SYNCHROCYCLOTRON SHIELD-LEAKAGE NEUTRON SPECTRA
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1. Introduction
In the last few years several investigations of the neutron energy composition outside high energy accelerator shields have been carried out\textsuperscript{1-8). But the information obtained on different accelerators does not allow to establish the regularities of the neutron energy composition variation depending on maximum proton energy and shielding compositions\textsuperscript{5). We make an attempt in this work to establish such regularities for 300-700 MeV proton accelerators, to verify the calculation method of the neutron energy composition in the shield and to develop the conversion formalism from the neutron spectral-angular distribution function inside the semi-infinite shield to the spectral angular distribution function of shield-leakage neutrons. In this connection the measurements of neutron energy composition outside the shield of the Dubna synchrocyclotron were carried out for three energies of accelerated protons and different shielding compositions.

2. Experimental Geometry
Plan and cross-sectional views of the synchrocyclotron building and the experimental lay-out are shown in Fig. 1. The shield was irradiated by high-energy particles from the beryllium target (80x40x25 mm\textsuperscript{3}), the copper vacuum chamber bombarded by protons and neutrons scattered by the walls of the building and the auxiliary equipment. The energy of protons which bombarded the beryllium target was varied by moving the target along the vacuum chamber radius. The measurements for the 350, 480, 660 MeV internal proton beam were carried out.
Spectra of high energy neutrons incident on the shield near experimental position 2 are shown in Fig. 2. The energy spectra of neutrons from the target were taken from ref. 11). Spectra of neutrons from the vacuum chamber for 650, 480 and 350 MeV proton energies were calculated with the semi-empirical formula12). It was expected that the vacuum chamber walls were a "thick" target for the protons of energies lower than 700 MeV. The beam loss distribution along the vacuum chamber was measured by carbon induced radioactivity in plastic scintillators.

3. Detectors and Measurement Methods

High energy strong interacting particle flux was measured by activation of carbon in liquid phosphors13). Neutron fluxes of energies lower than 20 MeV were measured by a BF3-counter with a set of cylindrical moderators14) and a "long" isotropic response counter\(^\#\)\(\) (2 eV \(< E_n \leq 2\) MeV). Combining the readings of these detectors the neutron fluxes in the energy ranges \(E_n \leq 0.1\) MeV,\(0.1\) MeV \(< E_n \leq 20\) MeV\(7)\), 2 MeV \(\leq E_n \leq 20\) MeV, \(E_n > 20\) MeV were obtained. Errors in the determination of fast (from 0.1 MeV to 20 MeV), intermediate (from 0.4 MeV to 0.1 MeV) and thermal neutron fluxes were equal to 25\%, 13\%, 10\%, respectively. The dose equivalent rate of neutrons of energies lower than 20 MeV was measured by the multisphere technique15,16,17).

\(^\#\) The detector was developed by V. Nazarov, a collaborator of Dubna. It consists of a thermal neutron sensitive element situated in a 35 mm diameter cavity inside a 200 mm diameter sphere with radial holes 10 mm in diameter and 30 mm deep. The response of this detector as a function of neutron energy is shown in Fig. 3.
4. RESULTS, DISCUSSION.

Figures 4 and 5, Table I show the energy distributions and dose equivalent compositions of neutrons outside the 2-meter ordinary concrete shield for the following cases: the shield is irradiated by high energy particles from target and vacuum chamber (position I); the shield is irradiated only by stray radiation from the building's walls and auxiliary equipment (position 5); two intermediate irradiation conditions (positions 3 and 4). As would be expected, the fraction of the flux and dose due to fast neutrons and high-energy particles increase with the contribution of high-energy particles to the radiation incident on the shield.

