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STAR Note 249

Ionization Modeling of P10

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Ionization and energy loss by minimum-ionizing particles in P10 are discussed, so as to estimate the reliability of the Geant 3.21 photo-absorbtion ionization (PAI) model implementation and to relate it to measurable ionization. Geant results are first compared to those of its parent code and found to be fairly consistent. They are then compared with the ionization distribution from an algorithm based on measurements of ionization clusters. The fitted 29.8 eV/ion pair calibration factor is larger than expected, but brings the distributions into remarkably good agreement, provided that the most probable energy loss is much larger than the ionization energy of the argon L-shell.

Introduction

A previous STAR note[1] discussed and compared the energy-loss algorithms in Geant 3.15 and 3.21. Geant was run with various switches, and results were also compared to experimental data. However, a lack of calibrated, directly applicable P10 data necessitated fit parameters in some cases. Most importantly for STAR, the data histograms in Figs. 7 and 8 of SN0185 (for a 2.3-cm step in P10 at 1 bar) were scaled in height, as well as energy, leaving some ambiguity as to Geant's accuracy.

[1]STAR Note SN0185, J. Mitchell and K. Chan (1994).

In this note, a different approach is used. The Geant 3.21 photo-absorbtion ionization (PAI) algorithm derives from contributed code, but parametrizes the photo-absorbtion data to speed initialization. It is useful to verify that the parametrization is adequate for P10, though this does not test the underlying model.

A comparison with ionization measurements does test the model in a relevant way, since Geant energy deposition must ultimately be translated into detectable ionization. This translation is usually done assuming that W, the energy cost per ion pair, is constant for a given material. This approximation is surprisingly good, even though the connection between energy loss and ionization is indirect: excitation does not necessarily yield ionization, and x-ray fluorescence may do at a considerable distance.

The test case is a minimum-ionizing π^+ beam passing through 2 cm of P10 gas with a density of 1.547×10^{-3} g/cm^3 (i.e., P10 at 23.9°C and 1 bar pressure). A mean, unrestricted energy loss of 4810 eV is predicted by the Bethe-Bloch formula, using the Berger and Selzer ionization energies.[2]

Energy Loss in Geant

Energy loss and straggling are discussed in the Geant User's Guide; see Sections CONS200, CONS210, PHYS331, PHYS332, PHYS333 and PHYS334. Based on these and SN0185, Geant simulations were run using the PAI model (STRA 1), with δ-rays produced above a 1-MeV threshold (LOSS 1). The π^+ "beam" was directed at the center of a 20 cm $\times$ 20 cm face of a 2-cm thick volume of P10, with a 5-kilogauss magnetic field perpendicular to it.

The discrete δ-ray threshold was left at the 1-MeV default for compatibility with SN0185 and to allow comparison with a cluster-model algorithm in which secondaries are not tracked. The secondaries between 1 MeV and the kinematic cutoff contribute significantly to the mean energy loss, but are so rare as to have little effect on the energy-loss distribution near the peak.

The Geant User's Guide, Section PHYS334, compares the Sandia parametrization of the photoelectric cross section with the data. This is clearly only a fair approximation for the xenon mixture shown, but the effect on the energy-loss distribution is not obvious, especially

[2]S. M. Seltzer and M. J. Berger, *Int. J. Appl. Radiation Isotope* **33**, 1189 (1982).

for P10. To answer this question, an unparameterized version of the algorithm[3] was provided by Pavel Nevski. The energy-loss distributions are compared in Fig. 1 and 2. The mean of the distribution from Geant is 2–3% higher for the plotted range, but the shape is reproduced rather well.

