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**Neutron measurements in the stray field produced by
158 GeV/c lead ion beams**

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ABSTRACT

This paper discusses measurements carried out at CERN in the stray radiation field produced by 158 GeV/c $^{208}\text{Pb}^{82+}$ ions. The purpose was to test and intercompare the response of several detectors, mainly neutron measuring devices, and to determine the neutron spectral fluence as well as the microdosimetric (absorbed dose and dose equivalent) distributions in different locations around the shielding. Both active instruments and passive dosimeters were employed, including different types of Andersson-Braun rem counters, a tissue equivalent proportional counter, a set of superheated drop detectors, a Bonner sphere system and different types of ion chambers. Activation measurements with ^{12}C plastic scintillators and with ^{32}S pellets were also performed to assess the neutron yield of high energy lead ions interacting with a thin gold target. The results are compared with previous measurements and with measurements made during proton runs.

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1. Introduction

Since 1994, during a few weeks each year, the CERN Super Proton Synchrotron (SPS) accelerates fully stripped $^{208}\text{Pb}^{82+}$ ions to an energy of 400 GeV per charge, i.e. 158 GeV/nucleon or 32.8 TeV total energy. The beam is extracted during a 4.8 s period within a cycle of 19.2 s. Heavy ion beams are used by several experiments - installed in both the North and West Experimental Areas respectively on the Preveessin and Meyrin sites of CERN - trying to reproduce the quark-gluon plasma which was supposed to exist for a short time in the early phase of the Universe which followed the Big Bang (Stöcker et al 1996).

In a first approximation a high energy heavy ion can be treated as a bunch of independent hadrons. The interaction of a lead ion with a target, dump or components in the beam transfer line produces a hadronic cascade with a much larger number of neutrons than that generated by a proton of the same energy per nucleon, because of the larger number of nucleons involved, and with an energy distribution outside the shielding which may be considerably different. There exist several Monte Carlo codes capable of generating and transporting the intranuclear cascade induced by high energy protons, while at present there are no accurate codes for simulating the transport of heavy ions. As heavy ion beams of very high energy are not commonly available, CERN offers quite a unique possibility to investigate the stray radiation field generated by such beams.

A series of measurements was conducted in November 1996 in the central part of the hall called EHN1 of the North Experimental Area, around the NA44 and NA45 experiments (installed in the H4 and H8 beam lines, respectively), to supplement previous measurements carried out in the West Area (Aroua et al. 1997). The NA44 experiment (Bearden et al. 1996; Zachary et al. 1996) uses a focusing spectrometer to study two and three particle interferometry as well as single identified particle inclusive spectra. The beam interacts with a 2 mm-thick lead target and is subsequently stopped in a compact target calorimeter which also acts as a beam dump. The NA45/CERES experiment measures electron-positron pairs and direct photons produced in heavy ion collisions (Agakichiev et al. 1995). The CERES spectrometer (Bau et al. 1994) essentially consists of two Ring Imaging Cherenkov detectors, one in front and one behind a short superconducting double solenoid, two silicon radial-drift chambers and a multi-wire proportional chamber with pad readout located behind the spectrometer. The lead beam impinges on 0.2 mm thick gold target and is then stopped in a dump located about 30 m downstream.

The purpose of the measurements described in the present paper was twofold: 1) to test and intercompare a number of active and passive detectors, mainly neutron measuring devices, in the stray field outside the shielding and 2) to assess the neutron spectral fluence as well as the microdosimetric (absorbed dose and dose equivalent) distributions. The results are compared with measurements made under similar conditions during proton runs and with those of Aroua et al. (1997). All measurements were purely "parasitic", i.e. they were conducted without interfering neither with the

operation of the beam lines nor with the experiments. The beam intensity monitored by the experiments was used as a reference for the measurements, although no real normalization is possible, as will be discussed below. On the other hand, the SPS operation was remarkably stable over the entire measurement period (one week), with a beam intensity at the various experiments constant usually within 10%.

2. Experimental

The measurements were carried out at four locations (Fig. 1) around NA44 and NA45 (representative of the different radiation fields which may be encountered), namely: 1) on the gangway traversing the hall, in the forward direction with respect to NA44 (which we will refer to as “front NA44”); the beam is stopped in an iron dump backed by 80 cm concrete; 2) on the gangway on the side of the hall, at approximately 90° with respect to NA44 (“side NA44”), shielded by 2.4 m concrete; 3) on top of the dump downstream of NA45 (“dump NA45”), at a point of reduced shielding and 4) on a cable tray above the beam line, about 20 m downstream of the NA45 detector, in the forward direction with respect to the target in a position also little shielded, about 10 m before the dump (“NA45”). Positions 3 and 4 are fenced and inaccessible by personnel. These four locations were chosen as the radiation levels in the hall were in fact mainly caused by these two experiments; the beam intensity on NA49 (the other experiment running in parallel in the H2 beam) was about a factor 50 lower. With beam intensities of about 4.4×10^6 and 9.7×10^5 ions per pulse on NA44 and NA45, respectively, a radiation survey made with two rem counters and a Geiger-Müller instrument showed that the total dose equivalent rate in the part of the hall accessible by personnel ranged from about $2 \mu\text{Sv h}^{-1}$ up to about $45 \mu\text{Sv h}^{-1}$ (on the gangway in front of NA44, with little occupation factor).

