORMALISM

From a physical point of view, one can consider the neutron generator as a beam of deuterium atoms when striking on the TiT target with an energy $E_{0}$. A sufficiently thick target is used to stop completely the incident deuterium beam. Furthermore, it is assumed that the target has such a surface layer where practically no tritium is present but which can produce alo keV energy loss of the incident beam [3].

Taking into account the deuterium energy as a random variable, one can use the following probability density for reaction energy:

$$
\begin{equation*}
p^{k}(E d)=\frac{1}{P_{k}} C(E d) \sigma(E d) \frac{d E}{d X}{ }_{T i T}^{[E d]^{-1}} \tag{1}
\end{equation*}
$$

where:
C(Ed) : is the tritium concentration in the target, $\sigma(E d)$ the cross-section of the $T(d, n)$ He reaction, $d E / d x(E d)$ the rate of energy-loss by ionization. By knowing the stopping data of the deuterium beam in Ti and T [4] and by using the Bragg rule $[5,6]$, the specific energy loss can be calculated. The calculation is based on very accurate approximations both for $d+T$ experimental cross--section data and the energy-loss rate function.

The knowledge of the total probability of deuterium interaction inside the target ( $P_{k}$ ) permits to normalize the (I) probability densities to unity by using the following expression:

$$
\begin{align*}
& P_{k}=\int^{0} p^{k}(E d) d E d  \tag{2}\\
& E_{0} / k-\Phi
\end{align*}
$$

where $k$ denotes the type of ions: $k=1\left(d^{+}\right), k=2\left(d_{2}^{+}\right)$, $k=3\left(d_{3}^{+}\right)$.

Using the density function (1), one can obtain - by Monte Carlo method - a set of $\left\{E_{d i}\right\}$ values. This spectrum depends mainly on the incident beam energy $E_{0}$ and on the atomic composition because for $\mathrm{d}_{2}^{+}$and $\mathrm{d}_{3}^{+}$the acceleration energies are equal to $E_{0} / 2$ and $E_{0} / 3$, respectively.

There is an easy way to consider the different functions of the tritium concentration $C(E d)$ in the target, however, in this paper, a constant concentration - having no influence on the probability density $p(E d)$ - is assumed. From a set of $\left\{E_{d i}\right\}$ values, it is possible to calculate the mean interaction energy of deuterons $E_{d i}$ in the target, which can also be measured experimentally. Table l shows

TABLE 1. Dependence of the average deuteron energy in a TiT target on the composition of the beam at $E_{d^{+}}=120 \mathrm{keV}$

| Beam composition | Average deuteron energy |
| :--- | :--- |
| $100 \%-\mathrm{d}^{+}$ | 90.25 keV |
| $80 \%-\mathrm{d}^{+}, 20 \%-\mathrm{d}_{2}^{+}$ | 80.65 keV |
| $60 \%-\mathrm{d}^{+}, 40 \%-\mathrm{d}_{2}^{+}$ | 73.41 keV |
| $20 \%-\mathrm{d}^{+}, 8 \mathrm{C} \%-\mathrm{d}_{2}^{+}$ | 60.08 keV |

TABLE 2. Average values of physical parameters as a function of bombarding energy of $100 \% d^{+}$-beam at $150^{\circ}$ angle between the direction of $d^{+}$and a particles.

| $E_{d^{+}}$ | $\overline{E d}$ | $E_{n}$ | $\overline{E_{\alpha}}$ | $\bar{\Phi}_{n}[g r a d]$ | Mean flight time [ns] |
| :--- | :--- | :--- | :--- | :--- | :--- |
| 100 keV | 79.4 | 14.6 | 3.07 | 27.06 | 24.67 |
| 120 keV | 90.3 | 14.64 | 3.04 | 26.88 | 24.79 |
| 140 keV | 100 | 14.67 | 3.01 | 26.73 | 24.89 |
| 160 keV | 108.5 | 14.70 | 2.99 | 26.60 | 24.98 |
| 180 keV | 116.2 | 14.73 | 2.98 | 26.50 | 25.05 |

the calculated values of the mean interaction energy of deuterium for different atomic beam compositions. In Table 2, the same values are shown as a function of the initial energy of a pure deuteron beam. If the $d^{+}$ratio decreases one can observe the same trend also in the mean interaction energy of the deuterons (see fig.l also).

This involves practically a decreasing value of the neutron flux at $\bar{E}_{d}$ far from the resonance energy $\left(E_{r e s}=\right.$


Fig. 1 Variation of the deuteron mean energy as a function of the percent of $d^{+}$and $d_{2}^{+}$ions.
$=109 \mathrm{keV})$ of the $T(\mathrm{~d}, \mathrm{n})^{4}$ He reaction. Similar behaviour happens when the incident deuterium beam energy $E_{o} d e-$ creases as it can be seen in Table 2.

