Technical Inspection and Safety Division

CERN-TIS-2003-010-RP-PP

THE RESPONSE OF A BONNER SPHERE SPECTROMETER TO CHARGED HADRONSS. Agosteo¹, E. Dimovasilis², A. Fassò³ and M. Silari²¹Politecnico di Milano, CESNEF, Via Ponzio 34/3, 20133 Milano, Italy²CERN, 1211 Geneva 23, Switzerland³SLAC, P.O. Box 4349, Stanford, CA 94309, USA**Abstract**

Bonner Sphere Spectrometers (BSS) are employed in neutron spectrometry and dosimetry since many years. Recent developments have seen the addition to a conventional BSS of one or more detectors (moderator plus thermal neutron counter) specifically designed to improve the overall response of the spectrometer to neutrons above 10 MeV. These additional detectors employ a shell of material with a high mass number (such as lead) within the polyethylene moderator, in order to slow down high-energy neutrons via (n,xn) reactions.

A BSS can be used to measure neutron spectra both outside accelerator shielding and from an unshielded target. Measurements were recently performed at CERN of the neutron yield and spectral fluence at various angles from unshielded, semi-thick copper, silver and lead targets, bombarded by a mixed proton/pion beam with 40 GeV/c momentum. These experiments have provided evidence that under certain circumstances, the use of lead-enriched moderators may present a problem: these detectors were found to have a significant response to the charged hadron component accompanying the neutrons emitted from the target. Conventional polyethylene moderators show a similar behaviour but less pronounced. These secondary hadrons interact with the moderator and generate neutrons, which are in turn detected by the counter. To investigate this effect and determine a correction factor to be applied to the unfolding procedure, a series of Monte Carlo simulations were performed with the FLUKA code. These simulations aimed at determining the response of the BSS to charged hadrons under the specific experimental situation. Following these results, a complete response matrix of the extended BSS to charged pions and protons was calculated with FLUKA. An experimental verification was carried out with a 120 GeV/c hadron beam at the CERF facility at CERN.

*Presented at the NEUDOS9 conference, Delft, The Netherlands, 28 Sept - 3 Oct 2003**Submitted for publication in Radiation Protection Dosimetry*

CERN, 1211 Geneva 23, Switzerland
9 October 2003

1. Introduction

Bonner Sphere Spectrometers (BSS) are employed in neutron spectrometry and dosimetry since many years. Recent developments have seen the addition to a conventional BSS of one or more detectors (we call here “detector” the moderator plus thermal neutron counter) specifically designed to improve the overall response of the spectrometer to neutrons above 10 MeV. These additional detectors employ a shell of material with a high mass number (such as lead) within the polyethylene moderator, in order to slow down high-energy neutrons via (n,xn) reactions.

A BSS can be used to measure neutron spectra both outside accelerator shielding and from an unshielded target. Whilst in the former case the contamination of the neutron field with other types of hadrons is usually comparatively small, when measuring the neutron emission from an unshielded target bombarded by a high-energy particle beam, a large contribution of other particles may be present. These secondary hadrons may interact with the moderator and generate neutrons, which are in turn detected by the counter. This paper investigates the importance of this effect when using a extended-range BSS in a mixed high-energy radiation field and provides a response matrix to charged hadrons along with an experimental verification.

2. BSS measurements at high energy accelerators

Measurements were recently performed at CERN of the neutron yield and spectral fluence from 50 mm thick copper, silver and lead targets bombarded by a hadron beam (composed of about 80% positive pions and 20% protons) of 40 GeV/c. The neutron emission per incident hadron on target was measured at 60 cm from the target in the angular range from 30° to 135° with respect to the beam direction [1], using the same experimental set-up employed for previous measurements with high-energy heavy ions [2]. The measurements were performed with an extended range Bonner sphere spectrometer (BSS) [3], in which two lead-modified moderators were added to a conventional set of five polyethylene spheres (with diameter of 81 mm, 108 mm, 133 mm, 178 mm and 233 mm). The spectrometer used a Centronics ³He proportional counter; the sphere with diameter 81 mm was also exposed with a 1 mm thick cadmium cover.

