

A PHOTONEUTRON SOURCE BASED UPON AN ELECTROMAGNETIC UNDULATOR

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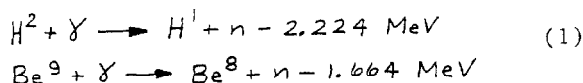
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Introduction

In 1978, Ereemeev [1] suggested that a bright, pulsed source of low-energy neutrons (no moderation required) could be realized by directing a low-divergence beam of high energy photons from an electron synchrotron along the axis of a thread-like target of beryllium; neutrons would then be produced via the photonuclear reaction $\text{Be}^9 + \gamma \rightarrow \text{Be}^8 + n - 1.664 \text{ MeV}$. A few years later, Baldwin [2] pointed out that one could not only (a) significantly reduce the deposition of heat in the target but also (b) dramatically narrow the energy distribution of the emitted neutrons by illuminating the target beryllium atoms not with the wide-band output of a bending magnet (as proposed by Ereemeev) but rather with the quasi-monochromatic output of a magnetic undulator. In the paragraphs below, we make the following points: First, if one is interested in obtaining (without moderation) low-energy neutrons in the energy range of say 0-100 eV, then the reaction $\text{Be}^9 + \gamma \rightarrow \text{Be}^8 + n - 1.664 \text{ MeV}$ is of no interest. Rather, one should concentrate on the reaction $\text{H}^2 + \gamma \rightarrow \text{H}^1 + n - 2.224 \text{ MeV}$. Second, if as a result of future advances in accelerator technology it becomes possible to produce intermediate energy ($E \sim 1 \text{ GeV}$), high current electron beams with both very high energy purity ($\Delta E/E < 10^{-5}$) and low divergence ($\Delta \theta_e < 10^{-6}$), then it should be possible to produce MeV photon beams with similarly outstanding properties (as regards energy purity and angular divergence) by passing the electron beam through an electromagnetic undulator consisting of a high-power, pulsed wave of CO_2 laser radiation travelling counter to the electron beam. And third, such a narrow-band, highly-directional photon beam--when tuned to the proper energy above the photonuclear reaction threshold--should permit the generation of low-energy neutrons having a high degree of correlation between energy and angle of emission, provided that this correlation is not destroyed by the irreducible zero-point motion of the target atoms. A neutron source with a high degree of correlation between energy and angle of emission would have a high brightness (= neutrons/time/source area/solid angle of emission) and would be of interest in connection with both neutron microscopy [3] and the pumping of a γ -ray laser [4]. The results described below are necessarily preliminary; detailed calculation of the many points raised will be published later.

Low-Energy Neutrons Without Moderation

The two photoneutron reactions with the lowest thresholds are



Each reaction is a simple two-body process whose kinematics--at least for the simplest case of a photon incident upon a stationary target atom--are easily worked out either nonrelativistically [5] or relativistically [6]. In view of the low energies involved in the above reactions, the nonrelativistic

treatment by Amaldi is entirely adequate for the calculations described below. The relativistic treatment by Jackson is of interest, however, not only because of the additional insights it provides but also because Jackson's calculation (based upon the Lorentz invariance of the scalar product of two four-vectors) can more easily be generalized to include the effects of the heat motion (or zero-point motion at absolute zero of temperature) of the target atoms.

According to Amaldi, when the incident photon energy just exceeds the threshold energy, neutrons are emitted with a fixed energy only in the forward direction. As the photon energy is increased, neutrons are emitted into a forward cone whose limiting half-angle increases monotonically with the photon energy. At each angle within the cone, except at the edge, there are emitted neutrons having two distinct energies, corresponding to the fact that neutrons emitted with equal energies at two different angles in the CM system are observed at some corresponding single LAB angle to have two different energies. The neutrons emitted in the CM system at the smaller of the two angles--hereafter referred to as Group I neutrons--will always have higher energy in the LAB system than the Group II neutrons which were emitted at the larger CM angle. In Eqs. (34.9) and (34.10) of his work, Amaldi gives complicated expressions for Thresh (θ_{max})--the incident photon energy required to cause neutron emission into a cone with limiting half-angle θ_{max} --and $E(\theta)$ --the kinetic energies of the emitted neutrons as a function of incident photon energy, laboratory angle of neutron emission, and the masses of the atoms involved.

If one uses atomic masses from Gibson [7], one finds after a bit of numerical calculation that for a given photon energy lying between Thresh (0°) and Thresh (90°), Group I (faster) neutrons decrease in energy with increasing LAB angle whereas Group II (slower) neutrons increase in energy. In addition, Group II neutrons stay within the energy range of interest--roughly 0-100 eV--for all angles of emission only if the incident photon energy is close to Thresh (90°). Evaluation of Amaldi's Eq. (34.10) gives for Be^9 , Thresh (90°) = Thresh (0°) + 20.8 eV, and for H^2 , Thresh (90°) = Thresh (0°) + 1322.8 eV. Since H^2 and Be^9 have photoneutron cross sections [8,9] which peak at approximately 1 mb at $\sim 10 \text{ KeV}$ and 6 KeV above threshold, respectively, and decrease rapidly with decreasing energy below the peak, we expect H^2 to be far more effective than Be^9 as a generator of low-energy photoneutrons. In the case of H^2 , one finds for an incident photon energy = Thresh (85°) = Thresh (0°) + 1312.3 eV that Group II neutrons vary in energy between $0.96 \times 10^{-2} \text{ eV}$ (0°) and 5.0 eV (85°). If the photon energy is increased just 6.4 eV to Thresh (87°) = Thresh (0°) + 1319.2 eV, then Group II neutrons vary in energy between $0.12 \times 10^{-2} \text{ eV}$ (0°) and 0.37 eV (86°).