The personnel film badges were irradiated to verify adequacy of the dose equivalent measured with the personnel film badges and neutron dose equivalent outside "good" and "bad" shields (I and 6 positions, accordingly). It can be seen from Table I that the film dosimeter readings outside the "good" shield are well over both the dose equivalent measured by multisphere technique and the total dose equivalent. It is likely to be the result of increasing a quantity of tracks in the nuclear emulsion due to charged particles which are identified as recoil protons. The personal film badge reading outside the "bad" shield (position 6) is in agreement with the dose equivalent measured by the multisphere technique. This agreement can be put down to negligible fraction of the charged particles at this experimental position.

*) The shield will be referred to as "good" shield, if outside this shield the major fraction of the dose is due to the particles of the leading energy group (high-energy particles for high-energy proton accelerators). In other cases the shield will be referred to as "bad" shield.
Table I presents also dose equivalent rates measured by the commercial scintillation dosimeter DH-I-A made in USSR which is for use in routine measurements of the dose equivalent due to neutrons with energies less than 20 MeV. DH-I-A readings exceed the dose equivalent measured by the multisphere technique due to the contribution of charged and high-energy particles to readings of DH-I-A. This circumstance can be used for broadening of the energy range of particles registrated.

Table 2 compares the calculated and measured neutron energetic composition inside the synchrocyclotron concrete shield (position 2) at the depth 500 g/cm². The calculation were performed for incident neutron spectrum \( E = 350 \text{ MeV} \) shown in Fig. 2 as Alsmiller's results 10) were used. The experimental data agree with the calculation for neutrons with energies more than 0.4 eV. Understation of measured thermal neutron flux as compared to the calculation is connected with availability of a number of elements with large absorption cross-section of thermal neutrons in the shield. Those elements were ignored in the calculation.

Table 3 shows neutron flux percent compositions at the depth 500 g/cm² in the semi-infinite ordinary concrete shield (position 2) and outside the ordinary concrete shield 500 g/cm² thick (position 1). When passing from the semi-infinite shield to the finite shield the contribution of high-energy nucleons to the total flux increases. Consider the shield-leakage neutron flux spectral-angular distribution function forming from the neutron flux distribution function in the semi-infinite shield. Let \( F(z, \Omega, E) \) be the spectral-angular distribution function of the neutron flux in the semi-infinite shield at the depth z in the case of plane monodirectional neutron source situated on the shield boundary;

\( \phi (z, \Omega, E) \) is the spectral-angular distribution function of neutron flux outside the slab z thick with plane
monodirectional neutron source on its front boundary;
\( \vec{n} \) is the external normal to the front shield boundary;
\( E_0 \) is the maximum energy of incident neutrons;
\( E \) is the neutron energy in the shield and outside
shield;
\( \vec{v} \) is the unit vector in the direction of the neutron
momentum. Charged particles are neglected. For \( E_0 \leq 400 \text{ MeV} \)
it is true with an accuracy of \( \sim 10\% \). On these assumptions

\[
F(z, \vec{s}, E) = \Phi(z, \vec{s}, E) + \sum_{n=1}^{\infty} \Phi_n(z, \vec{s}, E) \tag{1}
\]

where
\( \Phi_n(z, \vec{s}, E) \) is the spectral-angular distribution function
of neutrons after 2n-multiple reflections from the semi-
infinite shield of the neutrons whose distribution function
was \( \Phi(z, \vec{s}, E) \). Now, let operator \( \hat{A} \) be defined as

\[
\hat{A} \Phi = \oint dE' \oint dE'' \int_{\vec{s}} d\vec{s}' \Phi(z, \vec{s}, E') \hat{A}(E, \vec{s}', E, \vec{s}'') A(E, \vec{s}, E', \vec{s}'') d\vec{s}'' \tag{2}
\]

where \( A(E_1, \vec{s}_1, E_2, \vec{s}_2) \) is the probability that a neutron incident with energy \( E_2 \) and direction \( \vec{s}_2 \) will be reflected from the semi-infinite medium, after one or more scatterings, with an energy between \( E_1 \) and \( E_1 + dE_1 \) and a
direction between \( \vec{s}_1 \) and \( \vec{s}_1 + d\vec{s}_1 \). The equation (1) takes
the form

\[
F(z, \vec{s}, E) = \Phi(z, \vec{s}, E) + \sum_{n=1}^{\infty} \hat{A}^n \Phi(z, \vec{s}, E) \tag{3}
\]

where \( \hat{A}^n \Phi(z, \vec{s}, E) = \hat{A} \left[ \hat{A}^{n-1} \Phi(z, \vec{s}, E) \right] \).

