ISSN 1330–0016
CODEN FIZBE7

A NEW ANALYSIS OF THE $\nu_\tau \to \tau^- \to e^-$ CHANNEL IN NOMAD

MARIO STIPČEVIĆ and ANTE LJUBIČIĆ

"Ruđer Bošković" Institute, POB 1016, HR-10 001 Zagreb, Croatia

Dedicated to Professor Mladen Paić on the occasion of his 90$^{\text{th}}$ birthday

Received 1 September 1995

UDC 539.12

PACS 14.60.Pq

The NOMAD experiment at CERN is gathering its first data in the quest for neutrino oscillations, using the ν_μ wide band neutrino beam. The experiment is the most sensitive to oscillations $\nu_\mu \to \nu_\tau$, but $\nu_\mu \to \nu_e$ can be also studied as well as some additional physics. Here, the results of a novel study of the so-called "electronic channel", i.e. $\nu_\tau + N \to \tau^- + X$, followed by $\tau^- \to e^- \nu_\tau \bar{\nu}_e$, is presented. The study is done with a help of a program based on the LEPTO event generator and simple detector simulation. It is shown that a conceivable deterioration of spatial resolution of the drift chambers with respect to what has been originally proposed, would not deteriorate significantly the signal-to-noise ratio in this channel. On the other hand, the quality of the ϕ_{eh}–ϕ_{mh} cut is shown to be extremely sensitive to the knowledge of the exact angle of incident neutrinos with respect to the horizontal axis of the detector. Finally, a new cut, involving the hadronic calorimeter installed at the back field return yoke of the NOMAD magnet, is proposed and shown to reduce the background by a factor of about two.

1. *Introduction*

In fifty years after the discovery of ν_e , neutrinos still remain a big mystery and challenge. Since the first proposal of neutrino by Pauli in 1930, as a particle which could account for the observed electron spectra in nuclear beta decays, neutrinos have been actively searched for and studied but questions such as: "how many types of neutrinos there are ?", "are neutrinos their own antiparticles ?", "do they have a mass ?" or "do neutrinos mix among themselves ?" still remain open. Three types (flavours) of neutrinos have been experimentally established so far. In the Standard Model the three types of neutrinos, ν_e, ν_μ, ν_τ, belong to the three fermion families, differ from their antiparticles and are massless. However, there are strong indications from solar neutrino and double beta decay experiments that neutrinos do have a mass. There are also compelling reasons from cosmology that massive neutrinos should carry a part of the "invisible mass" of the Universe. LEP experiments at the Z^0 peak have shown that there are indeed three neutrino flavours, with mass $\leq$ 45 GeV, but they say nothing about very heavy neutrinos. Different theories relate masses of the three neutrino types to the masses of the corresponding leptons, giving a certain hierarchy of neutrino masses. For example, the GUT see-saw mechanism [1] gives the following relation for neutrino masses:

$$m_{\nu_e} : m_{\nu_\mu} : m_{\nu_\tau} \sim m_e^2 : m_\mu^2 : m_\tau^2. \tag{1}$$

In contrast to this, the recent exciting data from LSND [2] experiment currently under way at LAMPF (Los Alamos), combined with the cosmological constraints, suggest different mass hierarchy. In the scenario of Caldwell and Mohapatra [3], ν_μ has a very small mass whereas the other two flavours have slightly degenerate masses of about 2.4 eV. The mass splitting of the order of $\Delta m^2_{e\tau} \approx 10^{-5}$ eV^2 explains long-range phenomena, such as solar neutrino defficit, while the mass difference between the muon neutrino and the other two types makes possible short-range oscillations that were shyly claimed by the LSND collaboration earlier this year and which could also be observed at NOMAD [4] and CHORUS [5] experiments at CERN.

There are however, other proposals which take into account the LSND finding, giving different mass hierarchy [6] or introducing the four-neutrino scheme [7]. The decisive measurements on these theories may soon come from the LSND, NOMAD and CHORUS.