Several active instruments and passive dosimeters were used in the intercomparison, namely: different types of Andersson-Braun rem counters, a tissue equivalent proportional counter (TEPC), a set of superheated drop (bubble) detectors, a Bonner sphere system, different types of ion chambers and large ^{12}C plastic scintillators to detect high energy hadrons via ^{11}C production. Activation measurements with ^{32}S pellets - via the $^{32}\text{S}(\text{n,p})^{32}\text{P}$ reaction - as well as ^{11}C measurements were performed around the NA45 detector to assess the neutron yield produced by high energy lead ions on a thin gold target.

Five Andersson-Braun rem counters were employed, one of conventional design and four modified to extend their response to high energy neutrons. The first one, a Berthold LB6411 ⁽¹⁾, is a commercial unit with a response proportional to the ambient dose equivalent, $H^*(10)$, up to about 20 MeV: it consists of a spherical ^3He proportional counter at the centre of a spherical moderator made up of polyethylene and cadmium, directly connected to a compact electronics. The other four are two cylindrical and two spherical versions of the LINUS rem counter (Birattari et al. 1990, 1992, 1993, 1994, 1996, 1997), one of each type in use at CERN and at the University

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⁽¹⁾ Neutron probe LB 6411, EG&G Berthold, Bad Wildbad, Germany.

of Milan (UMi). LINUS is a rem counter with a modified moderator to extend its response to several hundreds of MeV: it is made up of either a cylindrical BF₃ proportional counter (2.54 cm diameter and 5.08 cm active length, 95% ¹⁰B enrichment, 80 kPa fill pressure) in a cylindrical moderator, or a spherical ³He counter (3.2 cm active diameter, 304 kPa fill pressure) at the centre of a spherical moderator. The moderator is made up of polyethylene, borated plastic and lead. It is connected via a preamplifier to an acquisition system (amplifier, single channel analyzer and scaler from EG&G Ortec) housed in a portable chassis. All details are given in Birattari et al. (1990, 1992, 1993, 1994, 1996, 1997). The two types of instruments were calibrated at the Physikalisch Technische Bundesanstalt (PTB, Braunschweig, Germany) and at the Paul Scherrer Institute (PSI, Villigen, Switzerland); they are considered as the reference instruments at CERN for the determination of the neutron ambient dose equivalent.

Another active instrument used was the Cerberus (Höfert 1975; Raffnsøe 1982). This is a “three head” detector introduced at CERN in 1970 for measurements around high energy accelerators, where the radiation field is a complex mixture of neutrons, photons, muons and charged particles with a broad energy spectrum. The Cerberus is composed of three ionisation chambers connected to an electrometer. The first is a *Rem Ionisation Chamber* (RIC) - an Andersson-Braun rem counter with a BF₃ detector used in the ionisation chamber mode - to measure neutrons up to 15-20 MeV; the second is a *Carbon Dioxide Chamber*, a CO₂ gas-filled ionisation chamber sensitive to photons and to a minor extent to charged particles; the third is a *Tissue Equivalent Chamber* (TE), in which both the wall material and the filling gas have a tissue equivalent atomic composition (10.1% H, 3.5% N and 86.4% C), which measures the absorbed dose in tissue from all types of radiations. The sensitivity of the RIC to neutrons is about twice than that to gammas, the CO₂ chamber is four times more sensitive to gammas than to neutrons and the TE chamber is only slightly more sensitive to gammas than to neutrons. The Cerberus is normally used in conjunction with ¹²C activation (see below) to determine the dose equivalent rate from hadrons (mainly neutrons) above 20 MeV.

The measurements are carried out in the integration mode. From the reading (R , in mV) of each chamber, its calibration coefficients to gammas and neutrons (ϵ_γ and ϵ_n , respectively in mV μGy^{-1} and mV μSv^{-1}) and the measurement time, one calculates the gamma dose rate $\dot{D}_\gamma$, the neutron dose rate $\dot{D}_n$ and the neutron dose equivalent rate $\dot{H}_n$ ($E_n < 20$ MeV) through the following system of linear equations:

$$\begin{aligned} R^{CO_2} &= \epsilon_\gamma^{CO_2} \cdot \dot{D}_\gamma + \epsilon_n^{CO_2} \cdot \dot{D}_n \\ R^{TE} &= \epsilon_\gamma^{TE} \cdot \dot{D}_\gamma + \epsilon_n^{TE} \cdot \dot{D}_n \\ R^{RIC} &= \epsilon_\gamma^{RIC} \cdot \dot{D}_\gamma + \epsilon_n^{RIC} \cdot \dot{H}_n \end{aligned} \quad (1)$$

From the neutron flux above 20 MeV measured by the ^{12}C activation, it is possible to derive the dose equivalent rate due to high energy neutrons; the total dose equivalent rate is thus given by:

$$H_{TOT} = D_{\gamma} + H_{n<20\text{MeV}} + H_{n>20\text{MeV}} \quad (2)$$

The ratio of total dose equivalent to total absorbed dose provides an estimate of the average quality factor $\langle Q \rangle$ of the radiation field.

