U.P.B. Sci. Bull., Series A, Vol. 73, Iss. 3, 2011 ISSN 1223-7027

MEASUREMENTS OF THE ATMOSPHERIC MUON FLUX IN THE UNDERGROUND OF SLANIC PRAHOVA SALT MINE

Bogdan MITRICA [1], Mirel PETCU[2], Iliana BRANCUS[3], Heinigerd REBEL[4], Andreas HAUNGS[5], Adrian OPRINA[6], Florinel CHIPESIU[7], Marian PETRE[8], Chivuta BADITA[9], Carmelia PETRE[10] Irinel PRECUP[11]

Masuratori ale fluxului de miuoni de mare energie in subteranul minei de sare de la Slanic Prahova, Romania au fost efectuate cu ajutorul unui nou detector mobil construit in cadrul IFIN-HH, Bucuresti. Detectorul este format din doua placi scintilatoare (cu suprafata de aproximativ 2 m^2), care masoara in coincidenta. Intreg sistemul este instalat pe un autovehicul, fapt ce permite masurarea fluxului de miuoni in difeite locatii, atat la suprafata cat si in subteran. Detectorul a fost utilizat pentru masuratori ale fluxului de miuoni in diferite puncte de pe teritoriul Romaniei si in subteranul minei de sare de la Slanic Prahova, Romania. Adancimea in metri echivalent apa a minei de la Slanic a fost determinat, iar rezultatele au fost comparate cu simulari Monte-Carlo efectuate cu ajutorul codurilor CORSIKA si MUSIC.

Measurements of the high energy muon flux in underground of the salt mine from Slanic Prahova, Romania was performed using a new mobile detector developed in IFIN-HH, Bucharest. The detector consists of 2 scintillator plates (aprx. 0.9 m^2) measuring in coincidence was installed on a van which facilitates measurements on different positions at surface or in underground. The detector was used to measure muon fluxes at different sites from Romania and in the underground of the salt mine from Slanic Prahova, Romania. The m.w.e. (meter water equivalent)

[1] Researcher, Horia Hulubei National Institute of Physics and Nuclear Engineering - IFIN HH, România, e-mail: mitrica@nipne.ro
[2] Researcher, Horia Hulubei National Institute of Physics and Nuclear Engineering - IFIN HH, România, România
[3] Researcher, Horia Hulubei National Institute of Physics and Nuclear Engineering - IFIN HH, România, România
[4] Prof., Karlsruhe Institute of Technology - Campus North, 76021, Karlsruhe, Germany
[5] Researcher, Karlsruhe Institute of Technology - Campus North, 76021, Karlsruhe, Germany
[6] Eng., National Company of Salt, SNS SALROM SA, Slanic, Romania
[7] Eng., National Company of Salt, SNS SALROM SA, Slanic, Romania
[8] Eng., Horia Hulubei National Institute of Physics and Nuclear Engineering - IFIN HH, România, România
[9] Researcher, Horia Hulubei National Institute of Physics and Nuclear Engineering - IFIN HH, România, România
[10] PhD student, Horia Hulubei National Institute of Physics and Nuclear Engineering - IFIN HH, România, România
[11] PhD student, Horia Hulubei National Institute of Physics and Nuclear Engineering - IFIN HH, România, România

depth of the mine was investigated, and the results were compared with detailed Monte-Carlo simulation performed with CORSIKA and MUSIC codes.

Keywords: muon flux, Monte-Carlo simulation, underground.

1. Introduction

As leptons muons are less affected by hadronic interactions and hence interact weakly with matter. They penetrate large thicknesses of matter before they are stopped and decay, and they are historically known as ”penetrating component” of secondary cosmic rays, even detectable in deep underground sites. These features imply a variety of aspects in different branches of science, in elementary particle physics as ”heavy electron”, as messenger of astrophysical processes, in environmental and material research inducing natural radiation damages, and with a role of cosmogenic production of long living isotopes. It is evident that the flux of atmospheric muons is a quantity of high interest and an information which characterizes the site of a nuclear physics laboratory which is planned for far reaching investigations.