Solving equation (3) for \( \Phi(z, \vec{s}, E) \) we have

\[
\Phi(z, \vec{s}, E) = F(z, \vec{s}, E) - \hat{A} F(z, \vec{s}, E) \tag{4}
\]

if \( (\hat{A}^2) < 0 \).

The authors are grateful to V.P. Gerdt and M.I. Salatskaya
for their help and to B.S. Sychev for his calculations of
the spectral-angular distribution function of the neutrons
generated by protons in "thick" copper target.
REFERENCES

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17) Л.Ветцель и др., Сборник докладов совещания по дозиметрии и физике защиты на ускорителях, Дубна, 201 (1970).
Figure Captions.

**Fig.1** Plan and cross-sectional views of synchrocyclotron building and layout of experimental positions.

**Fig.2** High-energy neutrons spectra incident on shield near 2 experimental position.

**Fig.3** Response of "long" counter versus neutron energy.

**Fig.4** Neutron energetic composition outside the synchrocyclotron shield for $E_p=660$ MeV.

**Fig.5** Neutron energetic composition outside the synchrocyclotron shield for $E_p=350$ MeV and $E_p=480$ MeV.
Table 1

Synchrocyclotron Shield-Leakage Neutron Dose Equivalent Rate.

<table>
<thead>
<tr>
<th>Position</th>
<th>Proton Energy, MeV</th>
<th>Dose Equivalent Rate, ( \text{mrem/h}) (^a)</th>
<th>Personal Film Badge, ( \text{mrem/h})</th>
<th>( \text{DH-A-1, mrem/h})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>660</td>
<td>150 ± 20</td>
<td>322 ± 60</td>
<td>3000</td>
</tr>
<tr>
<td></td>
<td>480</td>
<td>18 ± 3</td>
<td>42 ± 8</td>
<td>570</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>10 ± 2</td>
<td>15 ± 3</td>
<td>360</td>
</tr>
<tr>
<td>3</td>
<td>660</td>
<td>20 ± 3</td>
<td>64 ± 10</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>480</td>
<td>5,0 ± 0,7</td>
<td>8 ± 2</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>2,8 ± 0,4</td>
<td>3,6 ± 0,6</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>660</td>
<td>27 ± 4</td>
<td>115 ± 20</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>480</td>
<td>9 ± 1</td>
<td>15 ± 3</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>5,0 ± 0,7</td>
<td>12 ± 2</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>660</td>
<td>0,7 ± 0,1</td>
<td>&lt;1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>480</td>
<td>0,30 ± 0,04</td>
<td>&lt;1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>0,20 ± 0,3</td>
<td>&lt;1</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>660</td>
<td>32 ± 4</td>
<td>5,6 ± 0,7</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>660</td>
<td>0,56 ± 0,07</td>
<td>&lt;1</td>
<td>0,76</td>
</tr>
</tbody>
</table>

\(^a\) The flux density to dose equivalent rate conversion factor for high-energy particles measured by \(^{12}\text{C}(x,x\text{n})^{12}\text{C}\) reaction is believed equal to 0,28 \(\text{mrem}.\text{cm}^2.\text{sec}\)\(^h\).\text{particle}
Table 2
Neutron Flux Composition in Concrete ($\rho = 2.3 \text{ g/cm}^3$) Shield of Synchrocyclotron ($E_p = 350 \text{ MeV}$)

