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STUDIES ON NEUTRON PRODUCTION IN THE INTERACTION OF 7.4 GEV PROTONS WITH EXTENDED LEAD TARGET

S.R. HASHEMI-NEZHAD(1)*, R. BRANDT(2), M. OCHS(2), J.-S. WAN(2),
TH. SCHMIDT(2), E.-J. LANGROCK(2), P. VATER(2), J. ADAM(3),
V.P. BAMBLEVSKIJ(3), V. BRADNOVA(3), L.K. GELOVANI(3),
V.K. KALINNIKOV(3), M.I. KRIVOPUSTOV(3), B.A. KULAKOV(3),
A.N. SOSNIN(3), V.P. PERELYGIN(3), V.S. PRONSKIKH(3),
V.I. STEGAILOV(3), V.M. TSOUPKO-SITNIKOV(3), G. MODOLO(4),
R. ODOJ(4), P.-W. PHLIPPEN(4), J.-C. ADLOFF(5), M. DEBEAUVAIS(5),
M. ZAMANI-VALASSIADOU(6), K.K. DWIVEDI(7) AND B. WILSON(8)

[1] High Energy Physics Dept., School of Physics, University of Sydney, Sydney,
NSW 2006, Australia
[2] Kernchemie, Philipps-University, D-35032 Marburg, Germany
[3] Joint Institute for Nuclear Research, Dubna 141980, Russia
[4] Forschungszentrum Jülich, FZJ, D-54245 Jülich, Germany
[5] Institute de Recherche Subatomic, University L. Pasteur, F-67037 Strasbourg, France
[6] Physics Department, Aristotle University, Thessaloniki 54006, Greece
[7] Department of Chemistry, North-Eastern Hill University, Shillong 793003, India
[8] Los Alamos National Laboratory, Los Alamos, NM 87545, USA

ABSTRACT

A cylindrical lead target of diameter 8 cm and length 20 cm was irradiated with 7.4 GeV protons along the axis of the cylinder. The lead target was surrounded with a paraffin layer of thickness 6 cm to moderate the neutrons produced in p + Pb reactions. The spatial distribution of the slow and fast neutrons on different surfaces of the moderator were determined using LR 115 2B detectors (through $^{10}\mathrm{B}(n,\alpha)^{7}\mathrm{Li}$ reactions) and CR39 detectors (through proton recoils) respectively. Such results can be valuable in the studies and design of Accelerator Driven Subcritical Nuclear Reactors and Nuclear Waste Incinerators.

KEYWORDS

Neutron distribution; subcritical systems; LR 115 2B detector.

INTRODUCTION

Neutrons produced in the interaction of relativistic ions with extended heavy targets can be used in a new type of nuclear technology which is based on subcritical systems (see e.g. Andriamonje *et al.*, 1995; Ochs *et al.*, 1997). It is proposed that such systems can be used as a highly efficient means of energy production from relatively abundant and inexpensive fuel (thorium) (Fernandez *et al.*, 1996) as well as in the incineration of nuclear waste which is concern of the nuclear industry (Bowman *et al.*, 1992; Wan *et al.*, 1997). The viability and feasibility studies on design and operation of such subcritical systems require a detailed knowledge of the neutron production in the process of

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* e-mail: reza@physics.usyd.edu.au

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interaction of relativistic ions with a given target material. In this work we investigate the neutron distribution in a target-moderator system that is used for such studies.

EXPERIMENTAL PROCEDURE

(a) Sample irradiations

Figure 1 illustrates the target, moderator and detector systems. The lead target is a cylinder of diameter 8 cm and length 20 cm, composed of 20 disks of thickness 1 cm, surrounded with a paraffin moderator of thickness 6 cm on all sides except in the front base of the target cylinder where the proton beam strikes the target parallel and around the axis of the cylinder. The plastic detectors were mounted on the moderator as shown in Fig. 1. We will use the labels "FRONT", "TOP", "BACK" and "INside" for detectors that were mounted on the front, top, back and inside of the moderator respectively (Fig.1).