2. Principles of NOMAD and simulation the detector

A very promising way of revealing whether three known types of neutrinos have masses seems to be through the detection of neutrino oscillations. Namely, if at least two types of neutrinos have different masses and if their mass eigenstates are not simultaneous eigenstates of the weak force, then they "oscillate" i.e. change flavour with the time. In case of two neutrino mixing, say $\nu_\mu \to \nu_\tau$, the following unitary transformation relates the mass and weak eigenstates:

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix}_{t=0} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}_{t=0}. \tag{2}$$

Substituting the mass eigenstates with a free-particle solution:

$$\nu_i(t) = \mathrm{e}^{-\mathrm{i}E_i t}\nu_i(0), \quad i = 1, 2, \tag{3}$$

one can calculate probability that an initial ν_μ-neutrino will be found as the ν_τ-neutrino at a later moment:

$$\begin{aligned} \mathrm{P}(\nu_\mu \to \nu_\tau) &= |<\nu_\mu(0)|\nu_\tau(t)>|^2 \\ &\approx \sin^2(2\theta)\sin^2(2\pi\frac{x}{L}). \end{aligned} \tag{4}$$

The last expression is valid in the high-energy limit ($E_\nu \gg m_\nu$) where θ is the mixing angle, L the distance between the source and the detector in km, λ the oscillation period and

$$\lambda = 4\pi \frac{E_{\nu_\mu}}{m_2^2 - m_1^2} \approx \frac{5E_\nu(\mathrm{GeV})}{\Delta m^2(\mathrm{eV})^2}. \tag{5}$$

The basic idea of NOMAD is to detect the presence of a small fraction of tau neutrinos, possibly produced by virtue of the $\nu_\mu \to \nu_\tau$ oscillation, in the predominantly ν_μ beam. The mean energy of the ν_μ beam in the West Area Neutrino Facility at CERN is 27 MeV and it delivers approximately 6×10^{11} neutrinos per spill (14.4 seconds) spread over the face of the NOMAD detector. Tau neutrinos would be observed through their interaction with the central part of the detector (target) using kinematical cuts only. The challenge is to be sensitive in the region of small mixing angles. Using several decay channels of τ^- : $\mathrm{e}\bar{\nu}_e\nu_\tau$, $\mu\bar{\nu}_\mu\nu_\tau$, $\pi^-\nu_\tau$, $\rho^-\nu_\tau$, $\pi^+\pi^-\pi^-(n\pi^0)$, and the statistics of two years of running, NOMAD arives at the sensitivity of $\sin^2 2\theta \approx 3 \times 10^{-4}$, for large Δm^2, more than an order of magnitude better than the best existing limit.

As an example of kinematical cuts applied in NOMAD to isolate the signal, we show the main cut for the channel

$$\nu_\tau \mathrm{N} \to \tau^- \mathrm{X}, \quad \tau^- \to \mathrm{e}^-\bar{\nu}_e\nu_\tau. \tag{6}$$

The Feynman graph of this interaction and the definition of the kinematical angles ϕ_{mh} and ϕ_{eh} in the transverse momentum plane are shown in Figs. 1a and b. The most important background to this channel comes from the charged current (CC) ν_e interactions due to the presence of about 1% electron neutrinos in the beam:

$$\nu_e \mathrm{N} \to \mathrm{e}^- X \tag{7}$$

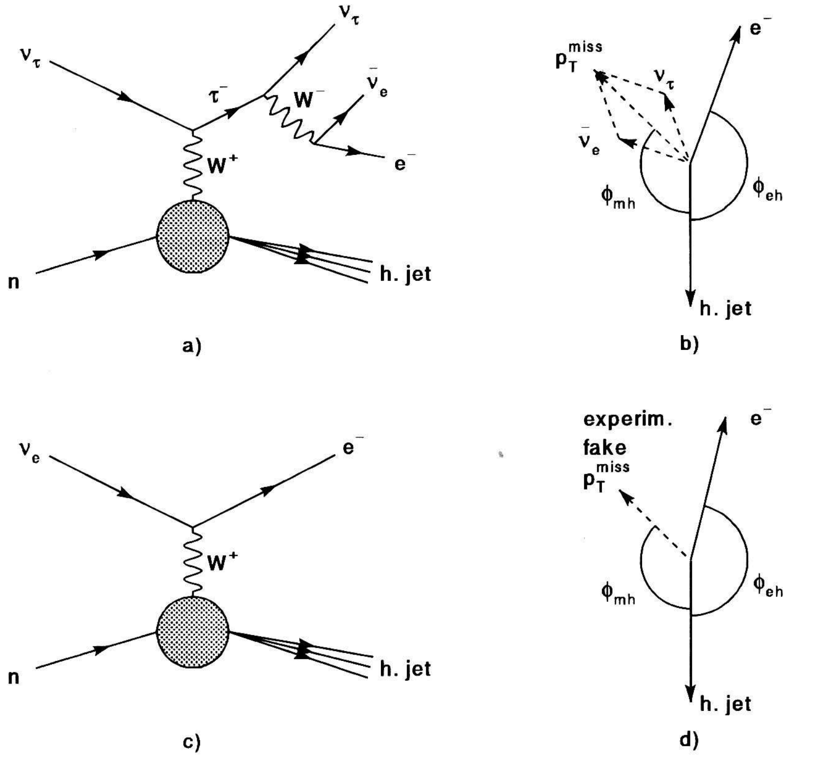

Fig. 1. Diagrams of the ν_τ signal (a) and the main background to this channel (c), and respective definitions of angles ϕ_{mh}, ϕ_{eh} in the transverse momentum plane (b,d).

(see Figs. 1c and d). Corresponding distributions of ϕ_{mh} versus ϕ_{eh} are shown in Fig. 2. The τ^- signal is characterized by a large missing transverse momentum, and a large spread of (ϕ_{mh},ϕ_{eh}) points (Fig. 2a). On the other hand, in the case of background, the electron balances the hadron system so that ϕ_{eh} tends to be close to π, while the fake missing p_T produced in the detector by unseen neutral hadrons, finite momentum resolution etc. can point in any direction (Fig. 2b). The graphical cut drawn in the plots is used to distinguish the signal from background.

To make possible precise kinematical measurements needed for such analysis, the whole detector (apart from the muon chambers and hadronic calorimeters) is placed within the reused UA1 magnet operating at 0.4 T, (Fig. 3)[1] with the field lines perpendicular to the beam axis. The target consists of 44 drift chambers with a total of 132 planes of wires perpendicular to the beam direction. It serves at the same time as the main tracking device, with a fiducial length of 4 m. The two

[1]Figure is courtesy of K. Varvell

aspects of the drift chambers are exclusive: as a target they should be as thick as possible in order to yield a high neutrino interaction rate, while as a tracking device they should be as thin as possible in order to reduce the multiple scattering which spoils their tracking ability. A compromising solution was found to be the target of only $1X_0$ thickness and a mass of 3 tons.

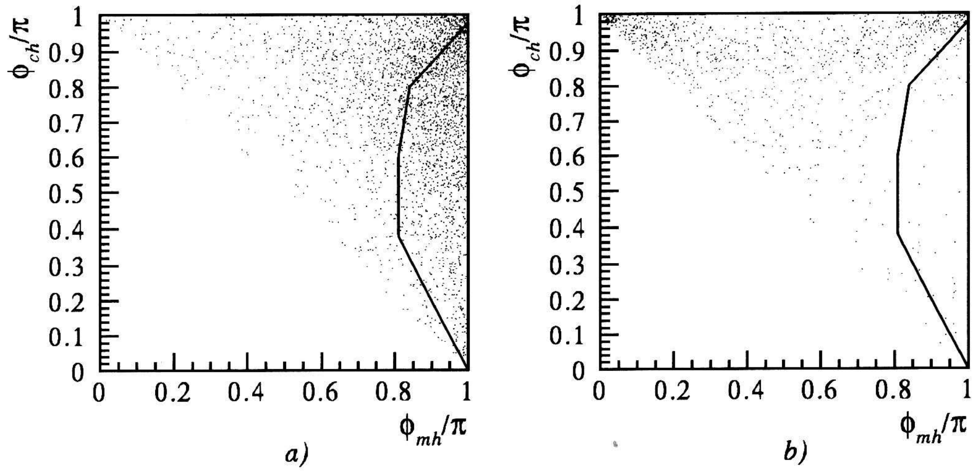

Fig. 2. Examples of the kinematical cuts used to isolate $\nu_\tau \to \tau^- \to e^-$ signal from background.