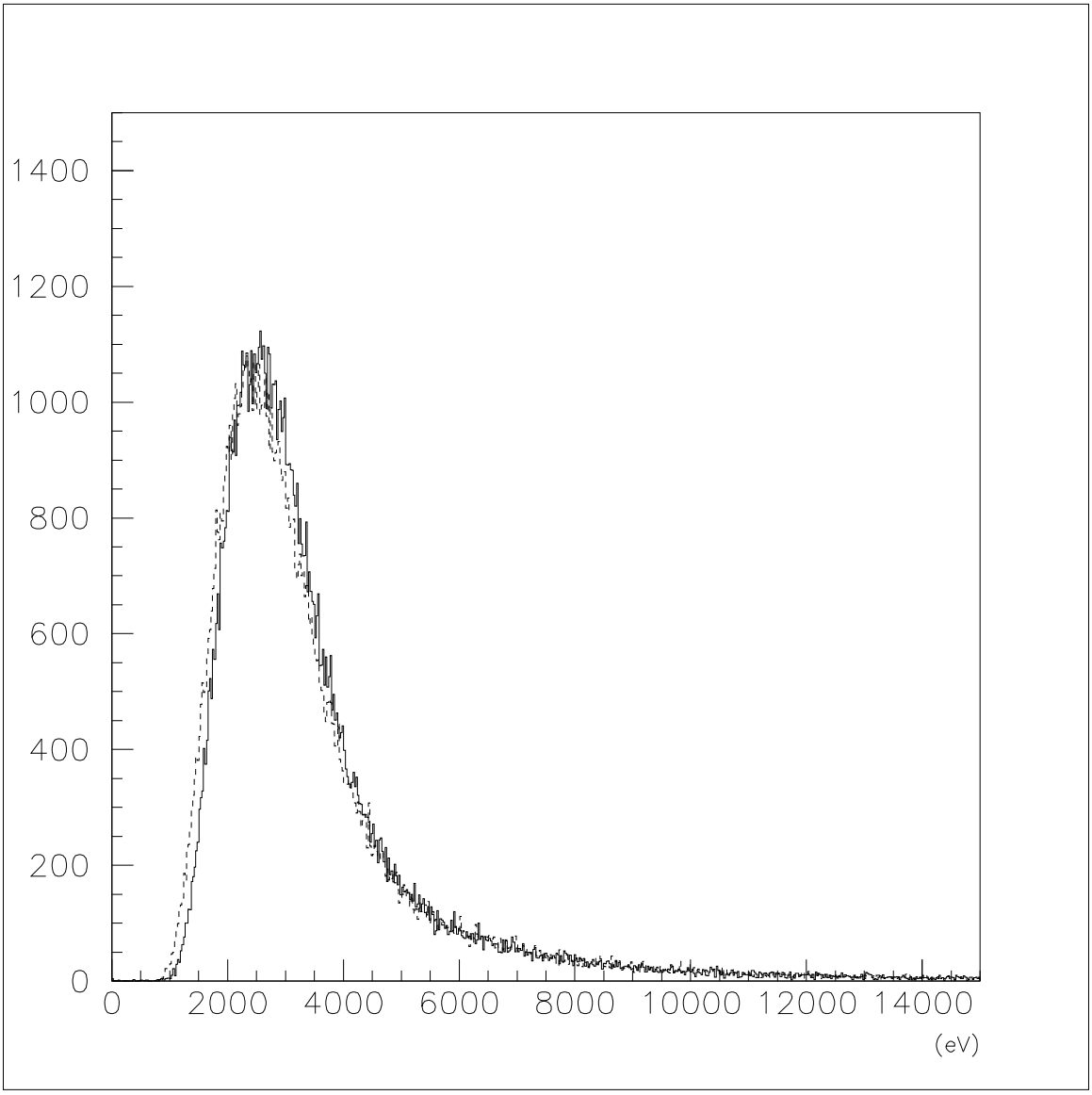

Figure 1: Energy-loss distributions for minimum-ionizing particles in 2 cm of P10 at 23.9°C and 1 bar; the Geant 3.21 PAI result (solid line) closely resembles that of the parent code (dashed line), but is biased towards higher energy loss.

[3]GASTEST, P. Nevski.