The dependence of the mean energy $\bar{E}_{d}$ on the titanium to tritium atomic ratio have also been studied. The influence of this dependence is low, nevertheless, the absolute magnitude of the total neutron flux must depend strongly on this ratio.

After a set of deuterium energies is determined, a weighted method is used to continue the simulation process instead of the direct method. This procedure allows to reduce the variances and statistical errors in the parameters considered. Figure 2 demonstrates the geometry used in the calculation of the emission angle of alpha particles. Three local coordinate systems $s l$,


Fig. 2 Coordinate systems used in the calculations.

S2 and S3 are introduced here, which related to the deuterium beam (with $z$ axis along the beam line), the tritium target and the alpha detector. First, the coordinates of detection point of alpha particles in 53 system are $p$ layed (named $M_{d}\left(x_{d}^{3}, y_{d}^{3}, z_{d}^{3}\right)$ ), after that the coordinates of tritium target spot in local system s 2 $\left[M_{t}\left(x_{t}^{2}, y_{t}^{2}, z_{t}^{2}\right)\right]$ are obtained. The next step is to transform the coordinates of both points to laboratory coordinate system $S I$, which is associated to the incident deuterium beam. If the angular straggling of incident deuterium beam is considered, it is necessary to determine the angles in which the deuterium reacts inside the tritium target $\left(\varphi_{S}\right.$ and $\left.\phi_{S}\right)$. The angle $\varphi_{S}$ is distributed uniformly between 0 and $2 \pi$. The functional dependence of angle $\varphi_{S}$ is more complex and for its description various probability densities have been proposed [7,8]. In this paper, a Gaussian probability with a $0^{\circ}$ mean value and an FWHM of $14^{\circ}$ has been selected to describe the angular
straggling because its good results and simplicity [9]. After the reaction angles are obtained one can calculate the outgoing angle of the associated alpha particle [ $\cos \phi_{\mathrm{i}_{\mathrm{i}}}$ ] with respect to the direction of the deuterium beam in the following way:

$$
\begin{equation*}
\cos \psi_{1 \alpha}=\frac{\left[\left(x_{m}^{l}-x_{d}^{l}\right) \cos \varphi+\left(y_{m}^{l}-y_{d}^{l}\right) \sin \varphi_{s}\right] \sin \phi_{s}+\left(z_{m}^{l}-z_{d}^{l}\right) \cos \phi_{s}}{d} \tag{3}
\end{equation*}
$$

where all coordinates have upper index 1 to denote that they correspond to the Sl system, furthermore; $d$ is the path of the alpha particles between the target and detector given by

$$
\begin{equation*}
d^{2}=\left(x_{d}^{1}-x_{b}^{1}\right)^{2}+\left(y_{d}^{1}-y_{b}^{1}\right)^{2}+\left(z_{d}^{1}-z_{b}^{l}\right)^{2} \tag{4}
\end{equation*}
$$

It is necessary to note that $\psi_{i \alpha}$ is the dispersion angle of alphas to the direction of deuterium beam in the sl system. This angle is also determined by $\varphi_{S}$ and $\phi_{S}$ (see figure 2). The emission angle of alpha particles in sl system can be calculated by

$$
\begin{equation*}
\cos \psi_{i \alpha}^{l}=\frac{\left(z_{d}^{1}-z_{b}^{1}\right)}{d} \tag{5}
\end{equation*}
$$

It is easy to verify that without straggling $\phi_{s}=0$ and therefore $\cos \psi_{i \alpha}^{l}=\cos \psi_{i \alpha}$ will be obtained.

To start a neutron history one plays first the type of the incident ion on the tritium target taking into account the composition of the accelerated deuterium beam. For the given ions one plays the $E_{d i}^{k}$ at which reaction occurs by means of the probability density $p^{k}(E d)$. In the knowledge of $E_{d i}^{k}$ and the angle $\psi_{i \alpha}$ one can obtain the energy $E_{n i}$ and the angular yields $\psi_{i n}$ of neutrons as well as the energy of the associated alpha particle $E_{i \alpha}$
using relativistic kinematics [l0]. It should be noted that the obtained neutron angle is not the neutron emission angle in laboratory system, because it is expressed in the local system in which the reaction occurs. Taking into account the spatial characteristic of the neutron cone (spatial distribution, mean angle, etc.) measured in the laboratory system, the emission angle is given by the following transformation:

$$
\begin{aligned}
\cos \psi_{i n}^{l} & =\left[\cos \psi_{i n}+\cos \psi_{i \alpha} \times \sin \psi_{i n} / \sin \psi_{i \alpha}\right] \cos \phi_{s}- \\
& -\cos \psi_{i \alpha}^{I} \times \sin \psi_{i n} / \sin \psi_{i \alpha}
\end{aligned}
$$