Though the intensity of the underground muon flux decreases with depth, so that experiments are more troublesome in acquiring the necessary statistical accuracy, careful measurements may provide details about the origin of high energy muons i.e. the relative contributions arising from decay of pions and kaons generated by the primary hadronic interaction processes [1]. A different reason for measuring the flux of the atmospheric muons in underground arises from the practical necessity of information on the cosmic radiation background for different sites. It should be noted that this background does not only consists of only muons which have survived the passage through the rock above, but also of contributions of natural radioactivity and of muon induced radiation like neutrons, which can play a decisive role for particular aspects.

A mobile device for measuring the muon flux was set-up and is in operation since the autumn of 2009, for measuring the muon flux at the surface and in the underground. Measurement of the water equivalent depth of any underground site could be done in a reasonable time scale. This feature is important in order to establish very accurately the overburden thickness in water equivalent of matter (mwe). First measurements have been performed on the underground site of the Slanic-Prahova mine where IFIN-HH is setting up a low -radiation level laboratory.

2. The LAGUNA project

LAGUNA [2] (Design of a pan-European Infrastructure for Large Apparatus studying Grand Unification and Neutrino Astrophysics) is a research project, supported by the European Union to setup the infrastructure for a large underground laboratory with a first step to explore adequate locations for looking for extremely rare events like proton decay or for the experimental research of Dark Matter. Seven underground laboratories of Great Britain, France, Spain, Finland, Italy, Poland and Romania are involved. For LAGUNA, three detector types are considered based on different active detection media: MEMPHYS with water [3], LENA, a liquid scintillator detector [4] and GLACIER using liquid argon [5]. The site for LAGUNA experiments will be chosen along different criteria: the depth of the site i.e. the ability to absorb and shield against high energy muons, the available space and possibility to install a large volume detector inside (larger than 100.000 m3), and the natural radiation background. The site proposed in Romania is located in the salt mine Slanic Prahova.

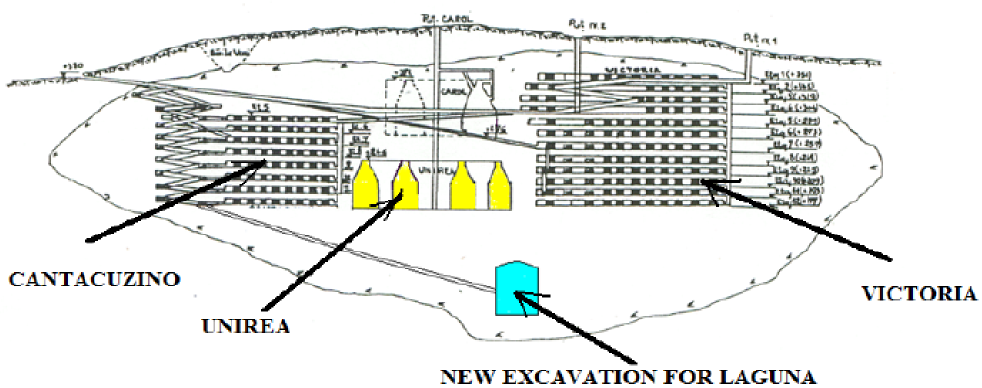

Fig. 1. The salt ore of Slanic

The salt ore from Slanic consists in a lens of 500 m thickness, few kilometers long and wide (see Figure. 1). The salt is extracted from the Slanic mine continuously since ancient times and, due to this fact, many galleries (i.e. shaped caverns) are already excavated.

The largest one is the ”tourist” mine ”Unirea” (see Figure.2) characterised by:

- temperature: 12.0 -13.0° C; - humidity: 65-70 %
- excavated volume: 2.9 million $m^{3;}$ - floor area: 70000 m^2
- average high: 52-57 m; - aerosols < 10µm: $2{\cdot}10^8$ part/m^3
- distance between walls: 32-36 m
- existing infrastructure: electricity, roads, railway, elevator, phone, Internet, GSM networks (also inside the galleries).