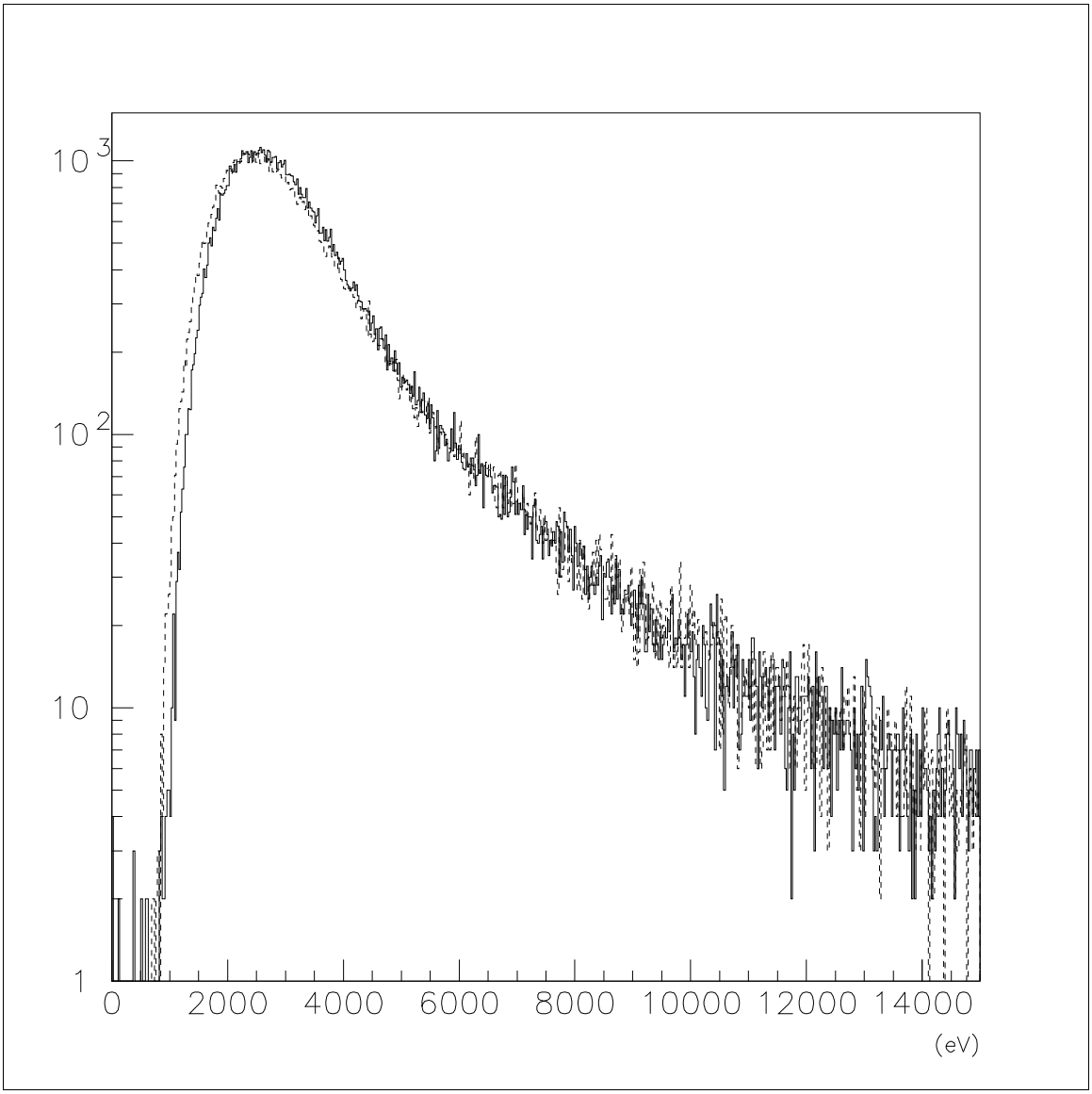

Figure 2: Same as Fig. 1, but plotted on a log scale.

Ionization Cluster Model

In principle, the mean separation between primary ionizations (clusters), together with the cluster-size distribution, completely specifies the ionization distribution. In practice, there are complications. A step length must be long enough that the extended size of clusters from hard δ-rays can be ignored. If a significant number of fluorescence x-rays are produced, they must be considered carefully, since, depending on their absorbtion length, they may or may not be detected in the volume of interest; this is true in cluster measurements and in the actual detector. Finally, ionization distributions may add non-linearly for gas mixtures, and even be sensitive to trace impurities.

Most of these complications are minor for P10 in the STAR TPC. X-ray yields in P10 are small: the fluorescence yield from the argon K-shell is only 12%.[4] Also, the CH_4 ionization energy is higher than the metastable level in Ar, so true Penning effect cannot occur, and ionization in P10 is only $\sim$2% higher[5] than expected from a linear combination of its components.

For this note, the primary ionization cross sections were taken from Rieke and Prepejchal.[6] Since their reported cross section for argon is significantly lower than values that are often quoted,[7] it is worth noting that essentially the same value was reported by Pansky et al.,[8] though with larger errors.