Of the two lead-modified spheres, the first (nicknamed “*Ollio*”) has a diameter of 255 mm and consists of moderator shells of (from the ³He proportional counter outwards) 3 cm polyethylene, 1 mm cadmium, 1 cm lead and 7 cm polyethylene thickness. This configuration suppresses the response to incident neutrons with energies lower than 100 keV and increases it for energies above 10 MeV and up to 1 GeV, as compared to the 233 mm sphere of the conventional BSS. However the response function still shows the peak at about 10 MeV which is typical for all large detectors of a BSS. The second detector (“*Stanlio*”), with a diameter of 118.5 mm, consists of moderator shells of 2 cm polyethylene, 1 mm cadmium and 2 cm lead thickness. Its response function does not show the peak at 10 MeV, so that *Stanlio* is a useful complement to the other detectors. At low energies it behaves like a small Bonner sphere, but at high energies the response is increased compared to the 233 mm sphere. The response functions of the various detectors are given in ref. [3].

The unfolding of the data obtained with the set of eight Bonner spheres was performed with a code based on the GRAVEL formalism [4], using as pre-information the neutron energy distribution calculated with the FLUKA Monte Carlo (MC) code [5,6]. In the MC simulations, the spectral fluence of secondary neutrons generated by a pencil beam of 40 GeV/c protons/pions striking a 50 mm thick target (made of either copper, silver or lead) was scored in void spheres with diameter of 133 mm (corresponding to that of the medium-size Bonner sphere) placed at the same positions used in the experiment (i.e., at angles of 30°, 45°, 60°, 75°, 90°, 105°, 120°, 135°).

As an example, the neutron spectral fluences at 30° resulting from unfolding of the experimental data and from the simulations are shown in Fig. 1 for a silver target (the full results of the experiment are given in ref. [1]). The experimental spectra show the two peaks predicted by the MC guess, an isotropic evaporation component centred at 3 MeV and a high-energy peak sitting around 100-150 MeV. However, the unfolded spectrum shows a much more pronounced high-energy peak

and a comparatively smaller evaporation peak with respect to the distribution predicted by the MC simulations. This discrepancy was eventually attributed to the contribution of secondary neutrons produced in the BSS detectors by charged hadrons coming from the target, a contribution which cannot be suppressed by background subtraction. These charged hadrons (mainly charged pions and protons) undergo inelastic interactions in the moderator (mainly in the lead shell), producing secondary neutrons which are subsequently slowed-down and thermalised by the polyethylene giving rise to additional counts in the ^3He detector.

Figure 1. Neutron spectral fluences from 40 GeV/c positive hadrons (80% pions + 20% protons) on a 50 mm thick silver target, at 30° with respect to beam direction, resulting from the MC simulations and from the uncorrected and corrected experimental data unfolding (see text).

A set of FLUKA simulations was performed to verify this hypothesis. First the spectral fluence of all secondary hadrons was calculated using the same geometry used for estimating the energy distribution of neutrons emitted from the target. As an example the spectral fluences of neutrons and charged hadrons at 30° are shown in Fig. 2. To save computing time, the calculations were only made for a primary pencil beam of 40 GeV/c positive pions (which make up most of the beam). It was found that the most intense components of the spectral fluence at all angles are protons and charged pions. Positive and negative pions have very similar energy distributions, with a peak at almost 1 GeV. Protons show a two-peak distribution centred at about 200-300 MeV and 500-600 MeV.

A second set of simulations was then performed to estimate the contribution to the ^3He count-rate of the secondary neutrons generated by these charged hadrons in the moderator. *Stanlio* and *Ollio* were first investigated since they use lead. The two spheres were assumed to be irradiated by parallel beams of neutrons, protons and charged pions having the energy distributions calculated at each angle in the previous set of simulations. For each particle the neutron spectral fluence was scored in the ^3He detector and subsequently folded with the $^3\text{He}(n,p)^3\text{H}$ cross sections [7] to evaluate the response. The same calculations were repeated for the 233 mm sphere, which showed a smaller response to charged

hadrons (about 10% at 30° and below 1% at 135°), confirming that this effect is far less serious for polyethylene. Following this result it was decided not to investigate the response to charged hadrons of the other polyethylene spheres of smaller dimensions. The ratios of the response to charged hadrons and neutrons to the total (all charged hadrons + neutrons) are listed in Table 1 for the silver target. The ratios of the neutron response to the total represent the correction factors to be applied to the experimental data to suppress the charged hadron contribution. The response of *Stanlio* and *Ollio* to charged hadrons is quite similar and contributes for more than 50% of the ^3He detector counts at 30°. The correction for the contribution of charged hadrons should also be applied at large angles since they are responsible for more than 6% of the counts even at 135°.