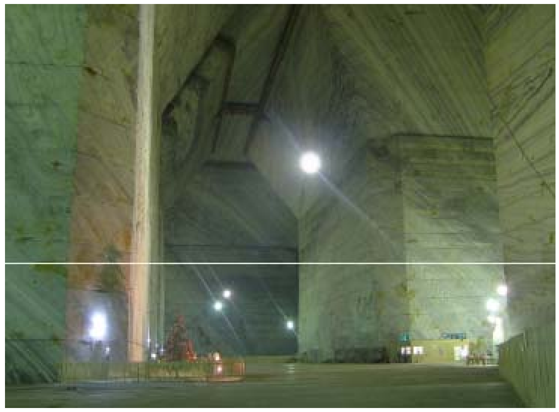

Fig. 2. UNIREA mine

Since 2006 a new laboratory (μBqlab) [6, 7] for low background measurements was installed by IFIN-HH in the UNIREA salt mine of Slanic Prahova. From the Slanic site a huge volume of material has been already excavated, but the shallow depth could induce a problem. Following [8] for the GLACIER experiment the Slanic mine could be a feasible location as for this technique a depth of only 600 mwe is necessary. Unfortunately, the water equivalent depth (mwe) of the Unirea mine has not yet been determined in detail.

3. Monte-Carlo simulation of the muon flux in underground

Monte-Carlo simulations were used to perform some preliminary explorations regarding the expected results of the experimental studies. Different simulation codes have been used:

- CORSIKA [9] (COsmic Ray SImulation for KAscade), a sophisticated Monte-Carlo code for simulations of the developmentof extensive air showers (EAS) in the atmosphere, has been used to estimate the muon flux at surface.

- MUSIC [10] (MUon SImulation Code) is a simulation tool for 3 dimensional simulations of the muon propagation through rock. It takes into account energy losses of muons by pair production, inelastic scattering, bremsstrahlung and ionisation as well as the angular deflection by multiple scattering. The program uses the standard CERN library routines and random number generators.

- GEANT [11], the detector simulation package from CERN has been used to simulate the interaction of the muons with the detector and for a proper calibration of the signal.

The muon flux on surface can also be estimated by semi-analytical formulae of Nash [12] and Gaisser [13]. Figure.3 displays the muon fluxes at surface (CORSIKA simulation) and in underground at 600 mwe (simulated by

MUSIC using the muon flux from CORSIKA as input). The triangles represent only the muons from surface that managed to pass through the rock.

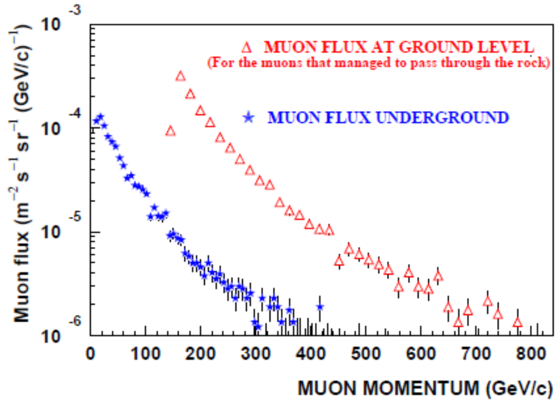

Fig. 3. The simulated muon flux at the surface and in the mine.

The energy cut off for the surviving muons is estimated to be around 150 GeV. By these simulation studies we estimate the expected muon rate at 600 mwe to about 10 muons/m^2min.

4. The apparatus

The mobile detector was set-up in IFIN-HH and it consists of 2 detection modules. Each module is a scintillator plate of 0.9025 m^2 and 3 cm thickness, see Figure. 4, divided in 4 parts (0.475 x 0.475 m^2) [14], readout by two photomultiplier tubes which receives the signal trough a central wave length shifter. Local variation of light transfer have been estimated at ± 4.5% [15]. The modules are arranged one on the top of each other (at 8.5 cm distance), in order to identify the transversing muons as coincidence event.

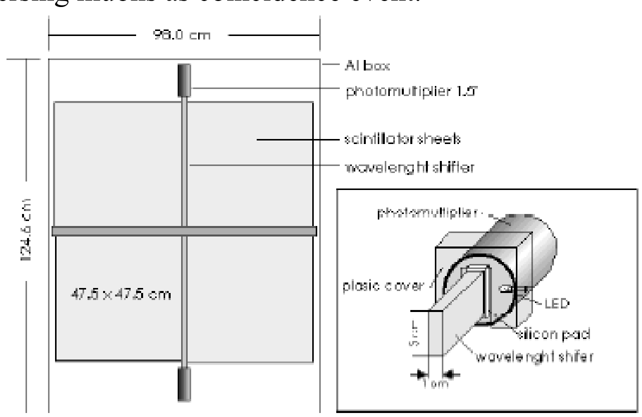

Fig. 4. The detection module. Design of KASCADE [14].