The cluster-size distributions were based on measurements by Fischle et al.[9] Fortunately, their distribution for argon was deconvoluted from a measurement of P10 using the cross sections of Rieke and Prepejchal, so recombining their results gives the distribution for P10 directly. However, extrapolation beyond the measured cluster sizes is done slightly differently here. Cluster sizes are increased by one to account for the charge of the initial δ-ray, though this has only a small effect on the result. In addition, the argon K-shell electrons are included in

[4] M. H. Chen, B. Crasemann and H. Mark, Phys. Rev. **A21**, 436 (1980).

[5] L. G. Christophorou, *Atomic and Molecular Radiation Physics* (Wiley, London 1971) find a maximum enhancement of 2% for 97% Ar, 3% CH_4; relevant data is quoted by W. Blum and L. Rolandi, *Particle Detection with Drift Chambers* (Springer-Verlag, Berlin 1993).

[6] F. F. Rieke and W. Prepejchal, Phys. Rev. **A2**, 1507 (1972).

[7] E.g., V. K. Ermilova, L. P. Kotenko and G. I. Merzon, Sov. Phys.-JETP **29**, 861 (1969).

[8] A. Pansky, G. Malamud, A. Breskin and R. Chechik, NIM **A323**, 294 (1992).

[9] H. Fischle, J. Heintze and B. Schmidt, NIM **A301**, 202 (1991).

the cross section for energy transfers greater than their ionization potential. This adds a small hump to the ionization distribution and improves the agreement with PAI models.

To compare ionization and energy-loss distributions, one must determine W. If one uses W=26.4 eV,[10] the distributions in Figs. 3 and 4 result. Clearly, W must be increased to align the peak with Nevski's.

The fit shown in Figs. 5 and 6 gives W=28.5 eV—significantly higher than expected. However, when one includes the relativistic suppression factor $(1 - \beta^2 T/T_{\max})$ in the δ-ray cross section and integrates the cluster-model ionization for P10, a similar value is needed to match the unrestricted energy loss (28.3 eV).

A plausible explanation for the low W values in the literature is that a small admixture of a hydrocarbon with a low ionization potential can dramatically increase the ionization yield. For example, the C_2H_6 ionization energy is comparable to the 11.6-eV Ar metastable energy level; adding 0.1% C_2H_6 to pure Ar lowers W by 15%. Toluene, a common contaminant in methane,[11] has an even lower ionization potential: 8.82 eV.

In fact, contaminants may be unavoidable to the extent that an accurate value for W in pure P10 is mostly of academic interest. Laser track calibrations often *assume* the existence of contamination, allowing two-photon ionization. However, without *a priori* knowledge of the real gas composition and the effect of contaminants, the most conservative approach is to use the higher value of W for uncontaminated gas.

The relative width of the PAI energy-loss distribution is larger than that of the cluster-model ionization distribution, even after scaling to align the peaks. This discrepancy is easily explained. Ionization measurements show much less structure than PAI model predictions. In particular, PAI models under-predict the cross section for energy depositions below the argon L-shell energy, and over-predict the cross section above it.[12] This bias toward large clusters makes the PAI distribution overly broad.

Finally, an effective value of W is needed for Geant-based simulations; a fit gives W=29.8 eV.

[10] L. G. Christophorou, *Atomic and Molecular Radiation Physics* (Wiley, London 1971); quoted by W. Blum and L. Rolandi, *Particle Detection with Drift Chambers* (Springer-Verlag, Berlin 1993).

[11] S. L. T. Drysdale et al., NIM **A252**, 521 (1986).

[12] See, for example, Fig. 12 from H. Fischle, J. Heintze and B. Schmidt, NIM **A301**, 202 (1991).