Figure 2. Spectral fluences of neutrons and charged hadrons at 30° from 40 GeV/c positive pions striking a 50 mm thick silver target.

The neutron spectral fluence at 30° resulting from unfolding the corrected experimental data is shown in Fig. 1. The agreement with the simulated spectrum is now satisfactory.

The procedure adopted for estimating these correction factors is very time-consuming since consisted of $8 \times 4 \times 3$ (angles $\times$ particles $\times$ number of spheres) simulations per each target material and is obviously specific to the present experimental conditions. On the other hand, if the response matrix of the BSS to charged hadrons is known, the correction factors can be determined directly by folding the response functions with the spectral fluence of charged hadrons coming from the target. Ideally one should be able to determine the spectral fluence or at least the yield of neutrons and charged hadrons from the experimental data, the response matrices of the BSS to the various particles and some pre-information on the relative importance of the various contributions. The determination of these response functions was the main purpose of the present work and is discussed in the following section.

Table 1. Ratios of the response of the 233 mm sphere, *Stanlio* and *Ollio* to protons, neutrons, positive pions (π^+) and negative pions (π^-) to the total (all charged hadrons + neutrons), for a 50 mm thick silver target bombarded by a 40 GeV/c protons/ π^+ beam.

Angle	Particle	233 mm	<i>Stanlio</i>	<i>Ollio</i>
30°	neutron	0.902±0.002	0.439±0.001	0.456±0.001
	π^+	(2.572±0.011)x10 ⁻²	0.204±0.001	0.194±0.001
	π^-	(5.688±0.019)x10 ⁻²	0.262±0.001	0.263±0.001
	proton	(1.537±0.004)x10 ⁻²	(9.427±0.005)x10 ⁻²	(8.700±0.014)x10 ⁻²
	$\pi^+ + \pi^- + \text{proton}$	(9.797±0.031)x10 ⁻²	0.561±0.001	0.544±0.001
45°	neutron	0.951±0.001	0.638±0.001	0.653±0.001
	π^+	(1.023±0.005)x10 ⁻²	0.117±0.001	0.109±0.001
	π^-	(3.085±0.006)x10 ⁻²	0.182±0.001	0.183±0.001
	proton	(7.879±0.063)x10 ⁻³	(6.255±0.005)x10 ⁻²	(5.410±0.010)x10 ⁻²
	$\pi^+ + \pi^- + \text{proton}$	(4.897±0.011)x10 ⁻²	0.362±0.001	0.347±0.001
60°	neutron	0.970±0.001	0.766±0.001	0.778±0.001
	π^+	(5.049±0.017)x10 ⁻³	(6.570±0.006)x10 ⁻²	(6.042±0.011)x10 ⁻²
	π^-	(1.994±0.003)x10 ⁻²	0.124±0.001	0.125±0.002
	proton	(4.909±0.023)x10 ⁻³	(4.449±0.004)x10 ⁻²	(3.674±0.010)x10 ⁻²
	$\pi^+ + \pi^- + \text{proton}$	(2.991±0.005)x10 ⁻²	0.234±0.001	0.222±0.001
75°	neutron	0.979±0.002	0.840±0.001	0.848±0.002
	π^+	(2.807±0.014)x10 ⁻³	(3.919±0.003)x10 ⁻²	(3.560±0.006)x10 ⁻²
	π^-	(1.438±0.003)x10 ⁻²	(8.829±0.007)x10 ⁻²	(8.999±0.017)x10 ⁻²
	proton	(3.442±0.017)x10 ⁻³	(3.262±0.004)x10 ⁻²	(2.630±0.007)x10 ⁻²
	$\pi^+ + \pi^- + \text{proton}$	(2.061±0.004)x10 ⁻²	0.160±0.001	0.152±0.002
90°	neutron	0.985±0.002	0.885±0.001	0.890±0.001
	π^+	(1.766±0.008)x10 ⁻³	(2.609±0.002)x10 ⁻²	(2.359±0.003)x10 ⁻²
	π^-	(1.114±0.002)x10 ⁻²	(6.771±0.008)x10 ⁻²	(6.941±0.008)x10 ⁻²
	proton	(2.214±0.011)x10 ⁻³	(2.188±0.002)x10 ⁻²	(1.731±0.004)x10 ⁻²
	$\pi^+ + \pi^- + \text{proton}$	(1.512±0.003)x10 ⁻²	0.115±0.001	0.110±0.001
105°	neutron	0.988±0.002	0.910±0.001	0.914±0.002
	π^+	(1.275±0.007)x10 ⁻³	(1.927±0.002)x10 ⁻²	(1.743±0.003)x10 ⁻²
	π^-	(9.589±0.018)x10 ⁻³	(5.640±0.004)x10 ⁻²	(5.820±0.010)x10 ⁻²
	proton	(1.396±0.008)x10 ⁻³	(1.377±0.002)x10 ⁻²	(1.042±0.004)x10 ⁻²
	$\pi^+ + \pi^- + \text{proton}$	(1.226±0.002)x10 ⁻²	(8.944±0.009)x10 ⁻²	(8.605±0.014)x10 ⁻²
120°	neutron	0.990±0.002	0.927±0.001	0.929±0.002
	π^+	(9.328±0.041)x10 ⁻⁴	(1.480±0.001)x10 ⁻²	(1.314±0.003)x10 ⁻²
	π^-	(8.492±0.018)x10 ⁻³	(4.955±0.004)x10 ⁻²	(5.126±0.007)x10 ⁻²
	proton	(8.972±0.062)x10 ⁻⁴	(8.697±0.001)x10 ⁻³	(6.469±0.018)x10 ⁻³
	$\pi^+ + \pi^- + \text{proton}$	(1.032±0.002)x10 ⁻²	(7.305±0.006)x10 ⁻²	(7.086±0.009)x10 ⁻²
135°	neutron	0.991±0.002	0.936±0.001	0.938±0.002
	π^+	(7.991±0.038)x10 ⁻⁴	(1.287±0.001)x10 ⁻²	(1.139±0.002)x10 ⁻²
	π^-	(7.591±0.015)x10 ⁻³	(4.468±0.004)x10 ⁻²	(4.643±0.007)x10 ⁻²
	proton	(6.055±0.043)x10 ⁻⁴	(6.094±0.008)x10 ⁻³	(4.448±0.018)x10 ⁻³
	$\pi^+ + \pi^- + \text{proton}$	(8.996±0.019)x10 ⁻³	(6.364±0.006)x10 ⁻²	(6.227±0.009)x10 ⁻²