The local system will coincide with the one by neglecting the angular straggling. Then

$$
\begin{equation*}
\cos \psi_{i \alpha}=\cos \psi_{i \alpha}^{l} ; \quad \cos \phi_{S}=1 ; \quad \cos \psi_{i \alpha}^{l}=\cos \psi_{i n} . \tag{6}
\end{equation*}
$$

It is noted finally the following statistical weight is used:

$$
\begin{equation*}
w_{i}=\frac{f(E d i, \psi i \alpha, E i \alpha)}{d^{2}} \tag{7}
\end{equation*}
$$

where $f\left(E d i, \psi_{i \alpha}, E i \alpha\right)$ is the anisotropy factor given by the ratio of the solid angle in center of mass system to the laboratory (SI) one:

$$
\begin{equation*}
f=\frac{\Omega l a b}{\Omega s c m}\left(E d i, \psi_{i \alpha}, E i \alpha\right) \tag{8}
\end{equation*}
$$

One can use the following relations to obtain the mear values of the important and measurable parameters:

$$
\overline{\Psi n}=\sum_{i} w i \cdot \psi_{n i}^{l} / \sum_{i} w i-n e u t r o n \text { cone mean angle. }
$$ particle to reach the detector.

$$
\begin{aligned}
& \overline{E n}=\underset{i}{\Sigma} \text { Wi.Eni/E Wi - neutron cone mean energy. } \\
& \bar{E}=\sum_{i}^{\Sigma} \text { Wi•Eai/ } \underset{i}{ } \text { Wi - detected particle mean energy. }
\end{aligned}
$$

Taking into account the fact that the alpha particle energy is less than 5 MeV , it is possible to use the non-relativistic kinematics to calculate - with a good accuracy - the time of flight of alpha particles from the tritium target to the detector. The time in nanoseconds can be obtained by the relation:

$$
\begin{equation*}
\mathrm{Tai}=\frac{\mathrm{d}}{\sqrt{2 \frac{\mathrm{E} \mathrm{\alpha}[\mathrm{MeV}]}{\mathrm{Ma}[\mathrm{MeV}]}} \cdot 2.99792458} \cdot 10^{-1} \mathrm{~ns} \tag{9}
\end{equation*}
$$

The code calculates the four average characteristics mentioned above for each group of incident deuterons. The dispersion is also calculated for each parameter by the expression

$$
\begin{equation*}
\sigma_{\bar{M}}=\left[\left.\left.\sum_{i}^{n} w_{i}\left(M_{i}-\bar{M}\right)^{2}\right|_{i=1} ^{n} w_{i}(n-1) \quad\right|^{1 / 2}\right. \tag{10}
\end{equation*}
$$

where $M_{i}$ is the given parameter ( $E_{\alpha_{i}}, \dot{E}_{n_{i}}, \Psi_{n_{i}}, t{ }_{\alpha_{i}}$ ) and $\bar{M}$ its average value. It should be noted that some calculations are carried out considering the energy loss of the alpha particles before they left the tritium target. This effect, as well as the straggling of alphas, can be neglected by which the computing times of the simulation process are decreased considerably.

In order to obtain the distribution profiles for each parameter the scales are divided into bins of equal width and the weight factors are sorted and summed. The alpha and neutron energy spectra in the correlated cones are calculated by this way. The time distribution of the alphas and also its resolution have been obtained. All results are summarized in the next section.
II. RESULTS AND CONCLUSIONS

The dependence of the neutron energy spectrum on the incident deuteron energy is shown in Fig. 3 at $\mathrm{Ed}=120,140$, 160,180,200 keV placing alpha detector at $150^{\circ}$ to the


Fig. 3 Dependence of neutron spectrum on the energy of incident $d^{+}$- beam.
direction of the $100 \% d^{+}$beam. As can be seen in the figure, the average neutron energy and its spread increases with the beam energy of deuterons. The increased energy spread is caused by the slowing down of deuterons in the target. This effect can also be observed in the associated particle spectra (energy and time of flight spectra) shown in the Figs. 4 and 5. The angular dependences obtained for the parameters to be measured are shown in the Table 3.