The simulation program used in this study sees the NOMAD detector as a tracking device (drift chambers) of fiducial volume of 2.6m × 2.6m × 4 m, followed by the transition radiation detectors (TRD) and a preshower used to identify electrons, and the electromagnetic calorimeter used to measure the energy of electrons and photons. Outside the magnetic field are the forward hadronic calorimeter (not simulated) and the back hadronic calorimeter (HCAL) which can signal the presence of a hadronic activity but is otherwise too thin to be used for hadronic energy measurement.

Logic of the simple simulation used in this study is the following. Minimum bias physics events are produced by the LEPTO and JETSET[2] event generators according to the incident neutrino flavour and type of interaction (CC or neutral currents (NC)), and the outcoming stable particles are introduced in the detector. Simulation program then tracks stable charged and neutral particles in the magnetic field and smears their momentum and energy according to the detection abilities of the subdetectors. Photons are allowed to convert before the electromagnetic calorimeter, and the energy deposition of hadrons in a thin hadronic calorimeter is parametrized in a simple way. The TRD can identify very efficiently electrons with the energy greater than about 1.5 GeV. To make the analysis simpler, electrons

[2]the versions used are lepto61r2, and jetset74

above this threshold and positrons with energy above 100 MeV are assumed to be detectable with an absolute efficiency. Positrons below 100 MeV are considered invisible. It was also assumed that momenta of electrons can be measured by the drift chambers what is not a trivial matter, because they sometimes suffer strong multiple scattering. A study using the full GEANT Monte Carlo simulation is needed in order to investigate this problem.

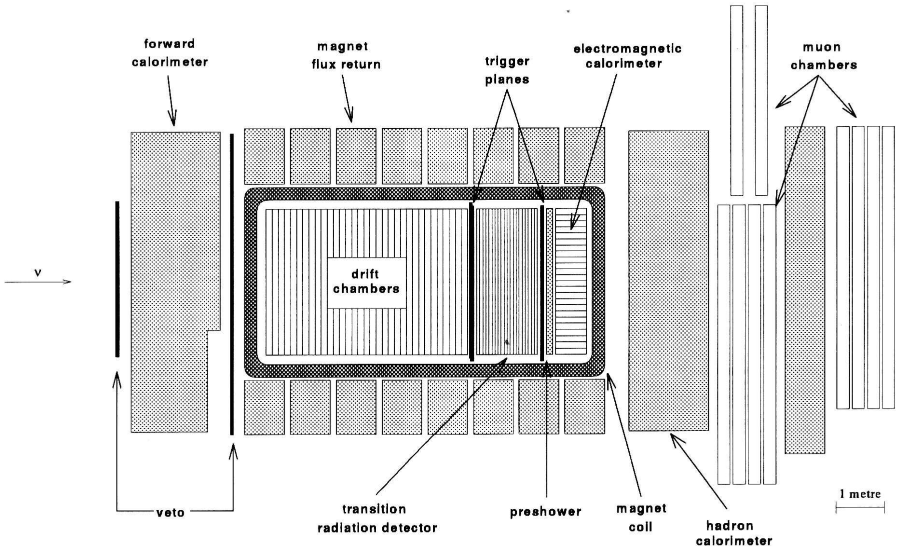

Fig. 3. Sideview of the NOMAD detector.

2.1. Results of the analysis

A set of cuts used in this analysis, together with their cumulative efficiency, is listed in Table 1. The numbers in brackets are the statistical errors introduced by the finite statistics of generated events. The hadronic calorimeter placed at the back of the NOMAD detector is as the matter of fact, the return yoke of the magnet. It is only 4 λ_i thick and, therefore, cannot be used for the energy measurement of hadrons, but is usefull as a veto. Namely, requiring that a candidate event deposits through neutral hadrons (such as K_L^0's or neutrons) less than 1.5 GeV of energy in the HCAL, reduces by a further factor of 1.5–2 the chances that a large missing p_T coming from neutral hadrons would fake the signal. The overall improvement of signal-to-noise ratio using the NOMAD hadronic calorimeter is by the factor of about two. The question of associating the energy deposition in HCAL to neutral hadrons was not addressed in the study, but it is expected that it would be possible, given the granularity of the calorimeter [8].