The signals from the 4 photomultiplier tubes are readout by a coincidence electronic system which is supplied by a high voltage NIM standard module for the 4 photomultipliers.

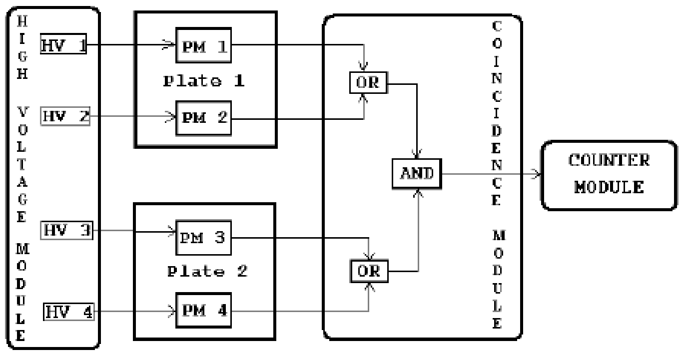

Fig. 5. The electronic detection system.

A coincidence NIM standard module processes the detector signals. The signals from the two photomultipliers from one detection module are set in anti-coincidence and then the resulting signals are analysed for coincidences - (1 or 2) and (3 or 4) (see Figure. 5). A counter module registers the coincidence events.

The detector response is simulated by use of the GEANT 3.21 code. The interaction of the muon with the active detector material and the deposit of the energy in the scintillator plates are analysed. Figure. 6 displays the energy deposit by muons (generated from CORSIKA output) in each detection plate.

The angular acceptance of the detector was also investigated considering only downward propagating muons, taking in to account the fact that not all muons interact with the first layer, but manage to pass to the second one (see Figure. 7). Thus, based on GEANT simulations (which include the detection efficiency of both planes), a correction factor of +9% has to be applied on the observed muon rate.

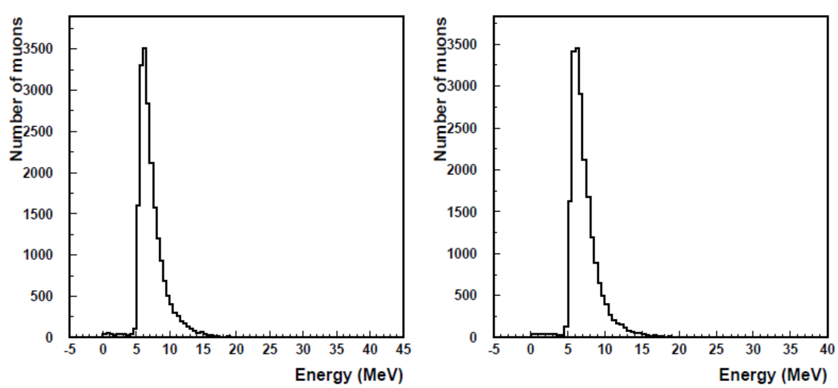

Fig. 6. The energy deposit in the scintillator plates (left - the top layer, right - the bottom layer).

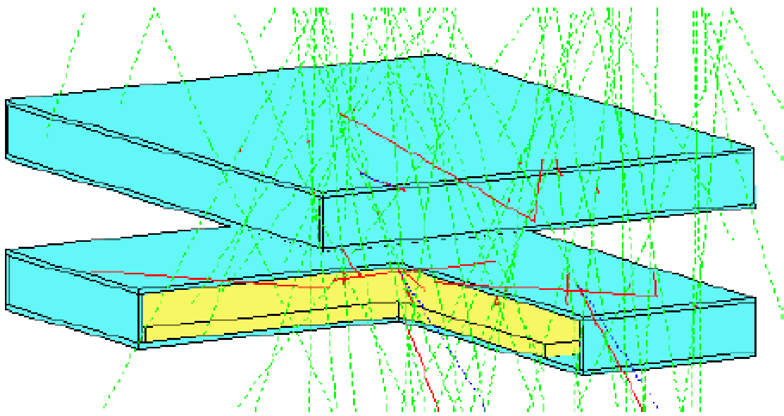

Fig. 7. The schematically view of the muons interacting with the detection system, as simulated with GEANT code (green lines are muons, red lines are secondary electrons).