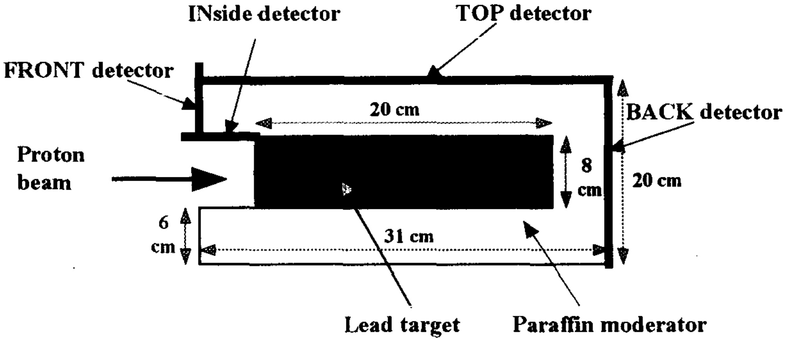

Fig. 1. The target-moderator assembly used in the experiment (see the text for details).

The detector assemblies are shown in Fig. 2. For each of the TOP, FRONT and INside locations on the moderator two sets of detector assemblies were prepared. In Fig. 2 these are labelled (a) and (b). Type (a) detector systems were installed to register α-tracks in LR 115 2B foils via $^{10}B(n,\alpha)^{7}Li$ reactions initiated by thermal and epithermal neutrons, while the CR39 detectors were used to register the fast neutron induced proton recoil tracks in the polythene converter on the CR39, as well as those produced within the CR39 detector itself. Type (b) detector systems consisted of LR- 115 2B foils that were covered by a Cd foil of thickness 0.75 mm as a thermal neutron shield. In both cases, the type (a) and (b) the detectors were mounted on a 2 mm thick perspex backing, and the whole system was wrapped in 10 μm thick polythene foil. The length of the TOP, FRONT and INside detectors were 31cm, 7 cm and 6 cm respectively. In the case of the BACK detector (with a length of 20 cm), 10 cm of the length was type (a) and the remaining 10 cm was type (b). The widths of the LR 115 2B, CR39 and Cd foils were all ~1.5 cm.

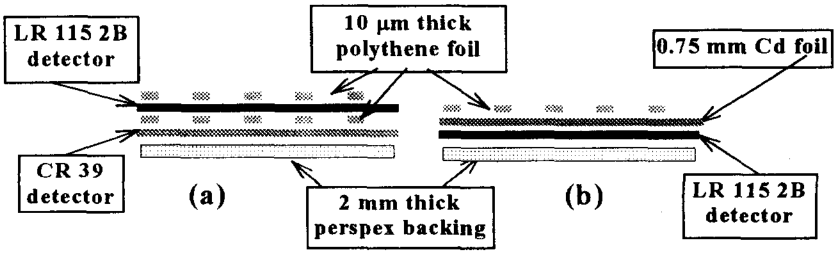

Fig. 2. Detector assemblies used in the experiments (see the text for details).

Both types of the (a) and (b) detector assemblies were mounted on the moderator as shown in Fig. 1. As the central region of the back surface of the moderator was occupied with a different sample (not discussed in the present paper) the BACK detector was mounted on a cord at a perpendicular distance of 3.3 cm from the centre. The target was irradiated with 7.4 GeV protons of fluence ~ 4 × 10^{11} at the Synchrophasotron of the Laboratory of High Energies (LHE), JINR in Dubna, Russia. The typical beam profiles for these irradiations are given by (Perelygin *et al.*, 1998).

b) Etching of the samples

The LR 115 2B detectors for each irradiation were etched together in 2.5 N NaOH at 60 °C for a period of 2h. As the sensitive layer of these detectors is only 12 μm thick, some fraction of the etched damage trails result in etched through tracks.

An examination of the etched samples under an optical microscope showed that the track density in the majority of the samples is too high and many of the tracks overlap, making the track counting almost impossible (Fig. 3a). However the number of the etched through tracks was not too high and the number of overlapped tracks was a few orders of magnitude less than the case when the all tracks were taken into account.