The energy purity required of the incident photons if there is to be a significant correlation

between neutron energy and emission angle is obviously very high. In addition, it should be noted carefully that the simple calculation above does not include the correlation-reducing effect of the thermal motion of the target atoms! But given that some of the neutrons of a pre-specified energy "cooperate" by leaving the thread-like target at the proper angle θ , how does one go about forming a parallel beam from these obliging particles? One possibility would be to surround the thread-like target with a truncated conical surface having its axis coincident with that of the thread. If the inside surface of the conical surface could be coated with a multilayer thin film neutron reflector [10], then proper selection of the apex angle of the cone and the composition of the multilayer could ensure that neutrons leaving the target at angle θ would be diffracted through such an angle so as to ensure their leaving the diffracting surface in a direction parallel to the target axis.

Undulator Generation of High Energy X-Rays

To proceed further, we require a number of fundamental results from the theory of (helical) undulators [11,12]:

$$\lambda = \frac{\lambda_u}{2\gamma^2} \left[1 + K^2 + \gamma^2 \theta^2 \right] \quad (2)$$

$$K = \frac{e B \lambda_u}{2\pi m c^2} \quad (3)$$

$$= 0.934 \times 10^{-4} B (G.) \lambda_u (cm)$$

$$\left(\frac{\Delta \omega}{\omega} \right) = \frac{1}{N} \quad (4)$$

$$\Delta \theta \sim \frac{1}{N^{1/2} \gamma} \quad (5)$$

$$\left(\frac{\Delta E}{E} \right)_e < \frac{1}{N} \quad (6)$$

$$\Delta \theta_e < \frac{1}{N^{1/2} \gamma} \quad (7)$$

Eq. (2) gives the wavelength λ of the undulator radiation emitted in the fundamental frequency at a small angle θ to the axis. Here λ_u = undulator period and $\gamma = (E/mc^2)$, where E = total electron energy. The so-called undulator parameter, K (Eq. (3)), depends upon both the undulator period and the on-axis transverse magnetic field B . The undulator radiation emitted on-axis has a homogeneously broadened full spontaneous width at half maximum given approximately by Eq. (4), where N is the number of undulator periods. Eq. (5) represents an approximation to the half-angle of the cone about the undulator axis into which the major part of the radiation at the peak of the power spectrum is emitted [11]. And finally, Eqs. (6) and (7) describe the very stringent requirements which must

be satisfied by the electron beam as regards energy purity and angular divergence if Eqs. (2)-(5) are to be valid at all.

From Eq. (4) above, it follows that to obtain undulator radiation with a high spectral purity, one requires an undulator with a large number of periods, N . If the undulator is to be of a reasonable length for N of the order of 10^5 - 10^6 , one requires the period length λ_u to be of the order of tens of microns or smaller. Let us therefore perform a simple calculation assuming that the undulating medium consists of a high-power, pulsed travelling wave of CO_2 laser radiation confined to the interior of a copper tube waveguide. Confinement of the wave to the interior of a waveguide prevents diffractive spreading of the wave and allows the wave intensity to be kept high and unattenuated over a long interaction length [13]. Assume, as in [13], that a CO_2 laser pulse of 10 GW power is launched into a waveguide with radius 0.4 cm. For simplicity, assume the propagating beam has the profile of a plane wave. We then have a power density of 1.99×10^{10} W/cm². A simple Poynting vector calculation gives an associated undulator magnetic field $B = 9310$ G. Since the beam electrons travel with speed $\sim c$ counter to the travelling wave of CO_2 radiation, the effective undulator length is not 10.6 μ but rather 5.3 μ [12]. Inserting $\lambda_u = 5.3 \mu$, $B = 9310$ G, $\lambda = 0.00557$ A (the wavelength of a photon with $E = 2.225$ MeV) and $\theta = 0$ (on-axis viewing) into Eqs. (1) and (2), one obtains $K = 0.45 \times 10^{-3}$, $\gamma = 2181$, and therefore E (electron) = 1.12 GeV. If one desires to have a photon spectral purity of 10^{-5} , one requires $N = 10^5$. From the equations above, one then obtains $\Delta \theta \sim 1.45 \times 10^{-6}$. In addition, the electron beam energy purity and angular divergence must be smaller than 10^{-5} and 1.45×10^{-6} , respectively. Note, finally, that quantum effects can be expected to be severe when a 1.12 GeV electron emits a 2.225 MeV photon!

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