<table>
<thead>
<tr>
<th>Neutron Energy</th>
<th>Flux Density, $\text{neutron/cm}^2\text{ sec}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E &lt; 0.4 \text{ ev}$</td>
<td>$252 \pm 25$</td>
</tr>
<tr>
<td>$0.4 \text{ ev} \leq E \leq 0.1 \text{ MeV}$</td>
<td></td>
</tr>
<tr>
<td>$0.1 \text{ MeV} &lt; E \leq 20 \text{ MeV}$</td>
<td></td>
</tr>
<tr>
<td>$E &gt; 20 \text{ MeV}$</td>
<td></td>
</tr>
</tbody>
</table>

Calculation a) | 974 | 184 | 261 | 100 |

a) Calculations are normalized to measured neutron flux density with energies more than $20 \text{ MeV}$.
Table 3

Neutron Flux Percent Composition outside/ in Concrete Shield

<table>
<thead>
<tr>
<th>Position</th>
<th>Outside Concrete ( (\rho=2.3 , \text{g/cm}^3) ) Shield (Shield Thickness (-500 , \text{g/cm}^2))</th>
<th>In Concrete ( (\rho=2.3 , \text{g/cm}^3) ) Shield at the Depth (500 , \text{g/cm}^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron Proton Energy Energy</td>
<td>(&lt;0.4 \text{ev})</td>
<td>(0.4 \text{ev}-10^3 \text{ev})</td>
</tr>
<tr>
<td>(E_p=350 \text{ MeV})</td>
<td>19%</td>
<td>14%</td>
</tr>
<tr>
<td>(E_p=480 \text{ MeV})</td>
<td>16%</td>
<td>15%</td>
</tr>
<tr>
<td>(E_p=660 \text{ MeV})</td>
<td>12%</td>
<td>9%</td>
</tr>
</tbody>
</table>
Fig. 2

Energy, Mev

Differential Neutron Flux, arbitrary units

$E_P = 660$ Mev

$E_P = 480$ Mev

$E_P = 350$ Mev
Fig. 5

Energy, Mev

Differential Flux Density, \( \text{neutrons/cm}^2\text{sec}\text{MeV} \)

- \( E_p = 480 \text{ MeV} \)
  - \( \text{position 1} \)
  - \( \text{position 4} \)
  - \( \text{position 3} \)
  - \( \text{position 5} \)

- \( E_p = 350 \text{ MeV} \)
  - \( \text{position 1} \)
  - \( \text{position 4} \)
  - \( \text{position 3} \)
  - \( \text{position 5} \)
DISCUSSION

Paper: Synchrocyclotron shield-leakage neutron spectra

DE FRANCESCHI: You mentioned a long counter with symmetrical response. Since the well-known modified long counter does not have such symmetrical response, did you use another type of long counter?

ALENIKOV: The counter consists of a thermal neutron sensitive element situated in a 36 mm diameter cavity inside a 200 mm diameter polyethylene sphere with radial holes 10 mm in diameter and 60 mm deep.

NAHTIGALL: Would you please say some words about your "isotropic long counter"? How is the response curve, what is the accuracy of the measuring points -- mainly in the intermediate energy range? I think there must be rather large errors, in the higher energy range due to the diffusion time of the neutrons in the moderating sphere, in the lower energy range due to the delayed neutrons.

ALENIKOV: The counter has a flat response curve in the energy range from 1 eV to 2 MeV. The accuracy of the measuring points in the intermediate energy range is better than 90%.

Energy characteristics of the counter in the energy range from 0.01 eV to 6 keV by time-of-flight method have been studied. The delayed-neutron background has been defined in the following way: the neutron beam was stopped by Cd, Mn, Co absorbers and the counts in the time analyser channels due to neutrons with energy less than 0.4 eV and neutrons of Mn, Co resonance energies were recorded. These counts were added to the neutron background. The correction for the diffusion time of the neutrons in the moderating sphere was made on the assumption that "life" time of the neutrons in this moderator was 180 μsec.