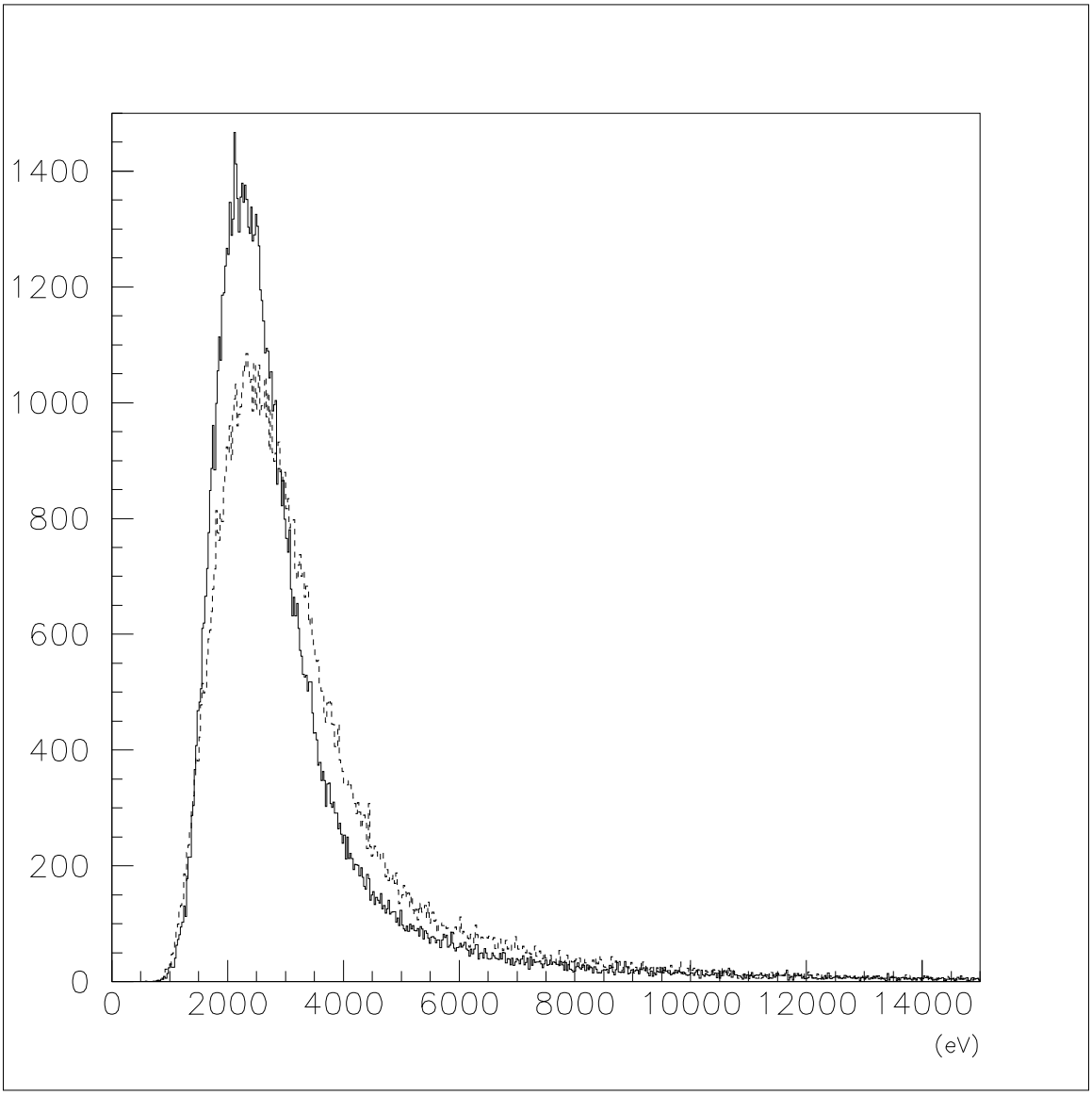

Figure 3: Energy-loss distributions for minimum-ionizing particles in 2 cm of P10 at 23.9°C and 1 bar; the result from the cluster model (solid line) peaks more sharply and at a lower energy than that from Nevski's code (dashed line). The cluster-model calculation used W=26.4 eV.