A set of 21 superheated drop (bubble) detectors were also employed. Superheated drop detectors (Apfel 1979; d'Errico and Alberts 1994; d'Errico et al. 1997) are suspensions of over-expanded halocarbon and/or hydrocarbon droplets (about 100 μm in diameter) which vaporize upon exposure to the high LET recoils from neutron interactions. The superheated droplets are dispersed in a gel-like medium contained in a vial and act as continuously sensitive, miniature, bubble chambers. Such a detector needs no power source, because the drops themselves represent stored energy which is released when triggered by radiation. The total amount of vapour evolved from the radiation-induced nucleation of drops gives an integrated measure of the total neutron exposure. This dosimeter underestimates the ambient dose equivalent from thermal and intermediate neutrons; on the other hand, it is completely insensitive to low LET radiation (X-rays, gammas and muons), which is a clear advantage if one wants to determine the neutron component in a mixed field. There also exist versions employed for neutron spectrometry (d'Errico et al. 1997; Rosenstock et al. 1995; Bamblevski et al. 1996). The type of units employed ⁽²⁾ are passive, integrating, pen-size dosimeters, temperature-compensated to give a uniform response in the interval 20°-37°, with an average sensitivity of 0.05 bubble μSv^{-1} over the energy range from 200 keV to 15 MeV. The bubbles are counted visually about half an hour after exposition.

Microdosimetric distributions in absorbed dose and dose equivalent were determined with a HANDI TEPC spectrometer (Aroua et al. 1995). This instrument measures an absorbed dose spectrum in lineal energy y of charged particle recoils. The spectrum is divided into 16 approximately equidistant channels on a logarithmic scale from $y=50 \text{ eV } \mu\text{m}^{-1}$ to $y=1.5 \text{ MeV } \mu\text{m}^{-1}$. Within the approximation of the instrument, y reproduces the linear energy transfer (LET) L and the dose equivalent is evaluated from the absorbed dose by the $Q(L)$ relationship of either ICRP21 or ICRP60 (Sannikov and Savitskaya 1993; Sannikov 1994). The sum of the contributions to absorbed dose and dose equivalent in the low LET interval $50 \text{ eV } \mu\text{m}^{-1} \leq y \leq 6.12 \text{ keV } \mu\text{m}^{-1}$ are traditionally called "gamma dose". Contributions to the dose from recoiling particles with a higher LET are referred to as "neutron dose". In the actual experimental conditions muons can contribute to the "gamma dose" and hadrons to both the "gamma dose" and the "neutron dose".

⁽²⁾ Neutron bubble detectors type BD PND, Bubble Technology Industries, Inc., Chalk River, Ontario, Canada.

Neutron spectrometry measurements were performed with a Bonner sphere spectrometer using the same type of spherical ^3He proportional counter mentioned above, employed with a set of six moderators, five polyethylene spheres (83 mm, 108 mm, 133 mm, 178 mm and 233 mm in diameter) and the spherical LINUS. The response functions of the six detectors are shown in Figs. 2 and 3 (Birattari, Esposito et al. 1997). It is apparent that the response of LINUS above 10 MeV compensates for the decreased sensitivity in the other channels. It should also be mentioned that the response function of the cylindrical LINUS is not substantially different from that shown in Fig. 2 (Birattari et al. 1990, 1993).

3. Neutron spectrometry

All detectors were in turn exposed, in the same place, in each of the four locations described above (Fig. 1). Two of the LINUS rem counters were also used as reference monitors in two fixed positions about one metre left and right of each exposure location. The intensity of the lead ion beam incident on the NA45 target was recorded pulse by pulse by the experiment and logged into a file. The intensity on the other targets (mainly NA44) was also monitored but only displayed on a TV screen. During each measurement the pulse by pulse intensity was read from the TV and recorded. Although no real normalization to the beam intensity is possible (as the stray radiation is the sum of several contributions coming from different loss points in the various beam lines), yet this procedure assured that data were taken under similar conditions and allowed an estimate of the contribution to the overall uncertainty of the measurement due to beam intensity fluctuations.

