sec is possible; the time required for the operation of the modulator is $\sim 3 \times 10^{-8}$ sec.

These figures clearly indicate the advantage of using image converters with localized mesh-dynodes which make possible the combination of fast image-electron accumulation at the anode, easily controlled resolving power at the output, and practically complete freedom from spurious scintillations on the output fluorescent screen for large values of the multiplication factor (down to $K \sim 10^9$). These features permit ultrafast photographic recording (during the accelerating pulse which may last for a time of several milliseconds) of developments in unusual processes under conditions of high noise and radiation backgrounds and they justify certain technical difficulties in the fabrication of fine-mesh dynodes of large dimensions (areas of 300 cm^2). Mesh tubes have the advantages of speed of operation, ease of control and reduction of noise as compared with multiple conversion tubes (for example, the tandem cascade tube due to Holst[2]) in which the intensification of the electronic image is accomplished at the expense of a long overall delay due to the delays (for luminescent phosphors suitable for use in vacuum devices) connected with the emission in the intermediate fluorescent screens.

Some general shortcomings of electron-optical detectors should be noted; the existence of distortions connected with the electron-optical conversions, the variations in the localized conversion parameters, the need for continual localized calibration of the apparatus if it is used for comparative measurements, the difficulty in obtaining stereoptic pictures of the tracks -- all these are substantial obstacles to the reproduction of an accurate picture of the interaction process. However, the inherent positive features of luminescent-electronic detection of elementary events -- the high detection efficiency, the high resolving power, the inertialess operation, the small dead time in detection, the comparative simplicity of transmitting the electronic image of the track and the ease of synchronous operation with a pulsed source of ionizing radiation indicate that this instrument may become a powerful experimental tool in cases where the reconstruction of a qualitative picture of an elementary process is needed in the search for new types of reactions.

Note *added in proof:* in a paper which appeared recently[3] there was reported the sucessful application of the idea of using an image converter for recording tracks of ionizing particles; however, no information was given concerning the image-converter which was used.

* This note is based on a thesis submitted to the physics faculty of Moscow State University by the writer in 1951.

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High Threshold Scintillation Neutron Detector

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(Submitted to JETP editor January 25, 1955)
J. Exper. Theoret. Phys. USSR **28**, 621-623(May, 1955)

AT the present time, most existing methods for detecting high energy neutrons (threshold detectors, the observation of the proton recoils) are characterized by a low efficiency-approximately 10^{-4} to 10^{-3}. Only in the last few years have scintillation liquids of large volume been used, permitting the detection of neutrons by proton recoils with an efficiency as high as 10%. However, these counters have a rather high sensitivity for undesirable background (for example, a γ-ray background). The methods using them and in particular the analysis of the results are rather complicated. In connection with these there is presented an interesting possibility of developing a simple and sufficiently efficient detector of high energy neutrons. In principle, the operation of this detector can be expressed by the reaction $C^{12}(n, 2n)C^{11}$, with a threshold at 20.2 Mev. A positron-emitting isotope, C^{11}, is formed, with a half-life of 20.2 min, and with the maximum energy of the β^+-spectrum being about 1 Mev. If ordinary graphite detectors whose activity is detected by means of a Geiger counter are used for observing this reaction, then the sensitive operating thickness of the detector is limited by the range in graphite of the positrons from the decay of C^{11}. This range is approximately equal to 300 microns. If the carbon which is activated by the high energy neutrons is a chemical constituent of an organic phosphor, and if the decay is detected by the subsequent light flashes in the phosphor, then it is possible to increase the sensitive operating thickness of the detector by factors of

