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THE YIELD OF RESONANCE NEUTRONS FROM A THICK COPPER TARGET
BOMBARDED BY ELECTRONS WITH ENERGIES UP TO 100 GeV

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ABSTRACT

The yield of low-energy neutrons at 90° from a copper target bombarded by high-energy electrons varies from $0.015 \text{ GeV}^{-1} \cdot \text{sr}^{-1}$ at 20 GeV to $0.035 \text{ GeV}^{-1} \cdot \text{sr}^{-1}$ at 100 GeV. This yield is higher than would be expected from calculations based on the yield of giant resonance photo-neutrons alone. It is also shown that simple estimates of the yield from high-energy photon spallation interactions are unable to account for the measured values or their apparent dependence on energy. The measured yields are not incompatible with the approximate value of 0.33 GeV^{-1} recommended for use in shielding assessment at high-energy electron accelerators.

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1. INTRODUCTION

The neutrons produced via giant resonance photo-neutron reactions in electron-induced cascades can in certain circumstances make important contributions to the radiological hazard around electron accelerators when electrons of energies greater than 20 MeV are lost in accelerator structures [1]. Such circumstances are met in the design of cable ducts and maze entrances or in the specification of 'thin' iron shields, where the high-energy (greater than 150 MeV) hadronic component is not yet dominant and the bremsstrahlung component is preferentially absorbed by the shield of high atomic number. The neutron component could also be important when considering radioactivation of the accelerator structure or radiation damage to inorganic components, e.g. silicon diodes, placed near electron loss points in the accelerator.

The spectrum of giant resonance neutrons from targets bombarded by high-energy electrons is known to be similar to an evaporation or fission-neutron spectrum [2]. The neutron yield per incident electron when the cascade is fully contained within the target (the 'thick' target) has been measured for a number of materials mainly at energies lower than 100 MeV, see for example Barber and George [3]. Swanson has shown that the measured data agree well with predictions made by folding calculated photon track length distributions with published photo-neutron cross-sections [4,5]. Using this method for materials and energies where experimental information is lacking, he found a slow dependence of the yield on atomic number (as $Z^{0.73}$) and a sigmoid shape for the curve of the yield per unit beam power as a function of energy, resulting in a plateau above some 100 MeV. This would indicate that, provided the incident particle energy is well above the neutron production threshold, the neutron yield is only proportional to the total amount of energy in the electron-photon shower.

Given the current CERN commitment to the LEP project (a Large Electron-Positron storage ring), it appeared prudent to investigate the thick target yield in an accelerator construction material (copper) for which only low energy data are commonly available at electron energies up to the highest energy of the LEP project, 100 GeV.

2. DESCRIPTION OF THE EXPERIMENT

The electron beams used for these investigations were derived from the E4 beam in the North Experimental Area, EHN1, of the CERN 400 GeV Proton Synchrotron, the SPS. The beam characteristics are described by Coet [6]. Electron-beam intensities were measured with an installed counter-telescope and checked by ion-chamber comparisons and pi-minus beam activation studies as part of the preparation for this experiment. The steering of the electron beam on to the target and the physical size of the beam were confirmed by means of horizontally and vertically arranged multiwire chambers placed just upstream of the target.

The copper target, a cylinder 5 cm in diameter by 30 cm long (equivalent to 20.7 radiation lengths), was placed in a light cradle at a height of 1.27 m above the concrete floor. The neutron fluence was measured by using a precision long counter (PLC) [7] placed with its effective centre at a distance of 1.23 m from the target. An elementary goniometer arrangement allowed the counter to be moved around the centre of the target between angles of 30° and 150° relative to the beam axis. These dimensions and positions were chosen so as to avoid scattering problems as far as was physically feasible. The physical arrangement of the apparatus is shown in fig.1.

The experiment consisted of placing the PLC at the required angular position and measuring the total counts over

ten beam pulses. Beam conditions were monitored by means of beam counters and an Andersson-Braun Rem Counter [8] fixed at 1.4 m from the target. Beam intensities and the target-to-PLC distance were chosen to avoid saturation effects in the counters used. After completing measurements at each angular position, the target was removed and the measurements repeated at each angle in order to determine the contribution of neutrons coming from electron interactions in the beam windows, chambers, etc., upstream of the target. Corrections for these extra sources amounted to approximately 1% (4% in the 20 GeV experiment). Background measurements were also made at regular intervals with the E4 beam stopped but other adjacent beams in the experimental hall operational. This correction was approximately 2.5% (12% in the 20 GeV experiment). Corrections for both of these effects were applied on an individual rather than a global basis for each angular position and electron beam energy used.