Let us first discuss the neutron spectrometry measurements. The data unfolding of the Bonner spheres was carried out by a code developed at the Department of Nuclear Engineering (CESNEF, Milan) and largely based on the theories currently applied in the field of flux adjustment (Matzke 1994). The final energy distribution generally aims at minimising the χ^2 -value obtained by comparing the experimental and the reconstructed data. Moreover in each iteration the modifications of the initial N group fluxes are also minimised, so as to be able to deal with underestimated problems, as in the case of Bonner spheres. Thus the global minimisation refers more properly to the so-called generalised χ^2 . The initial guess is a pure $1/E$ spectrum, which obviously gives a constant value in an $E \cdot \Phi(E)$ representation. In order to avoid negative values of the group fluxes, their logarithm is evaluated instead. The procedure introduces some approximations, particularly the truncation of a series expansion, and thus some iterations are usually required to reach the convergence. In the case of a roughly defined spectrum, say $N < 50$, the algorithm may be based, with some caution, on the inversion of a $N \times N$ matrix, whilst for a larger number of flux groups the procedure approaches the convergence by a purely iterative way, finely adjusting at each step the previous distribution. The procedure has been tested satisfactorily in a well defined neutron spectrum, namely the one emitted by an Am-Be source, by utilizing both moderated detectors (i.e. a Bonner sphere system, as in the present case) and an active

detector (the spectrum of the recoils of an ^4He proportional counter). From a purely statistical point of view, the experimental data of the Bonner spheres and of the LINUS detector are typically reproduced with a precision of a few percent as a mean on all detectors for each position.

The neutron spectral fluence in the various locations are shown in Figs. 4-7. As expected, a substantial contribution from high energy (above 10 MeV) neutrons is present in the position "front NA44", where measurements were made in the forward direction with respect to the beam line (the source is an iron dump completely absorbing the beam, backed by 80 cm concrete). The neutron spectrum is much softer for the position "side NA44", which is at about 90° to the source, and which is shielded by 2.4 m of concrete. The spectral fluences show features which are somewhat intermediate for "dump NA45" and "NA45". In the former case the neutrons comes from below (i.e. at 90°), but at the measurement point the shielding was quite thin and this explains the high energy tail. In the case of "NA45" the measurements were made at a point aligned with the beam line and virtually no shielded. The beam only interacted upstream with a very thin (0.2 mm gold) target, which explains the well-defined high energy peak, but in addition the spectrum shows a relevant contribution from scattered neutrons coming from the dump located about 10 m downstream. During a previous lead ion run, a significant high energy neutron component was also detected in measurements made with a set of Bonner spheres and with ^{209}Bi and ^{232}Th fission track detectors on top of a concrete shield in the West Experimental Area (Aroua et al. 1997), although no direct comparison can be made with the present measurements as the experimental conditions were not the same.

The neutron spectral fluences shown in Figs. 4-7 can be compared with the spectral fluences determined, with the same Bonner sphere system and with the same unfolding procedure, outside a 80 cm thick concrete and 40 cm thick iron shields when a reference radiation field was generated, under well-controlled conditions, by a mixed beam of proton and positive pions of 120 GeV/u incident on a thick copper target (7 cm in diameter and 50 cm in length) (Figs. 8 and 9) (Höfert and Stevenson 1994; Birattari, Ferrari et al. 1997). A similar evaporation peak is present at "NA45" and outside the 40 cm iron shield, and the large high energy component at "front NA44" is comparable, and somewhat more pronounced, with that measured outside the 80 cm concrete shield.

The interaction of a high energy proton (in the GeV range) with a material can be modelled by a three stage process, namely an intranuclear cascade with high energy secondaries mainly emitted in the forward direction, a pre-equilibrium emission and evaporation of the residual nucleus with the emission of hadrons in the MeV energy range. A similar mechanism should be valid in the case of a high energy lead ion if one assumes that the ion can be treated as a bunch of independent hadrons, with the difference that a larger number of evaporation neutrons can be expected. This is in fact seen at "front NA44", but in general it is found that the spectral shape is mostly dependent on experimental conditions (emission angle as well as thickness and composition of shielding), rather than on type of primary particle. The experimental

spectral fluences shown in Figs. 8 and 9 are in good agreement with those resulting from Monte Carlo calculations and discussed in detail by Birattari, Ferrari et al. (1997); this agreement confirms the validity of the technique and gives confidence in the present results.

4. Dosimetry intercomparison

As mentioned above, all detectors were in turn exposed in each of the four measurement locations. The results are compared in Table 1, while Table 2 summarises the relative response of the various detectors to neutrons normalised to the response of the LINUS_{sph,UMi}. Most of the active instruments are calibrated in terms of the “old” fluence to ambient dose equivalent conversion coefficients from ICRP21 (ICRP 1973), except the Berthold LB6411 which uses “new” data (Siebert and Schuhmacher 1995) as recommended by ICRP60 (ICRP 1990). Above 20 MeV the LINUS uses data of Stevenson (1986). The code used to elaborate the HANDI microdosimetric distributions provides values of dose equivalent rate for both sets of conversion coefficients (Sannikov and Savitskaya 1993) and both results are given in Table 1. The neutron spectral fluence determined with the Bonner sphere system was folded with both sets of conversion coefficients (Sannikov and Savitskaya 1993) to determine the dose equivalent rate also given in Table 1. The dose equivalent rate due to the high energy component as evaluated from ¹¹C activation was calculated using an average value of data above 20 MeV as given by ICRP21 (ICRP 1973), in order to be combined with the results of the Cerberus and determine the total dose equivalent rate (equation 2).