3. Response functions of the BSS to charged hadrons

The response functions to charged hadrons were calculated with the FLUKA code for the complete BSS, for monoenergetic broad parallel beams of protons, positive and negative pions with energy in the range 50 MeV – 150 GeV. The results are shown in Figs. 3-5. For the various detectors, the response functions to protons and positive pions is quite similar, with a rapid increase up to about 100 MeV followed by a flatter trend which is due to the fact the inelastic cross sections tend to the geometrical value. As expected, *Ollio* and *Stanlio* have a much higher response with respect to the polyethylene spheres. Negative pions show for most spheres an increased response below about 100 MeV. This is due to the fact that some π^- can be slowed down to rest inside the sphere, are captured and produce spallation reactions. This effect is expected to be larger for larger spheres, which is in fact the case except maybe for *Ollio*. Finally, it should be noted that the addition of a 1 mm cadmium shell to the 81 mm sphere increases its response to charged hadrons by a factor of 5 to 10.

Figure 3. Fluence response of the eight detectors of the BSS to protons.

These response functions were folded with the spectral fluences of neutrons and charged hadrons calculated for the 40 GeV/c positive pion beam on a silver target (Section 2), to verify the consistency with the former procedure used for estimating the percent contribution of neutrons and charged hadrons to the total ^3He count-rate. For this purpose the response functions of the BSS to neutrons, previously calculated up to 2 GeV [3], had to be extended to 40 GeV. The results of such a comparison are given in the next section.

4. Comparison of the two procedures to estimate the correction factor

In summary, the two methods used to determine the correction factor to be applied to the experimental results are the following:

Figure 4. Fluence response of the eight detectors of the BSS to positive pions.

Figure 5. Fluence response of the eight detectors of the BSS to negative pions.