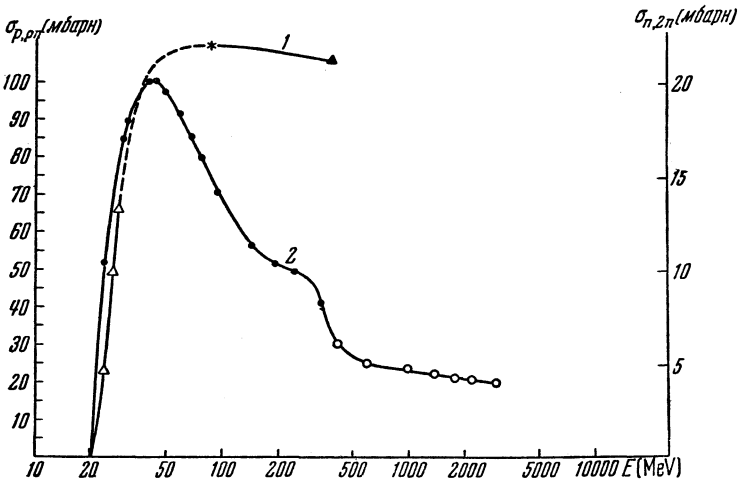

FIG. 1. $1-C^{12}(n,2n)C^{11}$; $2-C^{12}(p,pn)C^{11}$ from the data*-ref. 1, ▲-ref 2, Δ-ref. 3, ●-ref. 4, O-ref 5.

ten and one hundred. The reaction $C^{12}(n,2n)C^{11}$ was mainly used as a detector of high energy neutrons because the cross-section of the reaction remains practically constant in the neutron energy interval from 90 Mev (22×10^{-27} cm^2) [1] to 380 Mev (21.4×10^{-27}cm^2) [2]. In Fig. 1 is shown the excitation function for the reaction $C^{12}(n,2n)C^{11}$ (from the data of references 1-5), and for the similar reaction $C^{12}(p,pn)C^{11}$ up to proton energies of 3 Bev (from the data of references 4,5). From Fig. 1 it is obvious that with the aid of a detector, detecting the positrons from the decay of C^{11}, it would be possible to investigate both neutrons and protons with almost identical sensitivity over an extremely wide energy interval.

Use has been reported in the literature[6] of a scintillation detector (anthracene) in which the flashes of light from the decay of C^{11} were detected, but no definite description of the method was given. In the meantime, the usefulness of an organic crystal for observing the decay of C^{11} is in itself obvious, but the main practical difficulty of this method is the inability of obtaining the needed data with a minimum of unwanted background. Since most of the positrons from the decay of C^{11} have energies of about 100 kev, the noise arising from the photomultiplier (PM) was a hinderance. From the two widely used methods of decreasing the noise of a photomultiplier – strongly cooling the photomultiplier or using a coincidence scheme, which only detects those pulses in coincidence – we chose the latter for its simplicity and directness.

A block-diagram of the layout is shown in Fig. 2. A crystal phosphor (stilbene or tolan) in cylindrical form, 35 mm in diameter and 17-20 mm in thickness (weighing 18-24 gm), is placed between two photomultipliers, PM-19, close to their photocathodes. Pulses formed by the photomultiplier ($RC \approx 6 \times 10^{-8}$ sec) were passed through a cathode follower, were shaped by a shorted line, and were fed into a coincidence unit. The resolving time of the coincidence method is $\tau = 1.6 \times 10^{-8}$ sec for the case when the efficiency of the system is 50% for the detection of positrons from the decay of C^{11} in tolan. The absolute efficiency for detecting the decay of C^{11} was determined by comparing the activity of the crystal with the activity of an identically irradiated standard graphite detector. In an independent experiment, the ratio of the operating efficiency and the total mass has been determined. For the case of a high energy neutron field, $\pi = 20$ neutrons/cm^2 sec, a tolan crystal produces, for a 20 minute irradiation, an activity equal to ~ 0.1 sec^{-1}. The problem concerning the exactness of the measurement in detecting such a small neutron flux is affected by the detector's dependence on the value of the background and is approximately given by the tolerance dose of the neutrons.

Under the conditions of our experiment, the background of chance coincidences of the noise pulses was negligibly small (~ 0.005 sec^{-1}). It was assumed that the largest source of background counts was due to cosmic radiation and radioactive contamination (~ 0.7 sec^{-1}). The background

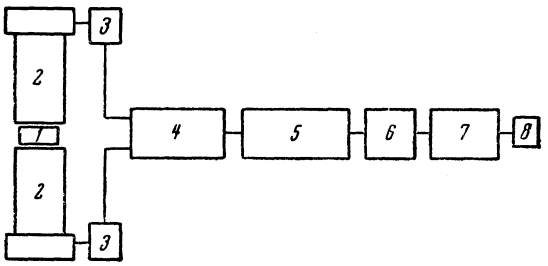

FIG. 2. Block diagram of the circuitry. *1* crystal; *2* PM-19; *3* cathode follower; *4* coincidence unit; *5* amplifier; *6* discriminator; *7* electronic counter; *8* mechanical counter.