We used the red colour of the LR 115 detectors as an advantage to improve the contrast of the etched through tracks. When LR 115 detectors were observed using appropriate green filters the etched through tracks appear as bright spots in black background which makes the counting of the tracks much easier (Fleischer *et al.*, 1975). Fig. 3 shows images of a field of view when observed using ordinary light and green light. Obviously the number of the etched through tracks in a given sample is related to the removed thickness of the detector (Hashemi-Nezhad, 1994).

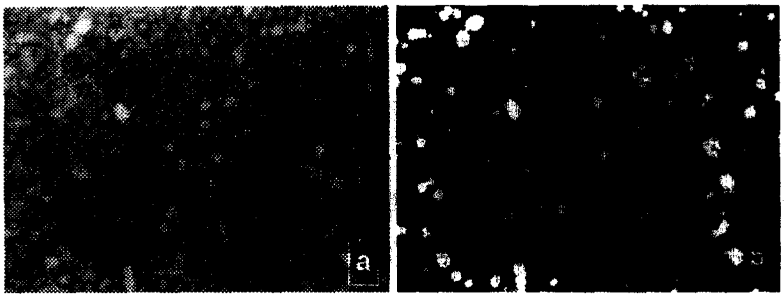

Fig. 3. Images of etched alpha tracks in LR 115 2B track detector corresponding to the same field of view when viewed by an optical microscope. (a) Tracks observed using ordinary light and (b) when observed using green light.

We used TASTRAK CR39 detectors (made by TASL, Bristol, UK), which were etched in 6 N NaOH at 70 °C for a period of 6 h. In these etching conditions the size of the tracks were adequate for the track counting process.

(c) Track counting

For a single exposure and the detector set-up used in this work the total length of the plastic detectors that must be analysed is 172 cm. We extended the abilities of our computer controlled optical microscope (CCOM), (Hashemi-Nezhad and Dolleiser, 1997) to include automatic focussing, scanning and track counting even though we are still restricted by the limited length of the stage movement (2.5 cm). In this system a track will be counted as an etched through track if the grey level of the captured image of the track is above a certain threshold value G_{th}. For many tracks the thickness between the end of the track and back side of the sensitive layer of the detector is small enough to allow the intensity of the transmitted light to be above G_{th}, without tracks being etched through. For this reason the measured quasi-etched through track densities cannot be directly translated into total track densities using the theoretical efficiency (Hashemi-Nezhad, 1994). Nevertheless the measured track density will be proportional to the total track density regardless of the G_{th} setting. This is due to the fact that, α-particles produced via $^{10}B(n,\alpha)^{7}Li$ reactions are initiated by thermal and epithermal neutrons, and $^{11}B^{*}$ compound nuclei do not carry a significant momentum. In such circumstances it is expected that the emitted α-particles will have a random emission direction upon decay of $^{11}B^{*}$ nuclei.

RESULTS AND DISCUSSIONS

Slow neutrons

Figure 4a,4b and 4c illustrate the alpha track distributions initiated by slow neutrons (thermal and epithermal) in LR 115 2B detectors, in FRONT, TOP and BACK detectors respectively and for type (a) and type (b) detector assemblies. The horizontal axis X, is the distance on the moderator surface. For TOP detectors the distance was measured from the left to right along the beam line and in the case of the BACK and FRONT detectors X, represents the radial distance from the common axis of the target-moderator assembly (Fig. 1).