- 1) Simulation of parallel beam irradiation by neutrons, protons, π^+ and π^- with source spectra obtained by scoring yields at various angles in a previous simulation of a target yield experiment. The correction factor for each angular interval is obtained as the ratio of the neutron response to the sum of the four responses to neutrons, protons, π^+ and π^- (section 2).
- 2) Calculation of energy response functions for parallel monoenergetic beams of protons, π^+ and π^- (and, when not already done, neutrons). Folding these response functions with the spectra obtained at various angles in the same previous target yield simulation as before, one obtains the contribution of each component. The correction factor for each angular interval is obtained as the ratio of the neutron contribution to the sum of the four contributions, neutrons, protons, π^+ and π^- (section 3).

The ratios of the results obtained with the two methods are listed in Table 2. The agreement is satisfactory for the 233 mm sphere and for *Ollio*. For *Stanlio* the agreement is satisfactory for neutrons, whilst data for charged hadrons show discrepancies up to a factor of 2. Although one is essentially interested in the correction factors for neutrons, this discrepancy is not completely negligible. One should also note that there are systematic trends in the discrepancy also for the other two detectors, which cannot be explained as random fluctuations but may rather point to a systematic error in one of the two procedures, possibly under-sampling of particles in the tail of the spectra. It should also be mentioned that the two procedures are based on the same calculated spectra, and therefore are not completely independent of each other

5. Experimental test with 120 GeV/c hadrons at CERF

A real “calibration” of the BSS response to charged hadrons would require the availability of broad beams of protons and charged pions of several defined energies up to tens of GeV, which is not really feasible. Nonetheless, an experimental verification of the response of the BSS to a monoenergetic beam of high-energy hadrons was performed at the CERF facility at CERN [8]. Each detector of the BSS was exposed to a 120 GeV/c positive hadron beam (composed of 1/3 protons and 2/3 pions) of Gaussian profile with FWHM of 30.5 mm and 31.7 mm in the horizontal and vertical planes, respectively (measured with a multi-wire proportional chamber). The beam impinged on each sphere at 25 mm from its centre (by irradiating the spheres at their centre, the count-rate was too high). MC simulations with the FLUKA code were performed reproducing the exact experimental conditions. The experimental data (counts per beam particle) are compared with the MC results in Table 3. The agreement is rather good except for the two smaller spheres where the experimental figure is about of factor 2 higher than the MC value. This may be due to the fact that, given the dimension of the sphere and the beam size, the sphere was not fully intercepting the beam. Even a small variation in the beam position and/or dimension would cause a significant variation in the count-rate. The good agreement between the MC predictions and the experimental data give confidence in the MC calculations of the BSS response functions.

6. Conclusions

Neutron spectral measurements performed at CERN in a high-energy radiation field have provided evidence that, when measuring around an unshielded target, the response of lead-enriched moderators in a BSS must be properly interpreted. These detectors were found to have a significant response to the charged hadron component accompanying the neutrons emitted from the target. Conventional polyethylene moderators show a similar behaviour although of lesser importance. MC simulations performed with the FLUKA code have allowed determining a correction factor to be applied to the unfolding procedure for the given experimental conditions. A complete response matrix of the extended BSS to charged pions and protons was subsequently calculated with FLUKA, for a more general use. An experimental verification of the response of the BSS to a monoenergetic beam of high-energy hadrons was performed at the CERF facility, confirming the MC calculations of the BSS

response functions. However, some discrepancies for one of the lead-loaded spheres (*Stanlio*) still have to be fully understood.

Table 2. Ratio of the percent contribution by neutrons, π^+ , π^- and protons to the total ^3He count-rate determined by the full MC simulations of the experimental set-up (see text, section 2) to that determined by folding the detector response function with the particle spectra (see text, section 3).