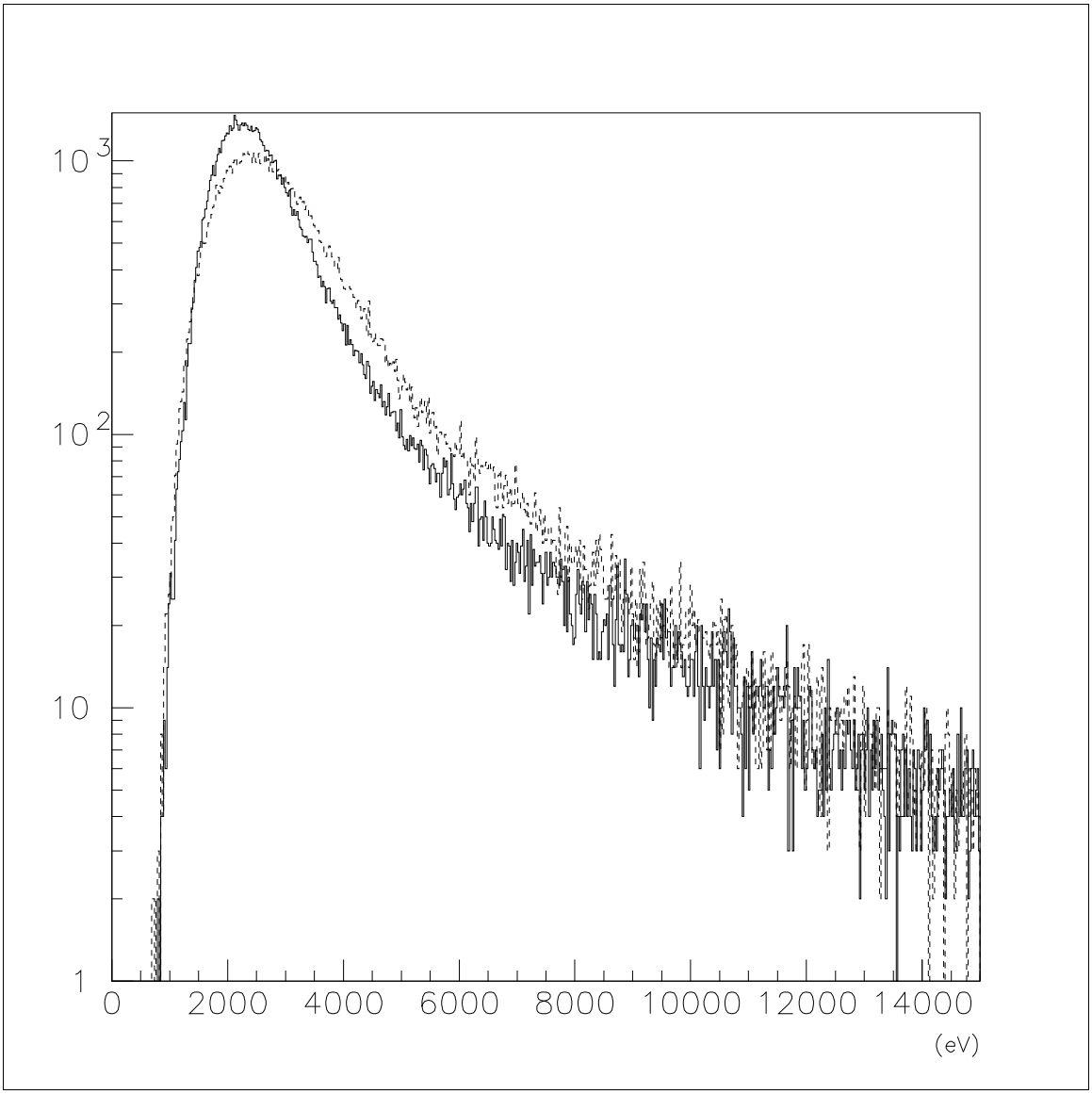

Figure 4: Same as Fig. 3, but plotted on a log scale.