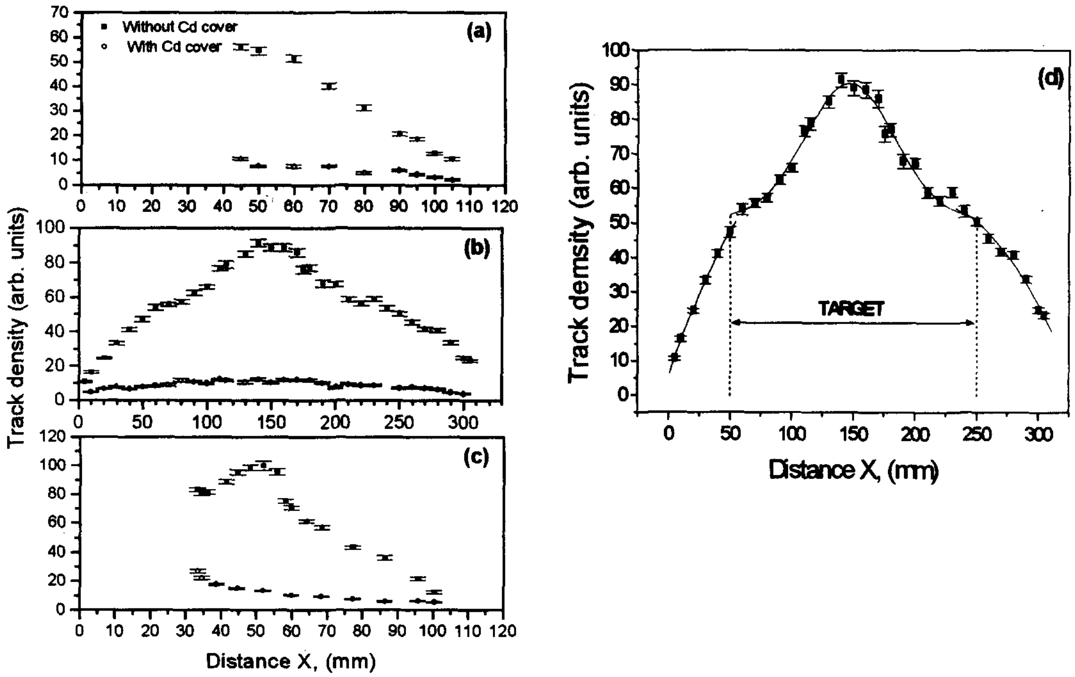

Fig. 4. Spatial distribution of slow neutrons on different surfaces of the moderator, as determined by means of α-tracks in LR 115 detectors via $^{10}B(n,\alpha)^{7}Li$ reactions. (a) FRONT (b) TOP and (c) BACK detectors. (d) Re-illustrates the track density distribution in TOP detector along with best fit curves to different parts of the distribution.

The length of the FRONT detectors was 1 cm longer than the moderator thickness of 6 cm and this extra length appears at distances X > 100 mm in Fig. 4a. Each data point in Fig. 4 represents the mean value of the track densities in more than 50 fields of view. The INside LR 115 2B detector was not analysed as the track density in this detector was too high and overlapping tracks were too many (even for perforated tracks). It can be seen from Fig. 4 that the Cd cover is capable of reducing the track densities dramatically when compared with the case of the detectors without Cd cover.

The track density distributions for unshielded detectors on the TOP (Fig. 4b) and the BACK (Fig. 4c) of moderator exhibit interesting features. In the case of the TOP detector there is a hump exactly on top of the lead target. Note that the target extends between 50 mm to 250 mm along the beam line and within the paraffin moderator (Fig. 1). The track densities for the region between 0 - 60 mm and 240 - 310 mm fits to second order polynomials, while the track densities corresponding to $x = 60$ - 240 mm fit very well to a Gaussian distribution. Figure 4d shows the track distribution in the unshielded TOP detector along with the best fit curves to the different regions of the distribution. With the knowledge of the total area under the fitted curves, between $x = 0$ and $x = 310$ mm, the best fit curves can be converted to probability functions as ;

$$p(x) = B_0 + B_1 x + B_2 x^2 \qquad \text{For} \quad 0 \le x \le 60 \ \text{mm} \quad \text{and} \quad 240 \le x \le 310 \ \text{mm} \tag{1}$$

$$p(x) = y_0 + \frac{A}{w\sqrt{\pi/2}} e^{-2\frac{(x-x_c)^2}{w^2}} \qquad \text{For} \quad 60 \le x \le 240 \ \text{mm} \tag{2}$$

The parameters of the functions are given in Table 1. These probability functions can be useful in generalising the neutron fluence evaluations say by radiochemical methods when the slow neutron fluences in a limited number of locations on the moderator are known.