3.RESULTS

The results of the angular distribution measurements are given in fig.2 for each electron beam energy used in this investigation, namely 20, 50, 80 and 100 GeV. The neutron yield is expressed in neutrons/steradian per incident electron. Apart from the 20 GeV case, the curves in fig.2 are symmetrical about the 90° point. The existence of a pronounced maximum at 90° contrasts with the general assumption of isotropy for giant resonance neutrons [9], and with a previous experiment with 6.3 GeV photons incident on copper [10]. A similar shape, however, was encountered in an experiment at the Stanford Linear Accelerator Centre using 7 GeV electrons [11], where the increased yield at 90° was explained by scattering effects due to the proximity of the walls. The angular distributions found in this experiment could be attributed to a basic anisotropy in the neutron emission mechanism, as has been suggested by some low-energy

studies [11,12], although the anisotropy in these investigations for copper as the target material is not evident. More likely the shape of the curve reflects secondary interactions of the neutrons before they leave the target. A crude estimate of this effect was made using a removal coefficient* of 0.173 cm^{-1} [13] and assuming a point-like neutron source located at the centre of the target. The yield curves corrected for absorption in the target which are shown in fig.3 seem to confirm an isotropic production.

An estimate of the magnitude of random errors on the measured yields was obtained from the distribution of the ratio of the PLC counts to the beam intensity monitor. Standard errors on the mean value amounted to 1% for the 50, 80 and 100 GeV measurements and 2.5% for the 20 GeV measurements.

Systematic errors on the fluence as measured by the PLC arise from two sources: the first depends on the position of the effective centre of the long counter and the second concerns the response of the PLC to neutrons of different energies. The magnitude of both of these errors depends on the form of the neutron energy spectrum.

An extensive investigation into the response of the PLC has been reported by Thompson et al [14]. They measured the energy dependence of the PLC and the variation of the position of the effective centre for a variety of neutron energies. The problem is to choose which of their spectral conditions matches most closely the energy distribution of neutrons in our experiments. Tesch compares spectra from high and low-Z targets published by various authors [15]. Kaushal et al. have published spectra for medium- and high-Z materials [16]. The energies of the photo-neutrons extend up to 30 MeV if a

* sometimes called the macroscopic removal cross-section.

light target such as aluminium is used, whereas the spectrum from lead is comparable to a fission spectrum. The mean energies of photo-neutrons from lead and aluminium are 1.9 and 5.3 MeV, respectively. That for a neutron spectrum from copper is 4.1 MeV, rather close to the value of 4.4 MeV for neutrons from an Am-Be neutron source. Hence we base our estimate of the position of the effective centre on this latter spectrum. At the target-to-detector distances used in this experiment an error of 1 MeV in the assumed mean energy of the spectrum would lead to an error in the fluence of 2% [14]; we therefore estimate that our error due to uncertainties in the position of the effective centre is 0.6%.

The neutron spectra of photo-neutrons from aluminium, copper and lead were folded into the response curve of the PLC. The response for a spectrum like that from aluminium, which extends significantly beyond 10 MeV, will be some 5% low for a PLC calibrated with Am-Be neutrons. For lead the difference is less than 1%. For a medium-Z material such as copper, the systematic error arising from the energy response of the PLC is practically zero.

Another source of systematic error could be pion contamination in the electron beam. In order to estimate the effect of this, a separate experiment using a 200 GeV pi-minus beam incident on a 1 cm diameter by 5 cm long copper target was performed. The Monte Carlo hadron cascade program FLUKA [17] was used to determine the total number of inelastic interactions in the target whose primaries had energies of greater than 50 MeV (stars) and thus, from measurements of the yield, the neutron yield to total star ratio. Similar calculations of the total number of stars were performed for the thick copper target of the electron experiments at pion energies equal to the electron energies used. These star totals were multiplied by the neutron/star ratio determined from the pion irradiation and by the calculated number of pions in the electron beams [18] to derive the proportion of

neutrons in the electron irradiations coming from the pion contamination. This proportion was always less than 1%.

4.COMPARISON WITH PREVIOUS STUDIES

Since previous studies have not corrected the measured neutron yields for absorption in the target, the uncorrected value of the neutron yields from the experiments described here will be used in the following comparisons. In addition for most practical purposes such as shielding assessment this self-absorption is unimportant. The yield figures used are the number of neutrons per steradian at an angle of 90° taken from fig.2.

