PROTON DECAY IN LAr — STUDIES FOR THE ICARUS DETECTOR*

Dorota Stefan

The H. Niewodniczański Institute of Nuclear Physics
Polish Academy of Sciences
Radzikowskiego 152, 31-342 Kraków, Poland

(Received June 23, 2010)

The search for proton decay is nowadays one of the most important subjects of particle physics. To improve the current lower bound on the proton lifetime, massive detectors should be constructed. In the present paper attention is paid to the LAr detector. The golden channel of proton decay for this detector is $p \to K^+\bar{\nu}$, favored by supersymmetric models. We present a new approach to the problem of particle track reconstruction implemented in the software of the T600 detector at the ICARUS experiment.

PACS numbers: 02.70.Uu, 13.30.Eg, 14.20.Dh, 29.40.Gx

1. The searches for proton decay

Proton decay is predicted by Grand Unification Theories (GUT), which attempt to unify the three basic forces of nature — the weak, the electromagnetic, and the strong nuclear force [1]. An experimental detection of proton decay would constitute a landmark discovery in particle physics.

So far, no proton decay events have been observed. The best current lower limits for the proton lifetime come from the water Cherenkov detector at the Super-Kamiokande experiment. In this experiment several proton decay channels have been searched for. The highest value of lower limit for the proton lifetime was obtained for the channel $p \to \pi^0 e^+$ and is 8.2×10^{33} years [2]. In order to significantly improve these searches it is essential to increase the sensitivity of measurements by at least a factor of ten. Since water Cherenkov detectors are relatively cheap and well understood this technique is very popular. Thus huge water Cherenkov detectors in Japan [3], in the USA [4] and in Europe [5] are being discussed.

* Presented at the Cracow Epiphany Conference on Physics in Underground Laboratories and Its Connection with LHC, Cracow, Poland, January 5–8, 2010.

By contrast, the LAr detector has never before found application in the searches for proton decay. It should be stressed that a 100 kton liquid argon detector would allow the verification of several GUT models with ten years of data-taking. In particular, for the $p \to K^+\bar{\nu}$ mode, all the range of lifetimes predicted by theorists would be covered. The construction of a LAr detector is considered in the USA [6] as well as, within the Laguna project [7], in Europe.

The LAr detector filled with 600 tons of liquid argon, T600 [8, 9], has started data taking this year. The detector is placed at the underground laboratory in Gran Sasso. It will detect mainly muons, pions, kaons and protons created in interactions of neutrinos coming from the CNGS beam. It must be pointed out that 600 tons of liquid argon is too little to improve the current limits for the proton lifetime. However, studies of real data, especially of low energy hadrons, will increase our knowledge about the possibilities of liquid argon technology in the searches for proton decay.

In the experiment it is possible to detect particles only after they have left the nucleus. Therefore, it is very important to study the nuclear processes which take place in nuclei and in consequence their influence on the energy spectrum of particles which leave the nuclei. The description of both the nucleon states inside nuclei and the propagation of particles through nuclei must be taken into account. The calorimetric and spatial resolution of the LAr Time Projection Chamber (TPC) gives an opportunity to study the particle characteristics with high precision. However, in order to fully use the detector potential, very good track reconstruction is required. One should stress that the better the method of reconstruction, the better particle identification is. In the following chapters the energy spectra of particles leaving the argon nuclei are discussed and an innovative method of the 3D reconstruction is described.

2. The concept of the T600 detector

The advantage of the LAr TPC is its excellent spatial and calorimetric resolution which makes possible a perfect visualization of tracks of the charged particles. Currently the biggest liquid argon detector is the T600 TPC of the ICARUS experiment [9].

It is composed of two semi-independent modules, 300 tons of liquid argon each. In every module there is a cathode plane at the center, and there are two sets, each of three planes of anode wires, at the walls. All electrode planes are parallel to the largest sides of the module. The charge particles passing the detector volume, where between the cathodes and anodes a uniform electric field is applied, produce ion–electron pairs. The electrons from ionization drift towards the anodes and induce a current on the first two wire planes, called Induction planes, to be finally collected on the third plane, called Collection plane. For each anode wire plane the signal amplitudes and arrival times are recorded, with a sampling time of 400 ns, to provide full 3D measurements of the particle trajectories.