A comparison of the total area under the track density distribution in Fig. 4d with that corresponding to region $x = 50$ - 250 mm (i.e the target area) and under the Gaussian distribution alone (without considering the offset y_0 in Eq. 2), shows that 20.3% of the total tracks in the unshielded LR 115 detector lay under the hump.

Table 1. Parameters of the probability functions (Eqs 1 and 2), for slow neutron distribution on TOP of the moderator and along the beam line (Fig. 1).

x (mm)	y_0	A	w (mm)	x_c (mm)	B_0	B_1	B_2
0 - 60	-	-	-	-	$(3.41 \pm 0.24)\times10^{-4}$	$(5.91 \pm 0.22)\times10^{-4}$	$(-2.16 \pm 0.42)\times10^{-7}$
60 - 240	$(2.97 \pm 0.10)\times 10^{-3}$	0.204 ± 0.02	72.04 ± 4.05	146.83 ± 1.26	-	-	-
240 - 310	-	-	-	-	$(-7.42 \pm 7.22)\times10^{-3}$	$(9.87 \pm 5.2)\times10^{-5}$	$(-2.29 \pm 0.92)\times10^{-7}$

The track density distribution in the unshielded BACK detector shows an enhanced presence of slow neutrons around $X = 52$ mm. Note that in Fig. 4c the base of the cylindrical target within the moderator extends from $X = 0$ - 40 mm. An experiment with moderated laboratory neutron source and also a Monte Carlo simulation showed that such a behaviour is not the result of the detector setup which for the case of the BACK detector was type (a) and type (b) both occupying half the length. The track density distributions in the cadmium shielded TOP and BACK detectors do not show any obvious irregularities (Fig. 4).

Fast neutrons

Figure 5 shows the distributions of the tracks in CR39 detectors, measuring the fast neutrons, at the TOP, BACK, INside and FRONT of the moderator. For BACK and FRONT detectors (Fig. 5b and 5d), $X = 0$ represents the outer surface of the moderator. For BACK detector X is the distance along the cord that detector was mounted, while for the FRONT detectors the X measurements were made from the surface of the moderator towards the common axis of the target-moderator assembly (Fig. 1).

The tracks in CR39 detectors are produced predominantly by the recoil of the nuclei in the detector material (mainly hydrogen) in the process of elastic scattering of the energetic neutrons. Also there exists the probability of nuclear interaction of the fast neutrons with detector nuclei (such as $^{12}C(n,\alpha)^{9}Be$), resulting in particles with higher stopping powers than protons.

From consideration of the CR39 detector arrangements (Fig. 2a) it becomes clear that if α-particles produced in the boron coating of the LR 115 have energies $E_\alpha > 12$ MeV, they can penetrate the 112 μm thick layer of LR 115 2B foil and 10 μm thick polyethylene foil and leave tracks in CR39. Such α-particles can be produced by neutrons of $E_n > 9.7$ MeV. Although at these energies cross sections for H(n,n')H is less than that for $^{10}B(n,\alpha)^{7}Li$ reaction the number of p-recoil tracks must be much higher than α-tracks due to the much larger number of H nuclei that are available for interaction. It should be noted that the obtained distributions shown in Fig. 5, represent only those neutrons that are capable of leaving etchable tracks (through a nuclear reaction), under the etching and observation conditions used in this work.

The distribution of the fast neutrons on TOP and BACK of the moderator (Fig.5), fit perfectly to Gaussian distributions, with probability functions of the form given by Eq. 2 and with parameters shown in Table 2.