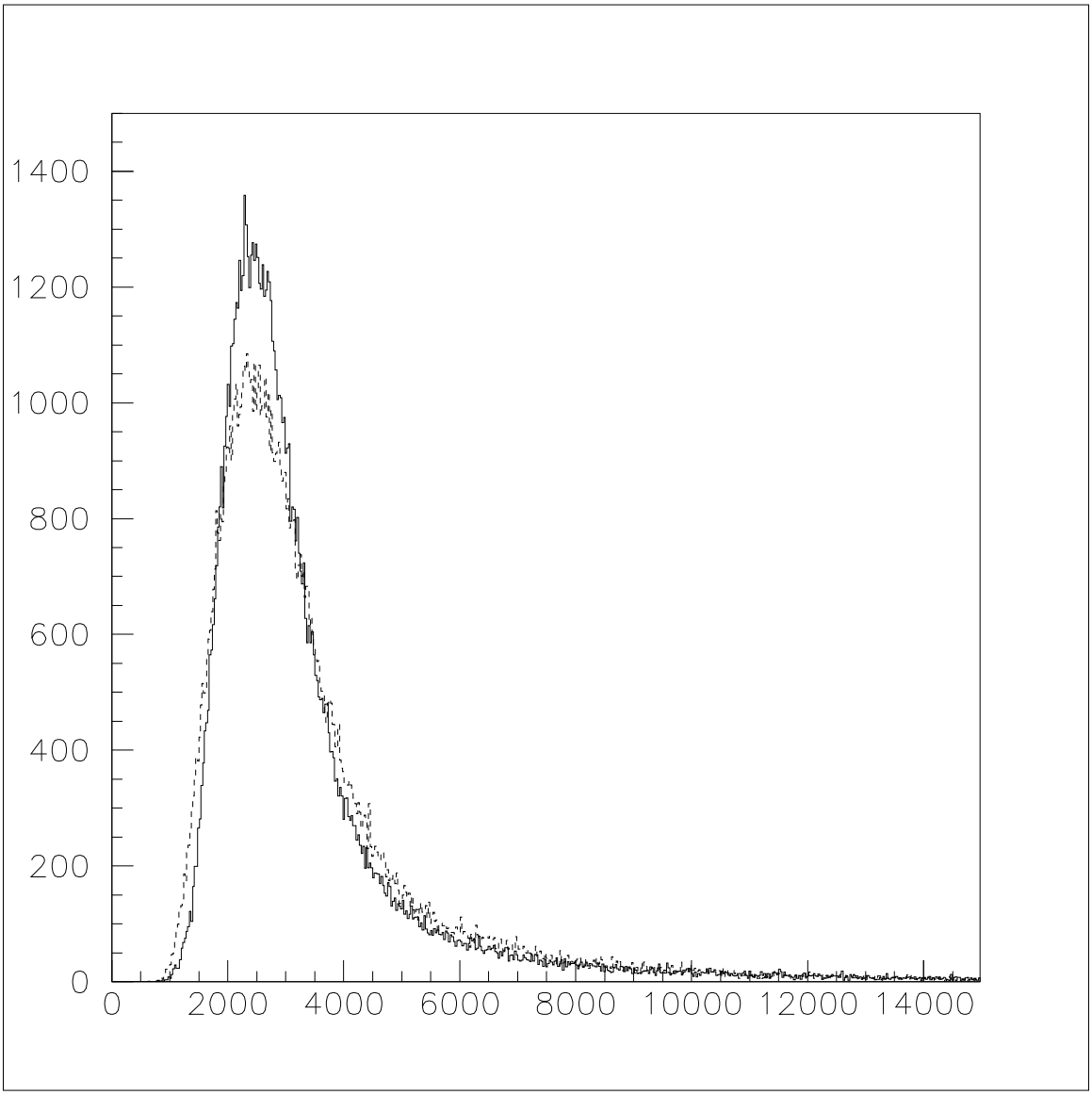

Figure 5: Energy-loss distributions for minimum-ionizing particles in 2 cm of P10 at 23.9°C and 1 bar. The cluster model distribution has been scaled in energy to match the peak from Nevski's code using W=28.5 eV. The cluster-model result (solid line) is still slightly narrower than that from Nevski's code (dashed line).