coming from cosmic rays can at least partly be removed by placing over the scintillation detector a layer of Geiger tubes connected in anticoincidence. Experiments have shown, however, that the presence of a background from other sources is approximately equal to 0.7 sec^{-1} when the PM has 1500 volts applied to it. The background sharply increases when the voltage is increased. While the background of cosmic and radioactive origin was removed on removing the crystal, on the other hand, another source of background was increased.

This additional background was completely removed by any thick opaque screen (aluminum foil, black paper), between the photocathodes of the two photomultipliers. In such a manner, the presence of coincidence background due to "optical coupling" was removed. By using the photomultiplier scheme PM-19-P (with "new surface") the effect (of optical coupling) showed up only in a very insignificant degree even with voltage supply of the photomultiplier, insuring an almost 100% efficiency for detecting the positrons from the decay of C^{11}.

In the experimental arrangement cited above, for a neutron flux $\pi = 20$ neutrons /cm^2 sec, the effective quantity in the phosphor was the 10 gm of carbon. Even for a background counting rate of ~ 1.4 sec^{-1} (i.e., without correcting for cosmic-ray background and "optical coupling" of the PM) the above indicated value of high energy neutron flux can be determined with an accuracy of 45% (for a 20 min exposure of the crystal and with optimum time for observing the decay of C^{11}, equal in this case to $\sim$ 38 min). Yet, even without additional improvement, the above described detector can be used as a dosimeter of high energy neutrons. We used this detector for observing the yield and angular scattering of high energy photoneutrons from various nuclei. In the general case, the accuracy of the measurement of the high energy neutron flux π by means of a crystal, in which

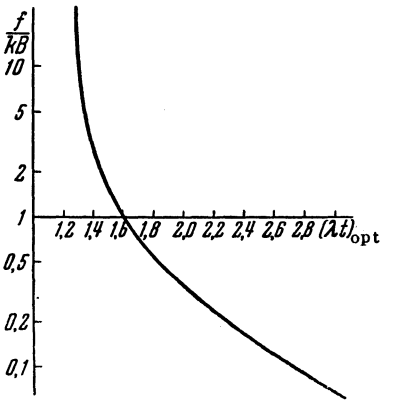

FIG. 3. Curve for determining the optimum length of time for observing the decay of C^{11}

N_{eff} carbon nuclei perform efficiently, is determined by the relationship

$$\delta = \sqrt{ft + A(1-e^{-\lambda t})} \quad A(1-e^{-\lambda t}), \qquad (1)$$

where $f(sec^{-1})$ is the background counting rate, λ, is the decay constant for C^{11}, t is the length of time for measuring the decay,

$$A = \frac{k}{\lambda} B = \frac{k}{\lambda}(1-e^{-\lambda\tau}), \quad k = \Pi N_{эфф}\sigma_{n,2n}\, e^{-\lambda T} \qquad (2)$$

and τ is the length of time of the exposure, and T is the interval of time from the exposure until the beginning of the counting of the decay of C^{11}.

For every given value of f/kB there is an optimum length of time for observing the decay of C^{11}. For determining this quantity see the curve in Fig. 3

A detector for high energy neutrons using the reaction $C^{12}(n,2n)C^{11}$ is sensitive to a γ-ray background only in a relatively narrow range of dipole "resonance" (near 22 Mev) because of the photonuclear reaction $C^{12}(\gamma,n)C^{11}$. The integral cross-section for the whole resonance range (breadth about 10 Mev) consists of about 0.05 Mev-bn [7].

The authors express sincere thanks to A.V. Kutsenko and T. I. Kovalev for valuable aid in preparing the apparatus for our work.

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Maximum Yield of Photoneutrons and a New Method of Determining the Integral Cross-Section of (γ, n) Reactions for High Energy Photons

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J. Exper. Theoret. Phys. USSR **28**, 623-626 (May, 1955)

DURING the past year, thanks to the use of the new methods of electron acceleration -- the betatron and the synchrotron -- a wide range of photonuclear reactions, originating under the action of hard bremsstrahlung, was investigated. It was soon established that for a series of photonuclear reactions, the dependence of the cross section on the photon energy was characterized by the presence of a maximum at the energies in the range 10-25 Mev. The cross section decreased rapidly on both sides of this maximum.

