Neutron focus in beryllium in a synchrotron-radiation field

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It is shown that in a synchrotron-radiation field it is possible to generate pulsed photoneutron fluxes of unprecedented space-time and spectral density. Possible new experiments are indicated.

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In recent years, progress in nuclear physics and solid-state physics has raised a number of problems that call for considerable improvements in the parameters of the pulsed neutron currents (for example, the problem of developing a γ laser). The known methods make is possible to study fluxes of thermal and resonant neutrons $\lesssim (2\text{–}3)\times 10^{16}$ neut/cm²sec at a generation density $\lesssim 10^{16}$ neut/cm³sec and at a pulse duration $\gtrsim 10^{-6}$ sec.[1] This limit is mostly the result of the large exothermy of the employed reactions and the high average spectral energy which sets the moderated-neutron losses at a value $\sim$0.02–0.1.

In the present paper is proposed a neutron-generation principle free of these shortcomings. It is based on the reaction of photoproduction in ${}_4\mathrm{Be}^9$ in the field of hard synchrotron radiation. This synchrotron radiation, with energy of several hundred keV at the maximum of the spectrum, is formed by a current of ultrarelativistic electrons in a magnetic field H of several dozen kOe. The principle differences and advantages of the method are due to the combination of the following properties:

1) High brightness of the synchrotron radiation, which ensures a large neutron-generation density; 2) The anomalously low threshold of the (γ,n) reaction in ${}_4\mathrm{Be}^9$ and the abrupt change in the cross section near the threshold $E_0 = 1.665$ MeV, which make it possible to obtain a soft neutron spectrum *without moderation* and to eliminate the indicated intensity losses; 3) The pulsed character of the synchrotron radiation, which makes it possible to generate ultrashort neutron pulses with duration $\sim 10^{-9}\text{–}10^{-10}$ sec; 4) the low number of Be and low energy of the employed γ quanta result in minimal radiation losses in the target per produced neutron. Since the divergence angle and area of the synchrotron radiation source are small ($\sim 10^{-4}\text{–}10^{-5}$ rad and $\sim 10^{-2}$ cm²), the effective volume of the generation region does not exceed 1 cm³, and its radius is much shorter than the mean free path of γ quanta of energy $\sim E_0$. Such an axially symmetrical source can conveniently be called a "neutron focus" (NF).

The spectral density of the NF is determined by the expressions

$$N(E_n) \approx N_{0\gamma}\frac{A}{A-1}\,\xi(E_\gamma, E_c, E_0)\frac{1}{E_0}\left(1 + \frac{A}{A-1}\frac{E_n}{E_0}\right)^{-1}, \tag{1}$$

$$\xi(E_\gamma, E_c, E_0) = \eta\left(\frac{E_\gamma}{E_c}\right)\frac{\Sigma_{\gamma n}}{\mu_\gamma}\left(1 - e^{-\mu_\gamma x_0}\right), \tag{2}$$

where $N_{0\gamma}$ is the integrated intensity of the synchrotron radiation, A is the mass of the target nucleus, Σ_{vn} is the macroscopic cross section of the (γ,n) reaction, μ_γ is the coefficient of attenuation of the γ quanta in a target of length X_0 in the direction of the synchrotron radiation beam, $\xi(E_\gamma,E_c,E_0)$ is the spectral neutron-yield function, $\eta(E_\gamma/E_c)$ is the spectral synchrotron-radiation function, which has in the region $E_\gamma \gg E_c$ the form $(E_\gamma/E_c)^{1/2}\exp(-E_\gamma/E_c)$, and $E_c \sim E_\beta^2 H$, is a parameter that determines the position of the maximum in the synchrotron-radiation spectrum. The neutron yield is determined by $\Sigma_{\gamma n}/\mu_\gamma$ and in the case of ${}_4\mathrm{Be}^9$ amounts to 2.5×10^{-3} neut/qu near the threshold. The function η and of the cross section $\sigma_{\gamma n}$ of Be are plotted in Fig. 1, while the spectrum of the photoneutrons is shown in Fig. 2. The results of precision measurements of $\sigma_{\gamma n}$[2] were used for the calculation. The spectrum