At “front NA44” the neutron spectrum presents a pronounced component below about 10 eV and above 1 MeV, extending up to several hundreds MeV. In this location there is a substantial agreement amongst the various devices. In particular, the agreement amongst three out of the four LINUS is excellent, whilst the response of LINUS_{cyl,CERN} is somewhat higher. This discrepancy may partly be imputed to small differences in the composition, density, machining or assembly of the moderator. As an example, a 5% variation was already observed in the response of two commercial (conventional) rem counters which were nominally identical (Birattari et al. 1993). In addition, the two cylindrical rem counters are equipped with a BF₃ proportional counter. In actual fact, the operation of BF₃ counters is not very stable with time. During extensive tests at the University of Milan on various BF₃ tubes, these detectors showed a deterioration in their response and recovery in an unpredictable way after a number of hours of running period, with variations as large as 20%. This type of problem, which has also been reported in the literature (Tomoda and Fukakusa 1984), is the reason why the most recent spherical version of the LINUS uses a ³He counter. The slight underestimation of the Berthold LB6411 is due to its reduced response above 20 MeV. The TEPC and the Bonner sphere spectrometer give slightly higher results with respect to the other instruments. For the Bonner sphere system, the

uncertainties associated to the results are only statistical and do not include the contribution coming from the fluence rate distribution assumed as a guess.

At “side NA44” the spectrum is dominated by a large relative contribution of neutrons below about 1 MeV and a much smaller high energy component. Here is LINUS_{cyl,UMi} which has a lower response as compared to the three other units; this behaviour can be explained as discussed above. The Berthold LB6411 and the bubble detectors have a somewhat lower response, for the reason also given above; this trend, more or less pronounced, is found in all measurement positions. In general there is substantial agreement, within the experimental uncertainties, amongst the various LINUS, the Bonner spectrometer, the Cerberus and the total neutron dose equivalent given by the Cerberus plus the high energy part determined by ^{11}C . This is correct as the high energy neutron component is not much pronounced. There is also agreement between the total dose equivalent (including the gamma component) determined by the HANDI TEPC and by the Cerberus + ^{11}C (equation 2). The neutron dose equivalent indicated by the TEPC is slightly higher, while it is worth mentioning that the Cerberus should in general slightly overestimate the dose equivalent due to some overlap of the response of the various detectors .

At “dump NA45” the spectral fluence is dominated by thermal and intermediate energy neutrons. The responses of the various instruments to neutrons are in substantial agreement, with the exception of LINUS_{sph,UMi} which measures slightly less (and this is not easy to explain) and the TEPC. There is also agreement between the total dose equivalent determined by the TEPC and by the sum Cerberus + ^{11}C . The HANDI TEPC gives a substantially higher response in terms of neutron dose with respect to all other devices. It should be borne in mind that this instrument “sees” all types of radiation and, as mentioned above, the “neutron dose” may actually contain contributions other than neutrons (and this may also explain the slight overestimate found in the other locations). The large dose measured by ^{11}C (which detects charged hadrons as well as neutrons) seems to confirm the presence of a substantial dose coming from charged particles, as the neutron spectral fluence shows very few neutrons above about 10 MeV (Fig. 6).

At “NA45” the neutron spectrum is dominated by a large intermediate energy component and by a pronounced contribution of neutrons with energy larger than 100 MeV. The latter are most likely coming directly from the target, as confirmed by the measurements described in section 5. In this location the agreement amongst the various instruments is satisfactory.

As for the gamma dose, there is a good agreement between the values measured by the HANDI TEPC and by the Cerberus in three out of four locations (no data from the Cerberus are available for “front NA44”). There is also a good agreement in the ratio of gamma dose to neutron dose for the two instruments for “side NA44” and “dump NA45”, whilst a discrepancy exists in the case of “NA45”. The large contribution of the “gamma dose” to the total dose equivalent found for “front NA44” and “NA45” is actually due to muons coming from the secondary production target upstream in the beam line rather than to gammas

The absorbed dose and dose equivalent distributions measured with the HANDI spectrometer are shown in Fig. 10. The microdosimetric spectra for “front NA44” and “NA45” show a marked presence of a low LET component which is due to muons, as just mentioned. The spectrum for “side NA44” shows a much less pronounced low LET component, which is essentially due to gamma radiation. The situation for “dump NA45” is somewhat intermediate. These spectra can be compared qualitatively with microdosimetric distributions measured outside a 80 cm thick concrete and 40 cm thick iron shields (Fig. 11), when the radiation field was generated by a mixed beam of proton and positive pions of 120 GeV/u incident on a thick copper target, as mentioned above (Höfert and Stevenson 1994; Birattari, Ferrari et al. 1997). The distributions are not substantially different. Instead, the present measurements show a marked low LET component which is missing in the microdosimetric spectra, obtained with the same HANDI TEPC, shown in the paper by Aroua et al. (1997). The lack of the low LET contribution may be explained by differences in the experimental conditions, which are not described by Aroua et al. (1997).