WYNCHANK: Can you please describe the time response characteristics of your long counter, the flight path length and the fast reactor pulse shape used for the calibration at different energies?
ALEINIKOV: The flight path lengths were 70 m and 1000 m. The fast reactor pulse shape was

HEINSELLENN: Die Angaben der Ergebnisse mit der Mehr-Kugel-Methode sind sehr genau (ca. 13%). Ist das nur der statistische Fehler, oder sind sämtliche systematischen Fehler berücksichtigt?

ALEINIKOV: The total error is given in the accompanying table.

HEINSELLENN: Ist Ihre Mehr-Kugel-Methode so gut, dass bei keiner Neutronenergie die Abweichungen der Äquivalentdosiskurve von der Empfindlichkeitskurve Ihrer Methode kleiner als 10 oder 20% sind, oder haben Sie Annahmen über das Neutronenspektrum gemacht?

ALEINIKOV: It was assumed that the accuracy of the measuring dose equivalent by this method was equal to the accuracy of the measuring dose equivalent in 1/2 neutron field.

GOLLON: We and others have observed that latent neutron tracks on neutron film dosimeters fade over a period of a few weeks under normal temperature and humidity. Developing and reading the film 2 - 4 weeks after the exposure can therefore result in an underestimate of the dose received by a factor of 2 or 3. Has anybody succeeded in circumventing this problem in a practical way?

ALEINIKOV: The regression of proton tracks on our neutron films under normal temperature and humidity over a period of six months after Pu-Be neutron irradiation of films was within the accuracy of the measurement.
DUTRANNOIS: What calibration factor (mrem per track) did you use for your emulsion, specially when you had a great percentage of high-energy particles.

ALEINIkov: The emulsions were calibrated by Pu-Be neutron source. The calibration factor was equal to

\[ 2.2 \times 10^{-4} \, \text{mrem cm}^2 \text{ track}^{-1} \]

NICOLAE: Je veux signaler que j'ai étudié, il y a quelques années, le "fading" de l'image latente dans les films d'émulsions nucléaires employées pour la dosimétrie des neutrons rapides et je me suis rendu compte que ce facteur joue un rôle très important pour des durées d'emploi des films allant jusqu'à un mois. Pour les films d'émulsion nucléaire, employés dans l'emballage original, dans les conditions ambiantes le pourcentage de la diminution de la densité des traces peut aller jusqu'à 50% au bout d'un mois et jusqu'à 25% pour les émulsions qui ont été conservées dans un emballage étanche de polyéthylène. Il faut donc accorder une grande importance au fading des traces lors de l'établissement des doses dues aux neutrons rapides.

PORTAL: Pour répondre à votre observation et compléter mon commentaire précédent, je préciserai que ce procédé est généralisé en France et, à ma connaissance, a été adopté par quelques laboratoires étrangers.

Dans notre seul laboratoire, nous traitons ainsi depuis 1962, 6500 dosimètres individuels à NR chaque mois. On peut donc le considérer comme un procédé parfaitement "Opérationnel".

Je me bornerai à faire un bref commentaire au sujet de la description des traces dans les émulsions nucléaires. Je crains que ce commentaire ne paraisse pas très original, car il se rapporte à des travaux assez anciens que nous avons publiés à la conférence de Madrid en 1963.

Depuis les travaux de Faraggi et al., on sait que ce phénomène est consécutif à une oxydation des grains de bromure d'argent, oxydation qui entraîne une régression de l'image latente. Elle est favorisée par le pH de l'émulsion et la température de conservation. On ne peut cependant
agir sur ces deux paramètres. Par contre, nous avons montré que si l'on
dessèche les dosimètres à émulsions nucléaires et si on les emballe sous
atmosphère d'azote dans des matériaux étanches, tels que les complexes
thermosoudables "Aluminium-Polyéthylène", le "fading" est pratiquement
négligeable même après 1 ou 2 mois de conservation.

Nous avons effectué les essais pour des irradiations de neutrons de
14 MeV et 2,5 MeV; nous n'avons pas d'expérience pour les énergies in-
férieures.