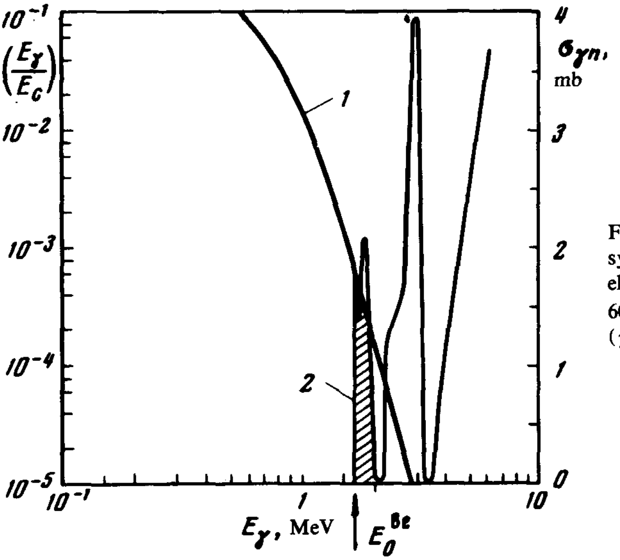

FIG. 1. Spectral function of the synchrotron radiation formed by electrons with $E_\beta = 7$ GeV in a field 60 kOe (1) and the cross section of (γ,n) in ${}_4Be^9$ near threshold (2).

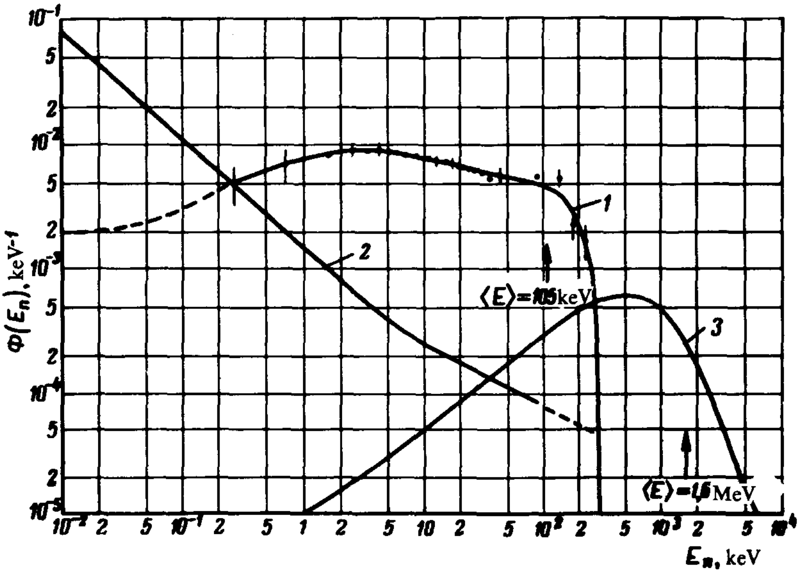

FIG. 2. NF spectrum (1), spectra of photoproduction neutrons in U(3) and moderated neutrons in H_2O (2), normalized to 1. The errors of the measurement of $\sigma_{\gamma n}$ of ${}_4Be^9$ and the average energies of the production spectra are indicated.

differs in having a high neutron density in the resonant region and low values of the average and end-point energies. The behavior of the spectrum in the thermal region can be traced only qualitatively, owing to a lack of data on $\sigma_{\gamma n}$ below $E_\gamma - E_0 = 0.5$ keV. Extrapolation of the results of[2] to zero shows, however, that in the thermal region, too, an appreciable neutron density is preserved because of the recoil of the nucleus upon absorption of a γ quantum and because of the cancellation of the decrease of $\sigma_{\gamma n}$ by the exponential increase of η. Also shown are the spectra typical of the reaction $(\beta \to \gamma, n)$.