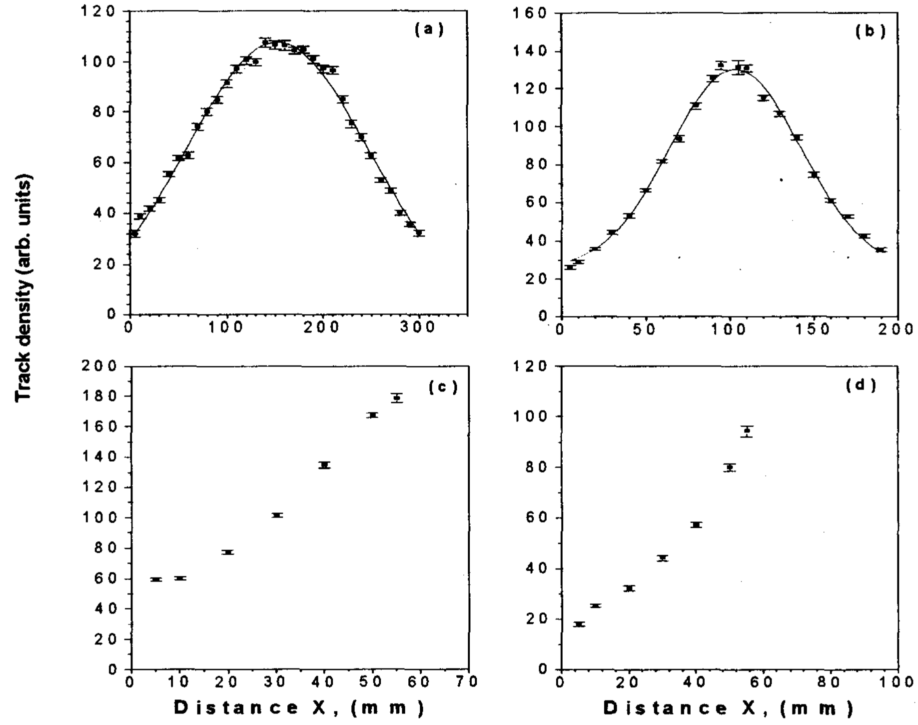

Fig. 5. Spatial distribution of the fast neutron induced tracks in CR39 detectors on (a) TOP (b) BACK (c) INside and (d) FRONT of the moderator. Fast neutrons in TOP and BACK of the moderator have a Gaussian distribution. The horizontal axis, X, represent distance on different surfaces of the moderator (see the text for details). In the case of the INside detector (c), X= 60 mm represents the surface of the target (Fig.1).

Table 2. Parameters of the Gausssian probability functions (Eq. 2) describing the fast neutron distributions on TOP and the BACK of the moderator (Fig. 1).

	y_0	A	w (mm)	x_c (mm)
TOP	$(8.91 \pm 31.50)\times10^{-5}$	1.075±0.21	185.81±10.77	152.51 ± 0.83
BACK	$(1.80 \pm 0.16)\times10^{-3}$	0.719±0.032	77.42±2.27	103.50 ± 0.55

It is interesting to note that the fast neutrons both on TOP and BACK detectors show no irregularities compared to the shape of the slow neutron distributions (Fig. 4). Furthermore the following remarks can be made on the observed neutron distributions on the moderator surface;

1. The track density distributions in CR39 detectors indicate that, there are quite large numbers of neutrons that leave the moderator surface as fast neutrons.
2. The fast neutrons in the TOP surface have a distribution which is symmetrical around a plane perpendicular to the beam line and passing though (about) the centre of the target.
3. Fast neutrons on the BACK surface have a distribution which is symmetrical around beam line.
4. Significant numbers of fast and slow neutrons leak out of the front face of the moderator.
5. The INside CR39 has the highest track densities, as it is exposed to a larger area of the moderator.
6. Although the neutrons resulting from target nuclei spallation are forward peaked, the observed slow and fast neutron distributions on the different surfaces of the moderator, indicate that the neutron distribution tends to become isotropic in the process of moderation in lead and paraffin. This conclusion becomes more obvious when one detects almost comparable number of slow and fast neutrons in front and back faces of the moderator.