The ratio of the values of total dose evaluated from the HANDI spectra with the ICRP21 and ICRP60 coefficients ranges from 0.71 (for “side NA44”) to 0.89 (for “front NA44”) and that of the neutron dose from 0.69 to 0.82. The variations from one location to the other are due to differences in the spectral fluences which in turn reflect into different microdosimetric distributions. As these variations are almost within the experimental errors, it can be stated that on the average the uncertainty in the evaluation of the ambient dose equivalent due to the choice of the set of conversion coefficients is never larger than 20% and most likely around 10%.

The total and neutron quality factors evaluated from the data of the HANDI TEPC and of the Cerberus are given in Table 3. Except for “side NA44”, where the neutron quality factor determined by the Cerberus is 50% higher than that determined by the TEPC, the agreement is satisfactory. The data of Table 3 can be compared with the quality factors assessed from HANDI measurements during a proton run (Fig. 11) as given in Table 4.

Finally, it should be mentioned that the values of dose equivalent rates given in Table 1 are averaged over the entire SPS cycle. During the 4.8 s of the pulse the instantaneous dose rate is 4 times higher and zero over the rest of the pulse.

5. Neutron fluence around the NA45 target

Activation measurements with ^{32}S pellets and ^{12}C plastic scintillators were performed around the NA45 0.2 mm gold target to get a rough estimate of the neutron flux produced by high energy lead ions. The ^{32}S activation detectors are disks 50 mm in diameter and 6 mm thick, exploiting the $^{32}\text{S}(n,p)^{32}\text{P}$ reaction which has a threshold at about 2 MeV; the cross section extends up to about 20 MeV and has its maximum (300 mb) in the interval 4 to 10 MeV. The second type of detectors are large volume cylindrical ^{12}C scintillators (12.6 cm in diameter and 10 cm thick), employed to detect

the high energy hadron component via the (n,2n) and (p,pn) reactions, which have a threshold around 20 MeV.

The detectors were placed at approximately 0°, 15° and 90° with respect to the beam axis, about 8 m, 3.5 m and 2 m from the target, respectively. The ^{32}S pellets were left in place for 14 days (as the half life of ^{32}P is 14.3 days), during which time the beam was continuously on except for a 52-hour interruption which was taken into account in the subsequent calculation of the activity (minor interruptions can be neglected due to the long half life of the product). The half life of ^{11}C is 20.38 minutes so that short 2-hour irradiations were sufficient for the activation of the ^{12}C scintillators.

As the target is very thin and there was little scattering material around, the detectors placed at 15° and 90° gave no results above background counting, i.e. no significant neutron fluence could be determined. The detectors placed in the forward direction (a few degrees with respect to the beam axis) gave a neutron fluence (at 8 m distance) of 0.11 cm^{-2} and $2.4 \times 10^{-3}\text{ cm}^{-2}$ per incident lead ion, for the low (<20 MeV) and high (>20 MeV) energy components, respectively. These values can be compared with the results of measurements of the hadron yield from a 3 mm thick copper target bombarded by 225 GeV/c protons (Stevenson et al. 1983). These measurements gave, at 1 m distance in the forward direction, a fluence of about $3 \times 10^{-4}\text{ cm}^{-2}$ in the energy range 6-25 MeV (measured via the production of ^{24}Na from aluminium and of ^{32}P from sulphur) and about $2 \times 10^{-3}\text{ cm}^{-2}$ above 20 MeV (measured via ^{11}C production from polyethylene). Although the target material and thickness are not the same, the fluence above 20 MeV seems to scale approximately linearly with mass number of the incident particle. On the other hand no direct comparison can be made for the component below 20 MeV, which is much higher in the present case. As the detector was placed in the tunnel (also shielded on the top) just downstream the NA45 zone (Fig. 1), the measurement is affected by a large scattering contribution which is not easy to estimate.

6. Conclusions

Despite the variation in the experimental conditions, the several independent sources contributing to the radiation field and the complexity of the field, except for a few cases the overall agreement amongst the various active and passive detectors is quite satisfactory. It should be underlined that in general the response of all of these devices above a few tens of MeV is known only approximately. For some of them there exists a calculated response function, but no actual experimental verification with (nearly) monoenergetic neutrons under well-controlled conditions, such as those offered by PTB in Braunschweig and PSI in Villigen.