The integrated characteristics of the NF were calculated for synchrotron radiation produced in a stationary or pulsed spatially-periodic field of length ~5 m by an electron beam with parameters typical of the storage ring VEPP-4 of the Institute of Nuclear Research of the Siberian Division of the USSR Academy of Sciences.[3] The calculation was performed at a synchrotron-radiation pulse repetition frequency $\nu \approx 10^6$ Hz and for $\nu \approx 20$ Hz, obtained by extracting the electrons into a channel with a pulsed field ~250 kOe. The results of the calculation are given in Table I, where they are compared with the data for a neutron source using the reaction $(\beta \to \gamma, n)$ in

TABLE I.

	Source / Parameters	NF, VEPP-4 GeV Be (γ, n), $E_\beta = 7$ GeV		Linear electron amplifier U$(\beta \to \gamma, n)$, $\nu \doteq 900$ Hz, H_2O = Moderator.
		$\nu = 10^6$ Hz, $\langle H \rangle = 60$ kOe	$\nu = 20$ Hz $H \approx 250$ kOe	
Pulsed	Pulse duration, sec	10^{-10}	10^{-10}	10^{-7}
	Intensity, neut/sec	3×10^{16}	3.5×10^{20}	2×10^{16}
	Flux, neut/cm²sec	$2.5\cdot10^{15}$	3×10^{19}	3.5×10^{13}
	Gen. density, n/cm³sec	$1\cdot10^{17}$	1×10^{21}	2.5×10^{13}
Average	Intensity, neut/sec	3×10^{12}	2×10^{12}	2×10^{12}
	Flux, neut/cm²sec	2.5×10^{11}	1.5×10^{11}	3×10^{9}
	Gen. density, n/cm³sec	1×10^{13}	6×10^{12}	2.5×10^{9}
	Power in target, kW	0.3 1)	0.3	4.0
	Quality, neut/sec	$3\cdot10^{32}$	2×10^{32}	2×10^{26}
	Effective gen. volume, cm³	0.3	0.3	785 2)
	Radiation losses in target, MeV/neut	450	450	1250 3) 13000 4)

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1) With allowance for filtering the synchrotron radiation below E_0.

2) Moderator volume, thickness 3 cm.

3) Per neutron produced in the target.

4) Per neutron moderated to an energy 10–3×10^5 eV.

the energy region $E_n = 10–3 \times 10^5$ eV (the linear electron accelerator of the Kurchatov Institute[4]). The quality parameter is defined as the ratio of the average intensity to the square of the pulse duration.

It is obvious from the presented data that the NF is promising. Thus, even at the VEEP-4 storage ring parameters the NF is comparable with respect to the generation density and the flux with the best of the presently designed pulse sources–the strong-current 800-MeV proton synchrotron of the Argonne National Laboratory (1985 project).[1] When the field and the electron energy are increased, the "brightness" of the NF increases rapidly on account of the function η and of the increase of the shaded area under the $\sigma_{\gamma n}$ curve in Fig. 1. At the realistic increase of E_β to 15–20 GeV,[3]the average data of Table I should be multiplied by a coefficient $\sim 5 \times 10^3$, while the pulsed data should be multiplied by $\sim 2 \times 10^4$. The quasistationary neutron flux then reaches the contemporary record (HFR reactors), while the pulsed flux reaches $\sim 10^{20}$ neut/cm^2 sec. The latter can be obtained by using a pulse field of ~ 250 kOe without increasing E_β.

The presented NF parameters may turn out to be sufficient for the study of $n-n$, $\beta-n$, and $\gamma-n$ interactions. The properties of the NF (large pulse flux at ultrashort duration, characteristic form of the spectrum with maximum in the resonant region, and minimal Compton losses in Be) are apparently adequate to the conditions of realizing induced coherent nuclear γ radiation.[5] The NF will make it possible to study for this purpose the spatial, energy, and (principally) temporal parameters of the coherent processes in resonant absorption and scattering of neutrons in crystals. It is not excluded that in such experiments one can observe neutron isomerism of nuclei.

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