Angle	Particle	233 mm	Stanlio	Ollio
30°	neutron	0.97	0.71	1.03
	π^+	1.34	1.48	0.98
	π^-	1.32	1.45	0.99
	proton	1.32	1.44	0.95
45°	neutron	0.99	0.81	1.02
	π^+	1.36	1.70	0.97
	π^-	1.28	1.66	0.97
	proton	1.36	1.62	0.92
60°	neutron	0.99	0.88	1.02
	π^+	1.39	1.83	0.97
	π^-	1.25	1.79	0.94
	proton	1.32	1.73	0.89
75°	neutron	0.99	0.92	1.02
	π^+	1.38	1.90	0.95
	π^-	1.21	1.85	0.92
	proton	1.35	1.78	0.87
90°	neutron	1	0.94	1.01
	π^+	1.37	1.94	0.94
	π^-	1.18	1.89	0.89
	proton	1.35	1.81	0.85
105°	neutron	1	0.96	1.01
	π^+	1.39	1.96	0.93
	π^-	1.16	1.90	0.87
	proton	1.36	1.82	0.82
120°	neutron	1	0.96	1.01
	π^+	1.35	1.97	0.91
	π^-	1.15	1.91	0.86
	proton	1.38	1.82	0.81
135°	neutron	1	0.97	1.01
	π^+	1.36	1.98	0.91
	π^-	1.14	1.92	0.85
	proton	1.35	1.82	0.80

Table 3. Counts per beam particle of the BSS detectors exposed to a narrow beam of 120 GeV/c protons/positive pions. The beam impinged on each sphere at 25 mm from its centre. The MC results are the weighted sum of the response to protons (1/3) and pions (2/3).

	81 mm	108 mm	133 mm	178 mm	233 mm	<i>Stanlio</i>	<i>Ollio</i>
MC	(4.95±0.04) x10 ⁻⁵	(2.24±0.02) x10 ⁻⁴	(4.30±0.04) x10 ⁻⁴	(8.97±0.10) x10 ⁻⁴	(1.31±0.01) x10 ⁻³	(2.59±0.03) x10 ⁻²	(4.47±0.01) x10 ⁻²
Experimental	(7.81±0.78) x10 ⁻⁵	(3.41±0.34) x10 ⁻⁴	(3.88±0.39) x10 ⁻⁴	(1.16±0.12) x10 ⁻³	(1.69±0.17) x10 ⁻³	(2.72±0.27) x10 ⁻²	(3.60±0.36) x10 ⁻²

Acknowledgements

The authors wish to thank T. Otto (CERN) and C. Birattari (University of Milano, Italy) for useful discussions. They are also indebted to A. Foglio Para (Polytechnic of Milano, Italy) for providing the unfolding of the experimental data.

References

1. S. Agosteo, C. Birattari, E. Dimovasili, A. Foglio Para, A. Mitaroff, M. Silari, L. Ulrici and H. Vincke, *Neutron production from 40 GeV/c hadrons on thin copper, silver and lead targets in the angular range 30°–135°*, to be published.
2. S. Agosteo, C. Birattari, A. Foglio Para, L. Gini, A. Mitaroff, M. Silari and L. Ulrici, *Neutron production from 158 GeV/c per nucleon lead ions on thin copper and lead targets in the angular range 30°–135°*, Nuclear Instruments and Methods B 194, 399-408, 2002.
3. C. Birattari, P. Cappellaro, A. Mitaroff and M. Silari, *Development of an extended range Bonner Sphere Spectrometer*, Proceedings of Monte Carlo 2000 – Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications, Lisbon (Portugal), 23-26 October 2000, Eds. A. Kling, F. Barão, M. Nakagawa, L. Távora and P. Vaz, Springer-Verlag (2001), p.1157-1162.
4. M. Matzke, *Unfolding of pulse height spectra: the HEPRO program system*. Braunschweig, Germany, PTB, Bericht 19 (1994).
5. A. Fassò, A. Ferrari, P.R. Sala, *Electron-photon transport in FLUKA: status*, Proceedings of the Monte Carlo 2000 Conference, Lisbon, 23-26 October 2000, A. Kling, F. Barao, M. Nakagawa, L. Tavora, P. Vaz eds., Springer-Verlag Berlin, pp. 159-164 (2001).
6. A. Fassò, A. Ferrari, J. Ranft, P.R. Sala, *FLUKA: Status and prospective for hadronic applications*, Proceedings of the Monte Carlo 2000 Conference, Lisbon, 23-26 October 2000, A. Kling, F. Barao, M. Nakagawa, L. Tavora, P. Vaz eds., Springer-Verlag Berlin, pp. 955-960 (2001).
7. <http://www-nds.iaea.or.at/ndsout/endlf2784.endf>
8. A. Mitaroff and M. Silari, *The CERN-EU high-energy Reference Field (CERF) facility for dosimetry at commercial flight altitudes and in space*, Radiation Protection Dosimetry 102, 7-22, 2002.