The detector is installed on a van (see Figure. 8) allowing to move quickly the system. The electric power for the entire system is supplied by a mobile electric generator of 1 kW power at 230 V AC or by a 12-230 V inverter of 1 KW power which transform 12 V CC from the car's battery to 230 V AC.

Using this mobile detector, measurements of the muon flux have been performed on different altitude levels and geographical locations at surface and on different mines of the salt ore of the Slanic site.

Fig. 8. Photo of the mobile detector.

5. Measurements and results

The measurements of the muon flux in the underground have been performed at the Slanic site at 3 different locations: in Unirea salt mine at 208 m below the entrance and in the active mine Cantacuzino, at 2 different levels, first one at 188 m and the second one at 210 m below surface. All campaigns were performed at approx. the same hour of the day (noon) in order to reduce the influence of the solar activity and atmospheric conditions. The acquisition time for each data set was aprox. one hour. In Cantacuzino mine, where an access road is available, the measurements have been performed using the detector installed on the van. In Unirea mine, the detection modules were removed from the car and transported by an elevator to the observation level. The results of the three measurement campaigns are displayed in Tab. 1.

The variation of the muon flux as a function of the water equivalent depth is given by [16]:

$$\Phi_{\mu}' = A \cdot \left(\frac{X_0}{X} \right)^{\eta} \cdot e^{-\frac{X}{X_0}}, \quad (1),$$

where A = 0.03 $m^{-2}s^{-1}$, X_0 = 1470 m.w.e. and η = 2.5.

The difference in the muon flux measured at approximately identical physical depths in Cantacuzino (-210 m) and in Unirea (-208 m) is associated to the different thickness of salt rock above the detection place. Unirea mine is consisting of a huge cavity up to 57 m between the floor and the roof. In contrast, the Cantacuzino mine has a relative homogeneous rock massive above.

Table 1

The muon flux data obtained in underground measurements

Location	Depth (from surface)	Muon flux ($m^{-2}s^{-1}$)	mwe depth
Unirea mine	- 208 m	0.18 ± 0.01	610 ± 11
Cantacuzino mine - Level 8	- 188 m	0.19 ± 0.02	601 ± 21
Cantacuzino mine - Level 12	- 210 m	0.09 ± 0.01	790 ± 29

Taking advantage of the mobility of the system, the measurements of the cosmic muon flux have been performed for many locations at different geographical positions and different elevations, from sea level up to 655 m. The results are in good agreement with measurements reported previously in ref. [17], that estimate a flux of 127 muon/m^2s at 259 m a.s.l. (above sea level). The results are compiled in Tab.2 and displayed in Figure. 9. During the campaigns at altitudes 70 m and 408 m the observation conditions were different (wind and low temperature) compared to the others, which led to different values and larger error bars.

Table 2

Measured muon flux at different elevations and locations (the altitude was determined with a GPS system)

Latitude (deg)	Longitude (deg)	Altitude (m a.s.l.)	muon flux ($m^{-2}s^{-1}$)
45.29	25.94	655 ± 5	146,74 ± 2,37
45.28	25.97	588 ± 5	145,30 ± 2,33
45.24	25.94	408 ± 5	143,24 ± 2,24

44.32	28.19	70 ± 5	128,05 ± 2,07
44.40	26.10	64 ± 5	122,28 ± 1,87
44.36	28.05	7 ± 5	119,07 ± 1,93

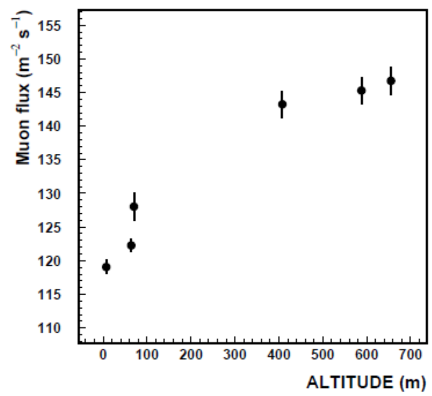

Fig.9. Measured results of the muon flux variation with altitude in m a.s.l.

6. Conclusions

Suggested by the muon flux measurements reported for other sites [18], the water equivalent depth of different places of the Slanic underground site were determined. The water equivalent depths of the Slanic mine are 610 m.w.e. for Unirea mine, 601 for Cantacuzino mine (level 8) and 790 m.w.e. for Cantacuzino mine (level 12), respectively.