The average values of neutron energy, alpha energy, neutron emission angle and alpha flight time for different

TABLE 3. Average values of physical parameters as a function of alpha emission angle for $120 \mathrm{keV} a^{+}$-beam.

| Alpha angle | $\overline{E n}$ | $\overline{E \alpha}$ | Mean $n$ angle | Mean flight time [ns] |
| :---: | :---: | :---: | :---: | :---: |
| $10^{\circ}$ | 13.45 | 4.23 | $168.8^{\circ}$ | 21.01 |
| $30^{\circ}$ | 13.54 | 4.14 | $146.7^{\circ}$ | 21.24 |
| $60^{\circ}$ | 13.80 | 3.88 | $114.4^{\circ}$ | 21.95 |
| $100^{\circ}$ | 14.24 | 3.43 | $73.7^{\circ}$ | 23.31 |
| $120^{\circ}$ | 14.44 | 3.24 | $54.5^{\circ}$ | 24.00 |
| $150^{\circ}$ | 14.64 | 3.03 | $26.9^{\circ}$ | 24.80 |

TABLE 4. Average values of physical parameters vs. beam composition at $E_{d^{+}}=100 \mathrm{keV}$ and $B_{\alpha_{D}}=150^{\circ}$.

| Beam composition | $\overline{E d}$ | $\overline{E n}$ | $\overline{E q}$ | $\overline{M e a n} \alpha$ ang. Mean flight cime-[ns] |  |
| :--- | :---: | :---: | :---: | :---: | :---: |
| $100 \%-d^{+}$ | 79.4 | 14.603 .07 | $27.06^{\circ}$ | 24.67 |  |
| $80 \%-d^{+} 20 \%-d_{2}^{+}$ | 71.4 | 14.563 .10 | $27.24^{\circ}$ | 24.55 |  |
| $60 \%-d^{+} 40 \%-d_{2}^{+}$ | 63.5 | 14.533 .13 | $27.41^{\circ}$ | 24.44 |  |
| $40 \%-d^{+} 60 \%-d_{2}^{+}$ | 55.5 | 14.493 .15 | $27.58^{\circ}$ | 24.33 |  |
| $20 \%-d^{+} 80 \%-d_{2}^{+}$ | 47.6 | 14.45 | 3.18 | $27.75^{\circ}$ | 24.22 |
| $0 \%-d^{+} 100 \%-d_{2}^{+}$ | 39.7 | 14.423 .21 | $27.92^{\circ}$ | 24.12 |  |

beam compositions are shown in Table 4. Variations in the parameter values are caused by the decreasing of average energy of deuterons.

As it can be seen in Fig. 6 a linear correlation exists between the average alpha energy and the average incident deuteron energy. This result points to a possible experiment for the determination of Ed by an absolute measurement having adequate resolution of the charged particle spectrum emitted in the $D-T$ reaction during the operation of the neutron generator.


Fig. 4 Dependence of the alpha particle spectrum on the energy of incident $d^{+}$-beam.


Fig. 5 Dependence of the time of fligth spectrum on the energy of the incident deuteron beam.


Fig. 6 Dependence of the mean alpha particle energy as a function of the average energy of incident deuterons.


Fig. 7 The neutron energy spectrum with and without angular staggling.


Fig. 8 The alpha energy spectrum with and without angular straggling.


Fig. 9 The time of fligth spectrum with and without angular straggling.


Fig. 10 Dependence of the mean neutron angle as a function of the percent of $d^{+}$and $d_{2}^{+}$in the beam.

The neutron energy distribution profile considering the neutron straggling is shown in Fig.7. As it can be seen in Fig. 7,8 and 9, the neutron energy, the associated particle energy and the time characteristics depend strongly on the straggling. In fact, different theoretical models dealing with the straggling lead to similar results in the magnitude of dispersion or FWHM. In our case, as mentioned above, a simple variant is selected.

Finally, in Fig. lo, the dependence of the average angles of neutron cone on the composition of the incident beam are presented. It seems to be possible to determine the ion composition of the incident beam by a precise measurement of the average cone angle.

These results can help in the selection of the system geometry in experiments based on the TCAPM-technique using
low-voltage neutron generators. For example, the absolute measurements of fission cross-sections using the TCAPM require the knowledge of the numbers of neutrons bombarding the fissile target in the given cone. The code permits the calculation of the correction factor for the specific geometry.

At double differential cross-section measurements, the calculated neutron spectrum can be used for taking into account multiple scattering corrections for the given geometry and sample position.

During irradiation, the tritium concentration profile can change because of the diffusion, heating, replacement of tritium by deuterium, etc,. However, a constant distribution of the tritium concentration in the target is considered in the code at present. It would be interesting to study the changes in the characteristics of the system (especially the position and distribution of the neutron cone) for different tritium profiles and to compare the results with experiments. As for the further details of such calculations and measurements see e.g. Ref. [11].

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