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REFERENCES

Andriamonje S., Angelopoulos A., Apostolakis A., Attale F., Brillard L., Buono S., Calero J., Carminati F., Casagrande F., Cennini P., Charalambous S., Del Moral R., Eleftheriadis C., Gallego E., Galvez J., Garcia-Tabares L., Geles C., Goulas I., Giorni A., Gonzalez E., Hussonnois M., Jaren J., Klapisch R., Kokkas P., Lemeilleur F., Lindecker G., Liolios A., Loiseaux J.M., Lopez C., Lorente A., Macri M., Martinez-Val J.M., Nifenecker H., Oropesa J., Pavlopoulos P., Pinston J.A., Revol J-P., Roche C., Rubbia C., Rubio J.A., Sakelariou K., Saldana F., Schussler F., Tamarit J., Trubert D., Vieira S., Vlachos S., Xuan Li, Zarris G. (1995) Experimental Determination of the Energy Generated in Nuclear Cascade by a High Energy Beam. *Phys. Lett.* **B 346**, 697-709.

Bowman C.D., Arthur E.D., Lisowski P.W., Lawrence G.P., Jensen R.J., Anderson J.L., Blind B., Cappiello M., Davidson J.W., England T.R., Engel L.N., Haight R.C., Hughes III H.G., Ireland J.R., Krakowski R.A., LaBauve R.J., Letellier B.C., Perry R.T., Russell G.J., Staudhammer K.P., Versamis G. and Wilson W.B., (1992) Nuclear Energy Generation and Waste Transmutation using an Accelerator-Driven Intense Thermal Neutron Source. *Nucl. Instrum.Meth.* **A 320**, 336-367.

Fernandez R., Mandrillon P., Rubbia C. and Rubio J.A. (1996) A Preliminary Estimate of the Economic Impact of the Energy Amplifier. CERN preprint, *CERN/LHC/96-01.*

Fleischer R.L., Price P.B. and Walker R.M. (1975) *Nuclear Tracks in Solids*, University of California Press, Berkely, P. 91.

Hashemi-Nezhad S. R. (1994) Determination of the Energy Limits and Efficiency of Track Detectors for the Formation of Etched Through Tracks. *Nucl. Instrum. Meth.* **B 86**, 303-310.

Hashemi-Nezhad S. R. and Dolleiser M. (1997) A Computer Controlled Optical Microscope for Three Dimensional Track Analysis. *Rad. Meas.* **28**, 839-844.

Ochs M., Abdullaev I.G., Adam I., Adloff C.J., Bersina I.G., Baradnova V., Brandt R., Bognitzki M., Bustev V.S., Debeauvais M., Dwivedi K.K., Fernandez F., Guo S.-L., Krivopustov M.I., Kulakov B.A., Langrock E.-J., Modlo G., Odoj R., Perelygin V.P., Priemyshev A.N., Pronskich V.S., Schmidt T., Sosnin A.N., Stegailov V.I., Sudowe R., Vater P., Wan J. -S., Zamani M. and Zupko-Sitnikov V.M. (1997) SSNTD and Radiochemical Studies on the Transmutation of Nuclei using Relativistic Ions. *Rad. Meas.* **28**, 225-268.

Perelygin V.P., Kulakov B.N., Krivopustov M.I., Petrova R.I., Abdullaev I.G., Bradnova V., Knjazeva G.P., Brandt R., Ochs M., Wan J.S., and Vater P., (1998) SSNTD Studies of Lead Nuclei Fission by Relativistic p, d, He and ^{12}C Projectiles Inside Massive Cu, Pb and U Targets (this issue)

Wan J.-S., Ochs M., Brandt R., Schmidt Th., Langrock E.-J., Vater P., Abdullaev I.G., Adam J., Bamblevski V.P., Bradnova V., Bustev V.S., Gelovani L., Golubev P.I., Kalinnikov V.K., Karachuk J., Krivopustov M.I., Kulakov B.A., Sosnin A.N., Perelygin V.P., Priemyshev A.N., Pronskikh V.S., Stegailov V.I., Tsoupko-Sitnikov V.M., Adloff J.C., Debeauvais M., Modolo G., Odoj R., Phlippen P.-W., Zamani M., Dwivedi K.K. and Wilson B. (1998) Transmutation of Radioactive Waste with the help of Relativistic Heavy Ions. *Kerntechnik*, **63**, 167-177.