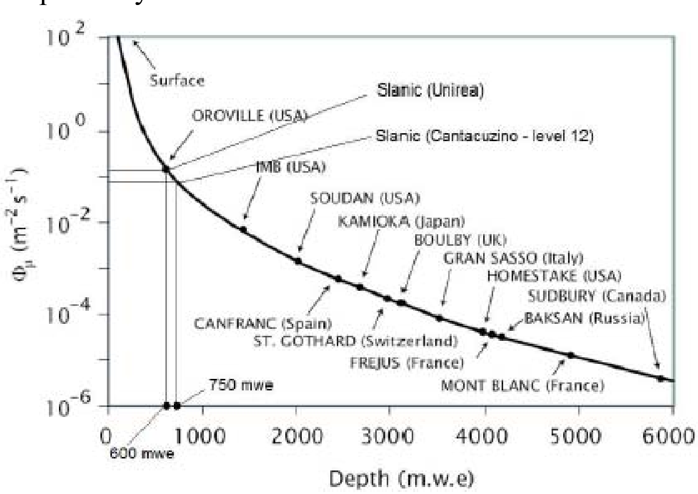

Fig. 10. MWE depths of different underground sites as function of muon flux.

The Slanic site is a feasible location for the GLACIER detector to be located in Unirea mine, with respect to the determined depth of 600 mwe (see Figure. 10). In addition, further promising locations for LAGUNA at the Slanic site are under consideration. A new cavern, 100 m below the Cantacuzino mine (see Figure. 1) could be excavated in a reasonable time scale [19]. In this case a depth of about 1000 mwe would be at disposal for experiments.

In near future, further measurements at different locations in Unirea mine will be performed, in order to get an improved overview on the variation of the Unirea mine's water equivalent depth. We expect that the muon flux varies for different locations of the mine due to the variation of the overburden at the Unirea mine.

Such muon flux measurements could be also used for geological studies, e.g. to explore variations in the rock density above the observation level. The mobility of the detector implies a considerable practical flexibility of using the procedure of measuring muon flux differences for various aspects.

A new detection system for the mobile detector is in construction and is estimted to start the aquisition at the begining of 2011. The system will use a new technology based on optical fiber and MPPC photo-dyodes. The new detector will perform precise measurements of the differential moun flux at surface and in underground. The data will be used to test the hadronic interaction models.

BIBLIOGRAPHY

[1] *P. Schreiner and M. Goodman*, Proc.29th ICRC Pune (India), **9**(2005)97-98
[2] *http://laguna.ethz.ch*
[3] *A. Tonazzo et al.*, Nucl.Phys.B Proc.Suppl. **168**(2007)363-365
[4] *T. Marrodan-Undagoitia et al.*, Prog.Part.Nucl.Phys. **57-1**(2006)283-289
[5] *A. Rubbia*, arXiv:hep-ph/0402110
[6] *R. Margineanu et al.,* Appl.Rad. and Isotopes **66-10**(2008)1501-1506
[7] *C. Simion et al.*, Jour. Lab. Comp. & Radiopharm. **53:5-6**(2010)307-311
[8] *A. Rubbia*, arxiv:0908.1286v1 [hep-ph] (2009)
[9] *D. Heck et al.*, Report **FZKA 6019** Forschungszentrum Karlsruhe (1998)
[10] *V. Kudryavtsev et al.*, Comp.Phys.Comm. 180-3(2009)339-346
[11] *GEANT* Detector Description and Simulation Tool, Cern (1993), Program Library Long Writeup W5013
[12] *J.R.Judge and W.F.Nash*, Il Nuovo Cimento, **XXXV-4**(1965)999
[13] *T.K. Gaisser*, Astropart. Phys. **16**(2002)285R
[14] *H. Bozdog et al.*, Nucl.Instr.Meth. A **465**(2001)455-471
[15] *T. Antoni et al.*, Nucl.Instr.Meth A**513**(2003)490-510
[16] *J.A. Formaggio, C.J. Martoff*, Annu. Rev. Nucl. Part. Sci. **54**(2004)361
[17] *T.K. Greisen et al.*, Phys.Rev. **61**(1942)212
[18] *J.M. Carmona et al.*, Astropart. Phys. **21**(2004)523-533
[19] *S. Arad et al.*, Acta Physica Polonica B., **41**(2010)1789-1802