3. The proton decay inside argon nucleus

The golden channel for proton decay in the LAr detector is $p \to K^+\bar{\nu}$. In this case, the simplest topology of the event is achieved when kaon decays into muon and neutrino. Then the analysis is easier as compared to other kaon decay channels. Fortunately, this is the most probable situation (63% [10]).

In the ICARUS experiment the simulation of a proton decay inside the argon nucleus is performed using the Fluka Monte Carlo program [11]. In Fluka the local momentum distribution of the nucleons is described by the Fermi gas model and the density profile of the nucleus is approximated with zones of constant density. In each zone nucleon momenta range from zero to the local value of the Fermi momentum. Constant binding energy is obtained from a mass table. Let us mention that there are attempts to use more accurate descriptions of the nuclear environment [12,13]. In the intranuclear cascade of the model, particles are transported in a nuclear mean field, in which the free hadron–nucleon cross-sections are used to describe collisions. For the details concerning the intranuclear cascade implemented in Fluka see [14].

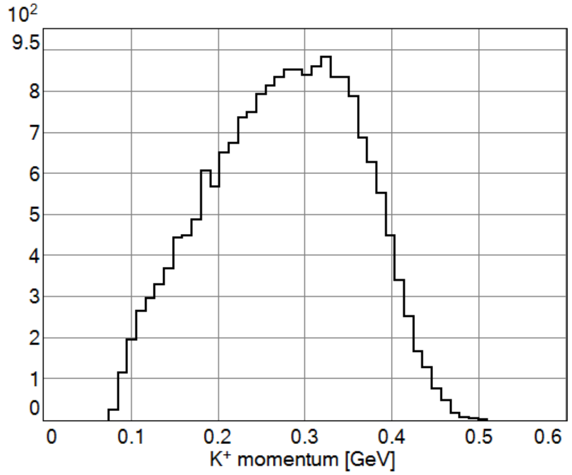

Fig. 1. Momentum distribution of kaons produced in $p \to K^+\bar{\nu}$ decays inside the argon nuclei. The histogram includes only the kaons which leave the nuclei, *i.e.* 19509 kaons out of the 20000 events generated in Fluka.

In Fluka, the position of the decaying proton in the nucleus is sampled from a probability distribution proportional to the density profile for the protons. The simulation shows that 2% of all the K^+ mesons from proton decays interact with neutrons producing neutral kaon and proton. The remaining positive kaons leave the nuclei with momenta distorted mainly due to the Fermi motion. The predicted momentum distribution of kaons leaving the nuclei is shown in Fig. 1.

4. New approach to track reconstruction

Track reconstruction in the T600 detector consists of three steps: signal finding algorithm, 2D track reconstruction and 3D track reconstruction [9]. The first two of them are responsible for finding the signals which are above of the electronic noise (hits) and for associating the group of signals with a single track. In the new method, there is one more step applied before the 3D reconstruction, in which hits are sorted from one end of a track to the other one. This results in an effective linking of the hits from two independent wire planes. Finally, there is the 3D reconstruction giving the real length of a track. The building of the 3D picture is based on the same drift time coordinates for corresponding hits in the views (wire planes) considered and on the order of hits.

4.1. Hits sorting

The hits are spread around the real trajectory of a track. This scattering depends on the ionization energy loss and also on the electronic noise level. The Polygonal Line Algorithm (PLA) is used to rearrange the hits along the 2D trajectory of a track (wire and electron drift coordinates). This is done according to the order of the projected hits on a fitted curve which approximately fits the signals. The description of the PLA algorithm can be found in a reference [15].