Data from experiments covering a wide range of energies are given in fig.4. For ease of comparison the yields have been divided by the incident electron energy in GeV. The low-energy data of Barber and George [3] are for a copper target about 4 radiation lengths long: the diameter is not given. Neutrons were detected by a set of moderated boron tri-fluoride counters in a nearly four-pi assembly. The point at 6.3 GeV was measured at DESY [10] with a target of about 17 radiation lengths long and a diameter of 5 cm. Several neutron detectors were used in this experiment. The data point given here refers to the neutron fluence as measured by thermal neutron activation of an indium foil inside a paraffin wax moderating sphere of 15 cm diameter. Of the detectors used, the response of this moderator compares most closely with that of the long-counter used here. It should be noted that an incident bremsstrahlung beam was used instead of electrons, but the results are normalized in terms of equivalent 6.3 GeV quanta. The 7 GeV data are taken from DeStaebler et al. [11]. The copper target was 16 radiation lengths long and had a diameter of 8 cm. Another measurement reported in the same reference has not been included in fig.4 since the yield is at least a factor of three higher than the

data reported here. The point at 15 GeV [19] has been included because it represents the highest energy measurements reported until the time of these experiments. It is not as reliable as the other points in fig.4 since it is an extrapolation of measurements made outside shielding around the target using a rem-meter. In addition the target material was iron and not copper. A correction was applied using the $Z^{0.73}$ power law mentioned previously [4,5].

Fig.4 also shows a curve calculated by Swanson [4,5] as described above. We have made similar calculations for the electron energies of our experiments but have generated the photon track length distributions using the electron-photon shower code EGS [20]. The points at 50, 80 and 100 GeV, although in approximate agreement with the lower energy plateau value, suffer from the fact that only the showers from a few incident electrons (about 30) can be followed with this analogue Monte Carlo code in a reasonable amount of computer time.

It would appear from this comparison that the experimental data below an incident electron energy of 15 GeV can be explained by the production of neutrons from the giant resonance process alone. The increase in neutron yield at the electron energies of our experiments cannot be explained by this single production mechanism. The production of higher energy neutrons via the photo-deuteron process and via pion formation is discussed in detail elsewhere [1,9,21], but the lower energy neutrons measured by the PLC in our experiments could originate in an evaporation-like process in the final stage of nuclear spallation reactions induced by high-energy photons. An attempt was made to obtain a rough estimate for such a contribution to the measured neutron yield by folding together the analytical photon track length distributions given by Zerby and Moran [22] with the hadron production cross-sections of Genzel et al. [23] and Caldwell et al. [24]. However, it was found that the very steep fall

of the thick-target photon track-length distribution (proportional to E_e/E_γ^2 , where E_e is the initial electron energy and E_γ the photon energy) together with an asymptotically constant cross-section only gives rise to a linearly increasing spallation yield with energy above the pion production threshold of approximately several hundred MeV, i.e. a constant contribution when divided by the electron energy as in fig.4. If one makes the reasonable assumption of 5-10 evaporation neutrons being emitted per spallation, a number consistent with the preliminary pion irradiations for these experiments, the extra neutron yield due to photon induced spallation via photo-pion production would be about one order of magnitude smaller than the increase measured here. Further cascading with other processes leading to low energy neutron production must be supposed and this will be investigated.

5. CONCLUSIONS

The yield of low energy neutrons from a thick copper target bombarded by high energy electrons was measured at electron energies of 20, 50, 80 and 100 GeV. The yield is higher than would be expected from consideration of giant resonance photo-neutrons alone. However the measured yields are only a factor of two higher than would be expected from this process, and so, even though the physical explanation of the measurements is unsatisfactory, they can be considered as justification of the yields used at CERN to estimate shielding and other neutron-induced effects in electron accelerators which are based on the figure of 0.33 GeV^{-1} , or $0.026 \text{ GeV}^{-1} \cdot \text{sr}^{-1}$, recommended by Swanson [19], see fig.4.

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FIGURE CAPTIONS

Figure 1. Sketch of experimental situation.

PLC - Precision Long Counter,
ABC - Andersson-Braun Rem Counter,
ICs - Thin-walled ionization chambers for beam
current measurement,
MWPC - Multi-wire proportional counters for beam
profile measurements,
H4 - adjacent beam vacuum tube (not in use).
Beam counter-telescope is about 50 m upstream
(not shown),

Figure 2. Measured yield of neutrons from the experimental
target for different electron energies (curves drawn
to guide the eye only).

Figure 3. Neutron yields corrected for absorption in the
target (curves drawn to guide the eye only).

Figure 4. Comparison of measured and predicted neutron yields
as a function of incident electron energy. The open
circles are from Barber and George [3], the closed
circles from DeStaebler et al. [1], the + sign from
Jenkins [19] and the x sign from Bathow et al [10].
The open squares are the experimental data and the
closed squares the EGS calculations of this work.
The dashed line is taken from Swanson [4,5]. The
arrow indicates the value proposed by Swanson [19]
for radiation protection purposes at high electron
energies.

a) PLAN VIEW

b) LONGITUDINAL SECTION

c) TRANSVERSE SECTION

Figure 1

Figure 2

Figure 3

Figure 4