The power of rejection of the background, when using the cuts listed in Table 2, is stable under fairly large changes in the track hit resolution of the drift chambers. The numbers in Table 2 show that even 3 times worse hit resolution than originally proposed (and eventually aimed) would not have dramatic effects. This is probably due to the fact that for an average charged particle (track length of 2 m, energy 5 GeV) the contribution of multiple scattering to the error on momentum measurement dominates.

TABLE 1.
Cumulative efficiency of proposed kinematical cuts.

	$\nu_\tau \to \tau \to$ e$^-$		$\nu_e \to$ e$^-$		ν_μ NC	
	100		100		100	
$\sphericalangle(\vec{p}_{n,K_L^0}, \vec{p}_{charged}) < 45°$	97.6	(1.0)	98.3	(0.2)	97.8	(1.0)
$E_{e^+} < 100$ MeV	97.2	(1.0)	97.6	(0.2)	29.3	(0.6)
e^- in the calorimeter	74.4	(0.9)	84.0	(0.1)	2.8	(0.2)
ϕ–ϕ scatter plot cut	29.4	(0.5)	5.0	(0.1)	1.6	(0.1)
$E_{visible} < 50$ GeV	22.9	(0.5)	1.72	(0.02)	1.2	(0.1)
$E_{e^-} > 1.5$ GeV	19.8	(0.4)	1.69	(0.02)	0.2	(0.05)
$\frac{\vec{p}_{e^-} \cdot \vec{p}_{had}}{p_{had}} > 300$ MeV	19.8	(0.4)	1.69	(0.02)	0.2	(0.05)
$p_T^{miss} > 400$ MeV	19.4	(0.4)	0.107	(0.002)	0.2	(0.05)
n, K_L^0 veto	14.0	(0.4)	0.050	(0.004)	0.15	(0.04)
Without HCAL	19.6	(0.4)	0.120	(0.006)	0.21	(0.05)

TABLE 2.
Dependence of the efficiency of cuts upon the hit resolution of the drift chambers.

	0.2 mm	0.6 mm	1.0 mm
$\tau \to e^-$	14.0 (0.4) %	14.0 (0.4) %	14.0 (0.4) %
CC ν_e	0.050 %	0.067 %	0.100 %

If the above study is repeated, assuming that the neutrino beam is slanted by 17 mrad (i.e. about 1°) from its nominal axis, then the $\nu_e \to$ e$^-$ background rises by a factor of 25, and if it is slanted by only 3.5 mrad (0.2°), the background is higher by 25 %. This is, of course, because particles produced by neutrino interactions have large longitudinal momenta, and if even only a small fraction of this is projected onto the transverse plane it can spoil the cuts. The most affected cut is the one requiring missing p_T greater than 400 MeV, what can be clearly seen from missing p_T distributions in Fig. 4.

Rising this threshold energy could improve the signal-to-background ratio, but at the expense of loosing an important part of the signal. A better approach would be to correct the measured momenta by rotating them according to the angles that the beam makes with the z axis of the detector in xz and yz planes (z is the longitudinal axis of the detector). These two angles can be measured from p_x/p_z and p_y/p_z distributions of muons from ν_μ CC interactions within the detector. A preliminary check using the data gave an indication that the two angles can be measured to better than 1 mrad.

In passing we note that almost all of ν_e CC events surviving all the cuts listed in Table 2 were c quark production. That observation may lead to ideas of how to further suppress this background. However, at such high level of suppression, fake backgrounds due to experimental difficulties will be more important, so further improvement of the cuts should be pursued using a full GEANT Monte Carlo simulations.

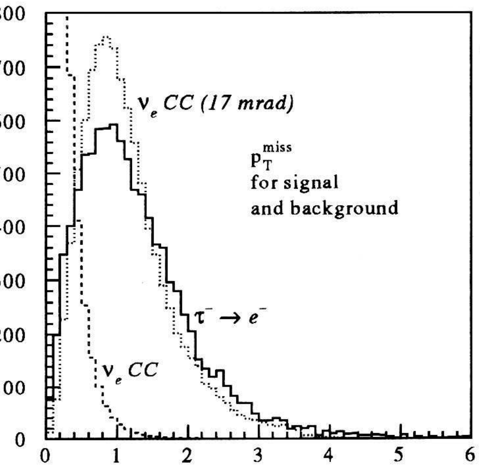

Fig. 4. The missing transverse momentum plot for the signal ($\nu_\tau \to e^-$), the main background ($\nu_e \to e^-$) and the same background as seen by the drift chambers tilted by 1° (17 mrad) with respect to the nominal beam axis.