4.2. 3D reconstruction

Besides the information about 2D position (wire coordinate, drift time coordinate), hits from Collection view include the information about ionization charge hence energy deposition, indispensable for particle identification. Therefore, they are important elements of 3D reconstruction, which should not be lost. The spatial coordinates of a real track are calculated from a formula that contains the 2D positions of the corresponding hits belonging to independent wire planes.

In order to make 3D reconstruction more efficient the following procedure is proposed. Projections in the Induction view are complemented so that wire coordinates are assigned to each drift time sample by interpolating between the drift time values fitted for the neighboring wires. This procedure helps in finding the corresponding positions of the projections in both Collection and Induction views. The best matching pair of projected hits is that with the minimal difference between drift samples. Figure 2 presents a reconstructed proton decay event from MC simulation. There is a short straight track of the kaon and a longer track of the muon which decays giving a short wavy track of the positron. Tiny dots are MC hits and the line is the result of the spatial reconstruction. The insertion shows a magnification of the track fragment with MC hits and the line found during the reconstruction with vertices corresponding to the reconstructed 3D hits.

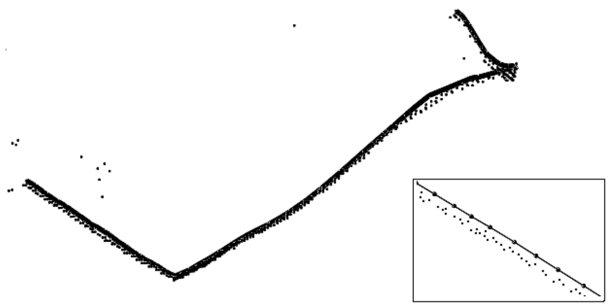

Fig. 2. The reconstructed chain of decay particles: kaon, muon and the shortest track comes from positron. The dots represent MC hits while line is the effect of the spatial reconstruction. On the right, at the bottom of picture a part of a track on a larger scale is shown.

It should be noticed that the reconstruction depends on the event topology. It always works for straight and bend tracks. However, if two tracks meet at a small angle, or tracks are too close to each other, it is possible to reconstruct at most one track and a part of the other track.

5. Particle identification

Successful particle identification depends largely on the efficiency of each step of track reconstruction. A well reconstructed track contains proper information about the particle trajectory and also about the energy deposition. If the particles stop in the detector, the two pieces of information are enough to determine the particle mass together with its momentum. This is because the amount of ionization along the length of the track depends on the kinetic energy of the particle [10].

Since charged particles coming from proton decays have low energies, concentrating only on stopping particles is justified. In particular, kaon, muon and positron from the proton decay chain can be observed in the detector. It results from the simulation of $p \to K^+\bar{\nu}$ that 95% of kaons decay at rest and in consequence muons have momentum equal 236 MeV corresponding to the kinetic energy equal to 152 MeV, see Fig. 3. In Fig. 3 there are two theoretical curves together with points coming from the measurements. The graph shows kinetic energy *versus* particle range for the kaon and the muon from one of the reconstructed proton decays. The reconstructed track lengths are in good agreement with the MC simulation; *e.g.* for a muon with kinetic energy equal to 152 MeV, the range should be 54 cm. From the figure one can see that the reconstructed range is around 55 cm and energy — 144 MeV, which is within the statistical fluctuation of the particle energy loss.

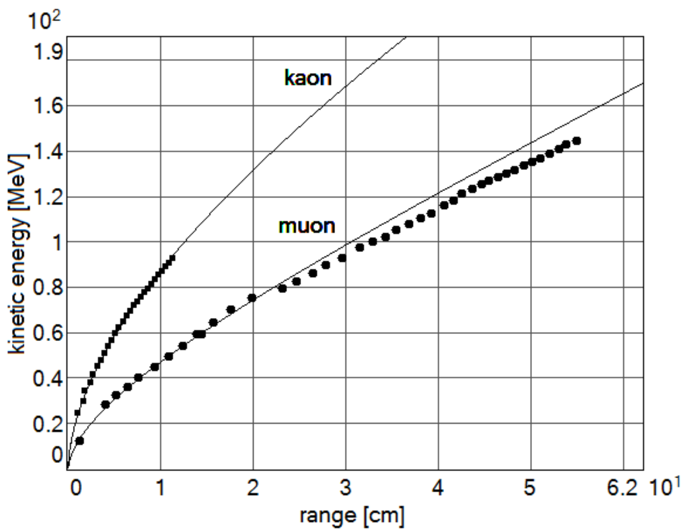

Fig. 3. Kinetic energy as a function of the particle range for the kaon and the muon from the selected, simulated proton decay. Lines represent theory and points results of measurements.