The dose equivalent response of the various devices in the stray radiation fields found around high energy accelerators is typically within 30%, which is sufficient for a radiation protection use (e.g., as area monitors). The actual choice of a given instrument or dosimeter (in particular, whether it should be active or passive) is

dictated by the specific experimental conditions (as well as, of course, on its availability).

A comparison with the results of the present paper with those of similar measurements made in the stray radiation field generated by proton/pion induced reactions has shown that the microdosimetric distributions, as well as the average values of the quality factor, do not differ substantially. This indicates that proton beams and beams of heavy ions having similar energy per nucleon produce similar a radiological risk outside the shieldings.

Finally, it should be stressed that CERN offers quite an unique opportunity for measurements in stray radiation fields produced by high energy heavy ions. As the lead ion experimental program will continue over the next few years, it might be of some interest to extend the present investigation in the future.

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Table 1. Ambient dose equivalent rate ($\mu\text{Sv h}^{-1}$) measured by the various detectors. The associated errors include contributions from counting statistics and uncertainties on the beam intensity in the H4 and H8 beam lines. In the case of the Bonner sphere system, the uncertainties do not include the contribution coming from the fluence rate distribution assumed as a guess. The dose equivalent in the upper and bottom parts of the table is evaluated using the fluence to dose equivalent conversion factors from ICRP21 and ICRP60, respectively. If not otherwise indicated, the value given is the neutron dose equivalent rate. The total given for the Cerberus + ^{11}C is the sum of the contributions due to gammas, neutrons below 20 MeV and neutrons above 20 MeV (equation 2).

Detector	Ambient dose equivalent rate ($\mu\text{Sv h}^{-1}$)			
	front NA44	side NA44	dump NA45	NA45
LINUS _{sph,UMi}	21.2 $\pm$ 0.2	22 $\pm$ 1	227 $\pm$ 22	108 $\pm$ 10
LINUS _{sph,CERN}	22 $\pm$ 1	21 $\pm$ 0.5	306 $\pm$ 15	78 $\pm$ 10
LINUS _{cyl,UMi}	21 $\pm$ 1	16 $\pm$ 1	304 $\pm$ 11	—
LINUS _{cyl,CERN}	28.5 $\pm$ 3	23 $\pm$ 2	348 $\pm$ 98	125 $\pm$ 12
bubble detectors	19 $\pm$ 4	13 $\pm$ 1.5	210 $\pm$ 44	78 $\pm$ 6
Cerberus (gammas)	—	4.5 $\pm$ 1	56 $\pm$ 13	92 $\pm$ 21
Cerberus (neutrons)	—	21 $\pm$ 3.4	338 $\pm$ 56	73 $\pm$ 12
^{11}C ($E_n > 20$ MeV)	15 $\pm$ 2	5.5 $\pm$ 0.5	200 $\pm$ 20	—
Cerberus + ^{11}C , neut.	—	26.5 $\pm$ 5	538 $\pm$ 103	—
Cerberus + ^{11}C , total	—	31 $\pm$ 9	595 $\pm$ 175	—
TEPC total (ICRP21)	48 $\pm$ 7	37 $\pm$ 6	617 $\pm$ 57	219 $\pm$ 33
gamma dose	18 $\pm$ 1.5	3 $\pm$ 0.2	68 $\pm$ 4	88 $\pm$ 11
neutron dose	30 $\pm$ 6	34 $\pm$ 6	549 $\pm$ 54	131 $\pm$ 24
Bonner (ICRP21)	28 $\pm$ 1	25.5 $\pm$ 1	257 $\pm$ 10	120 $\pm$ 7
TEPC total (ICRP60)	54 $\pm$ 6	53 $\pm$ 8	787 $\pm$ 80	251 $\pm$ 35
gamma dose	18 $\pm$ 2	2.9 $\pm$ 0.2	65 $\pm$ 5	85 $\pm$ 11
neutron dose	36 $\pm$ 5	50 $\pm$ 8	722 $\pm$ 91	166 $\pm$ 25
Berthold LB6411	16 $\pm$ 2	18 $\pm$ 1	228 $\pm$ 12	80 $\pm$ 4
Bonner (ICRP60)	31 $\pm$ 2	30 $\pm$ 1	333 $\pm$ 13	136 $\pm$ 8

LINUS_{sph,CERN} = spherical version of LINUS in use at CERN

LINUS_{sph,UMi} = spherical version of LINUS in use at University of Milan

LINUS_{cyl,CERN} = cylindrical version of LINUS in use at CERN

LINUS_{cyl,UMi} = cylindrical version of LINUS in use at University of Milan

Table 2. Relative response of the various detectors to neutrons normalised to the response of LINUS_{sph,UMi}.