3. Conclusion

It is shown that possible deterioration of spatial resolution of the drift chambers by as much as factor ot three from the original specification, would not affect significantly the signal-to-background ratio in this channel.

The hadronic calorimeter placed at the back of the detector was found to be an important tool for reducing background from the ν_e CC events having a substantial transverse momentum carried away by neutral hadrons.

The need for a very precise alignment of the detector, and one possible method to do it using the data themselves were shown.

No attempt was made to include effects of misidentification of particles or the nonperfect Monte Carlo event generator.

Acknowledgements

One of the authors (M. S.) wishes to thank to the colleagues from the NOMAD collaboration, especially A. Rubbia, S. Mishra and A. Geiser, for fruitfull discussions during elaboration of this study.

References

1) M. Gell-Mann, P. Ramond and R. Slansky in: *Supergravity*, ed. P. van Nieuwenhuizen and D. Freedman, North Holland, Amsterdam, 1979, p. 315; T. Yanagida, Prog. Theor. Phys. **B 135** (1978) 66; R. N. Mohapatra and P. B. Pal, *Massive Neutrinos in Physics and Astrophysics*, World Scientific, Singapore, 1991;
2) *Liquid Scintillator Neutrino Detector (LSND) A proposal to Search for Neutrino Oscillations with High Sensitivity in the Appearance Channels* $\nu_\mu \to \nu_e$ *and* $\bar{\nu}_\mu \to \bar{\nu}_e$. Proposal to Los Alamos Meson Physics Facility (1989);
3) D. O. Caldwell and R. N. Mohapatra, *An Inverted Neutrino Mass Hierarchy...*, UCSB-HEP-95-1 UMD-PP-95-107 (1995);
4) *Neutrino Oscillation Magnetic Detector (NOMAD), Search for the Oscillation* $\nu_\mu \to \nu_\tau$, CERN-SPSLC/91-21 SPSC P261 (1991) and CERN SPSLC M525 (1993);
5) *CERN Hybrid Oscillation Research Apparatus (CHORUS). A New Search for* $\nu_\mu \to \nu_\tau$, CERN-PPE/93-131 (1993) and CERN- SPSC/90-42 SPSC P254;
6) G. Raffelt and J. Silk, Berkeley preprint, (1995);
7) D. O. Caldwell and R. N. Mohapatra, Phys. Rev. **D 48** (1993) 3259;
8) S. Mishra, *The NOMAD Collaboration, A Proposal to Add a Hadronic Calorimeter to the NOMAD Experiment*, CERN/SPSLC SPSLC M525 (1993), private comunication.

NOVA ANALIZA $\nu_\tau \to \tau^- \to \mathrm{e}^-$ KANALA U NOMADU

Eksperiment NOMAD na CERNu prikuplja prve podatke u potrazi za neutrinskim oscilacijama, koristeći snop mionskih neutrina širokog energijskog spektra. Eksperiment je najosjetljiviji na oscilacije $\nu_\mu \to \nu_\tau$, ali mogu se također detektirati i oscilacije $\nu_\mu \to \nu_\mathrm{e}$, te studirati dodatna fizika. Ovdje dajemo prikaz rezultata nove studije tzv. "elektronskog kanala", tj. $\nu_\mu + N \to \tau^- + X$ nakon čega slijedi $\tau^- \to \mathrm{e}^-\nu_\tau\nu_\mathrm{e}$. Studija je sačinjena uz pomoć programa baziranog na LEPTO generatoru događaja i jednostavnoj simulaciji detektora. Pokazano je da moguća slabija prostorna rezolucija driftnih komora od one razmatrane u prvotnom prijedlogu samo marginalno utječe na omjer signal/šum u tom kanalu. S druge strane, kvaliteta ϕ_{eh}–ϕ_{mh} reza je izrazito osjetljiva na precizno poznavanje upadnog kuta neutrina s obzirom na horizontalnu os detektora. Konačno, pokazano je da dodatni rez, koji uključuje hadronski kalorimetar koji je instaliran straga u željeznoj jezgri elektromagneta, reducira pozadinu za otprilike faktor dva.