The characteristic resonance character of the excitation function of photonuclear reactions is connected with the excitation in the resonance region of the nuclear dipole oscillations, the theory of which was first given by Migdal[1]. Among the widely investigated photonuclear reactions posessing dipole resonances were reactions producing photoneutrons. In the experiment the following characteristics of the photonuclear reactions were determined: the threshold energy of γ-quanta, E_p, the resonance energy, E_r, as determined by the maximum in the cross section, the half-width of the resonance peak, ΔE, the maximum cross section for the reaction, σ_r, and the integral cross section $\int \sigma(E)\,dE = \sigma_{int}$. All of these characteristics were determined for independent reactions of the type, (γ, n), (γ, pn), $(\gamma, 2n)$. In most of the work these reactions were identified by radioactive isotopes that were produced. By far the smaller amount of work was that in which a neutron detector detected all the neutrons having been emitted by the elements under investigation (for papers or reported work on the production of photoneutrons see references 2, 3). Thus, the yield of photoneutrons in an independent (γ, n) reaction was shown to be similar to the total yield of photoneutrons for the given isotope. From this fact it is possible to conclude that the basic source for the production of photoneutrons, even at high maximum energy of the bremsstrahlung (320 Mev), is the simple (γ, n) reaction.

As a rule, in photonuclear investigations, thin samples have been used as photoneutron sources in which there has been no electro-photon multiplication of the emitted γ-quanta. In our work another goal was set -- the determination of the yield of photoneutrons under the conditions of total development of the electron-photon shower, i.e., the determination of the maximum coefficient for converting photons into neutrons. Thus, the measurements gave, simultaneously, the possibility of determining the integral cross section of the reaction producing the photoneutrons, as well as the possibility of using the equilibrium condition from shower theory[4], i.e., integrating according to the depth of the shower neutron spectrum, produced by the primary γ-quanta with dimensionless energy, ϵ_0 (where $\epsilon_0 = 2.29\,E/\beta$, and β is the critical energy for the given substance):

$$\Gamma_\Gamma(\varepsilon_0, \varepsilon) = (1/\beta\mu(\varepsilon))\,[\chi(\varepsilon_0, \varepsilon)\,\varepsilon_0/\varepsilon + 2{,}29\delta(\varepsilon_0 - \varepsilon)].$$

Here

$$\chi(\varepsilon_0, \varepsilon) = \varepsilon e^{\varepsilon}\int_{\varepsilon}^{\varepsilon_0} e^{-x}\frac{dx}{x^2} - \frac{\varepsilon}{\varepsilon_0^2}[1 - e^{-(\varepsilon_0-\varepsilon)}],$$

and the dimensionless cross-section for the absorption of the neutrons is

$$\mu(\varepsilon) = \sigma(E)\,Nt,$$

where N is the density of the substance (in number of nuclei per cm^3), and t is the unit shower length (in cm).

It is obvious that the maximum yield of photoneutrons from an infinite mass of the substance is

$$Q_{max} = \int_{E_1}^{E_2}\frac{\sigma_{\gamma n}(E)\,dE}{Nt}\int_{\varepsilon_1}^{\varepsilon_m}\Gamma_\Gamma\frac{ad\varepsilon_0}{\varepsilon_0},$$

where E_1 and E_2 are the lower and the upper limits of the resonance region, $\sigma_{\gamma n}$ is the photonuclear cross section of the reaction for the formation of photoneutrons, and the emitted spectrum of the bremsstrahlung takes the form $f(\epsilon) = a/\epsilon$ (we note, that for a calculation on the equilibrium spectrum this approximation gives a smaller error than for a direct determination of the cross section in a calculation of this form).

The first integration produces the result

$$Q_{max} = a\int_{E_1}^{E_2}\frac{\sigma_{\gamma n}(E)\,dE}{\sigma_{absorp}(E)\,E}\left[1 + \frac{I(\varepsilon)}{2.29}\right],$$