Detector	front NA44	side NA44	dump NA45	NA45
LINUS _{sph,CERN}	1.02	0.94	1.35	0.72
LINUS _{cyl,UMi}	0.99	0.72	1.34	—
LINUS _{cyl,CERN}	1.45	1.11	1.67	1.25
Bubble detectors	0.90	0.58	0.92	0.72
Cerberus (neutrons)	—	0.95	1.49	0.67
Cerberus (neutrons + ¹¹ C)	—	1.20	2.37	—
TEPC (ICRP21) (neutrons)	1.41	1.53	2.42	1.21
TEPC (ICRP60) (neutrons)	1.71	2.21	3.18	1.52
Berthold LB6411	0.76	0.80	1.01	0.74
Bonner (ICRP21)	1.31	1.14	1.13	1.11
Bonner (ICRP60)	1.46	1.34	1.47	1.26

Table 3. Total and neutron quality factors evaluated from the data of the HANDI TEPC and of the Cerberus.

Detector	front NA44		side NA44		dump NA45		NA45	
	total	n	total	n	total	n	total	n
TEPC (ICRP21)	2.2	7.6	6.2	11.0	5.1	9.7	2.1	7.6
TEPC (ICRP60)	2.5	9.3	8.7	15.9	6.5	12.8	2.4	9.6
Cerberus	—	—	5.7	23.9	4.8	5.1	—	—

Table 4. Total and neutron quality factors evaluated from the microdosimetric distributions measured with the HANDI TEPC during a proton run (Fig. 11), for 80 cm concrete and 40 cm iron shielding.

Detector	80 cm concrete		40 cm iron	
	total	n	total	n
TEPC (ICRP21)	3.5	8.0	7.0	10.0
TEPC (ICRP60)	4	9.3	9.5	14.0

Fig. 1 Plan view of the central part of the experimental hall EHN1 with the four exposure locations.

Fig. 2 Fluence response of the spherical rem counter LINUS. Shaded line and open circles are FLUKA calculations, the triangles are the experimental measurements. The curve of the ambient dose equivalent, $H^*(10)$, is also shown.

Fig. 3 Fluence response of the five polyethylene spheres. Lines are FLUKA calculations, symbols are the experimental measurements.

Fig. 4 Neutron fluence rate per unit lethargy, $E \cdot \Phi(E)$ (neutrons $\text{cm}^2 \text{ s}^{-1}$) obtained by unfolding the experimental data from the Bonner sphere system (the five polyethylene sphere plus LINUS_{sph,UMi}) at "front NA44". A constant guess was assumed.

Fig. 5 Neutron fluence rate per unit lethargy, $E \cdot \Phi(E)$ (neutrons $\text{cm}^2 \text{ s}^{-1}$) obtained by unfolding the experimental data from the Bonner sphere system (the five polyethylene sphere plus LINUS_{sph,UMi}) at "side NA44". A constant guess was assumed.

Fig. 6 Neutron fluence rate per unit lethargy, $E \cdot \Phi(E)$ (neutrons $\text{cm}^{-2} \text{s}^{-1}$) obtained by unfolding the experimental data from the Bonner sphere system (the five polyethylene sphere plus LINUS_{sph,UMi}) at "dump NA45". A constant guess was assumed.

Fig. 7 Neutron fluence rate per unit lethargy, $E \cdot \Phi(E)$ (neutrons $\text{cm}^{-2} \text{s}^{-1}$) obtained by unfolding the experimental data from the Bonner sphere system (the five polyethylene sphere plus $\text{LINUS}_{\text{sph,UMi}}$) at "NA45". A constant guess was assumed.

Fig. 8 Neutron fluence rate per unit lethargy, $E \cdot \Phi(E)$ (neutrons $\text{cm}^{-2} \text{s}^{-1}$) obtained by unfolding the experimental data from the Bonner sphere system (the five polyethylene sphere plus LINUS_{sph,UMi}) outside a 80 cm thick concrete shield, when the radiation field was generated by 120 GeV/u protons+pions stopped in a thick copper target. A constant guess was assumed.

Fig. 9 Neutron fluence rate per unit lethargy, $E \cdot \Phi(E)$ (neutrons $\text{cm}^{-2} \text{s}^{-1}$) obtained by unfolding the experimental data from the Bonner sphere system (the five polyethylene sphere plus $\text{LINUS}_{\text{sph,UMi}}$) outside a 40 cm thick iron shield, when the radiation field was generated by 120 GeV/u protons+pions stopped in a thick copper target. A constant guess was assumed.

Fig. 10 Absorbed dose and dose equivalent distributions measured with the HANDI TEPC spectrometer.

Fig. 11 Absorbed dose and dose equivalent distributions measured with the HANDI TEPC spectrometer outside a 80 cm thick concrete and 40 cm thick iron shields, when the radiation field was generated by 120 GeV/u protons+pions stopped in a thick copper target. The distributions are normalised to the beam intensity on target measured by a Precision Ionization Chamber (PIC), 1 PIC count corresponding to 2.2×10^4 incident particles.