6. Summary

Thanks to very good spatial and also calorimetric resolution the LAr detector is a perfect tool for searching for proton decay. The experience gained from the ICARUS experiment will be very valuable for future research in this field. As far as data analysis is concerned, one should stress that the fully automatic pattern recognition is very difficult and still under development. The approach described in this paper gives better results than the previously implemented 3D reconstruction algorithm [9], especially for the tracks parallel to the wire plane. In this case the method that is based on the comparison of the drift samples only, often fails.

I would like to thank to my supervisor Agnieszka Zalewska for support and helpful discussions. I would also like to thank my colleagues from the ICARUS software group, especially Paola Sala for providing me with the MC tool to simulate proton decay in the T600 detector and Robert Sulej for inspiration and fruitful discussions. The author is supported by the Polish Ministry of Science and Higher Education under the grant no. N N202 237637.

REFERENCES

[1] P. Nath, P.F. Perez, *Phys. Rep.* **441**, 191 (2007).

[2] H. Nishino *et al.*, *Phys. Rev. Lett.* **102**, 141801 (2009).

[3] K. Nakamura, *Int. J. Mod. Phys.* **A18**, 4053 (2003).

[4] The study report, all associated documents, presentations, plots, studies, spectra, are at `http://nwg.phy.bnl.gov/fnal-bnl`, Fermilab-0801-AD-E, BNL-77973-2007-IR; `arXiv:0705.4396 [hep-ph]`.

[5] D. Autiero *et al.*, *JCAP* **11**, 011 (2007).

[6] M. Soderberg, *Acta Phys. Pol. B* **40**, 2665 (2009).

[7] A. Bueno *et al.*, *J. High Energy Phys.* **04**, 041 (2007).

[8] C. Rubbia, CERN-EP/77-08 (1977).

[9] S. Amerio *et al.*, *Nucl. Instrum. Methods* **A527**, 329 (2004); The web page of the ICARUS experiment: `http://icarus.lngs.infn.it`

[10] C. Amsler *et al.* [Particle Data Group], *Phys. Lett.* **B667**, 1 (2008) and 2009 partial update for the 2010 edition.

[11] G. Battistoni, S. Muraro, P.R. Sala, F. Cerutti, A. Ferrari, S. Roesler, A. Fasso, J. Ranft, Proceedings of the Hadronic Shower Simulation Workshop 2006, Fermilab 6–8 September 2006, M. Albrow, R. Raja eds., AIP Conference Proceeding 896, 31–49, (2007); A. Fasso, A. Ferrari, J. Ranft, P.R. Sala, CERN-2005-10, INFN/TC-05/11, SLAC-R-773 (2005).

[12] D. Stefan, A.M. Ankowski, *Acta Phys. Pol. B* **40**, 671 (2009) [`arXiv:0811.1892 [nucl-th]`.

[13] A.M. Ankowski, J.T. Sobczyk, *Phys. Rev.* **C77**, 044311 (2008).

[14] M. Antonello *et al.*, *Acta Phys. Pol. B* **40**, 2519 (2009) [`arXiv:0912.0538 [hep-ph]`].

[15] B. Kegl, A. Krzyżak, T. Linder, K. Zeger, IEEE Transactions on Pattern Analysis and Machine Itelligence **22**, 281 (2000); `http://www.iro.umontreal.ca/~kegl/research/pcurves/algorithms/ polygonalline.html`