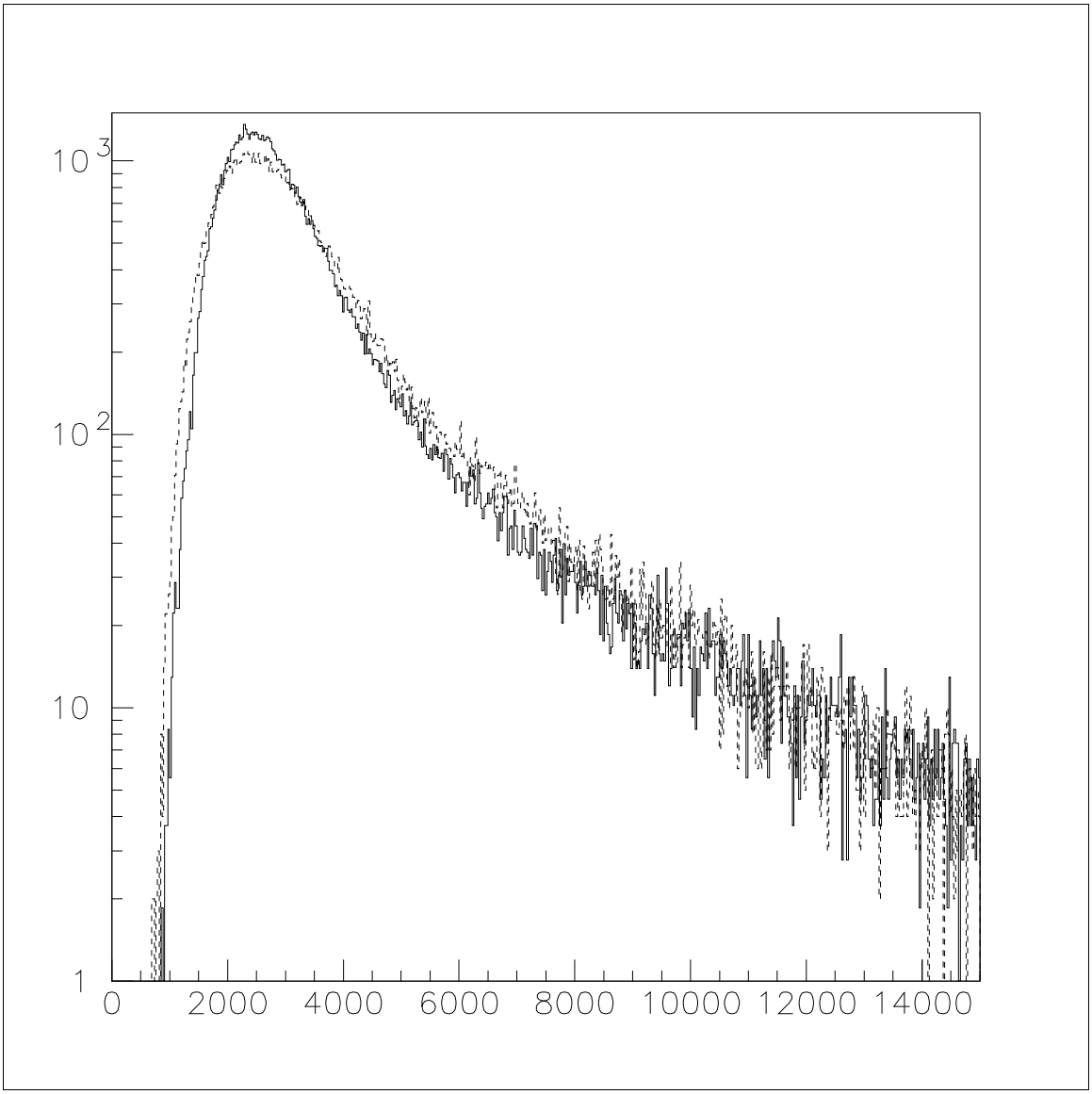

Figure 6: Same as Fig. 5, but plotted on a log scale.

The aligned distributions are shown in Figs. 7 and 8. Although the Geant distribution is still a bit wider than the cluster-model distribution, the differences are remarkably small. Also, experimental distributions tend to be broadened by various factors, such that the Geant distributions in Figs. 7 and 8 of SN0185 are *narrower* than the measured distributions.

The agreement begins to break down when the typical energy deposition in a volume approaches the ionization energy of the argon L-shell (245–320 eV). As discussed above, the PAI model over-estimates the cross section in this region. This effect is evident in Fig. 9 in which the distributions are plotted for a step of 0.5 cm, still using W=29.8 eV. Conversely, the agreement improves when the typical energy deposition is well above the energies of the argon shell structure, as shown in Fig. 10.

Conclusions

The Geant PAI algorithm is in good agreement with cluster measurements for P10, provided that the mean energy loss in a volume is at least a few KeV and one uses $W \approx 29.8$ eV. On the other hand, PAI models break down when the mean energy loss is a few times the ionization energy of the argon L-shell, or less. Therefore, subdivision of the energy loss in small gas volumes (as in the STAR TPC Slow Simulator) can be more accurately done using a cluster model, rather than a PAI model. (Unfortunately, cluster-size distributions are not available for many gases, limiting this approach to a few cases—such as P10.)

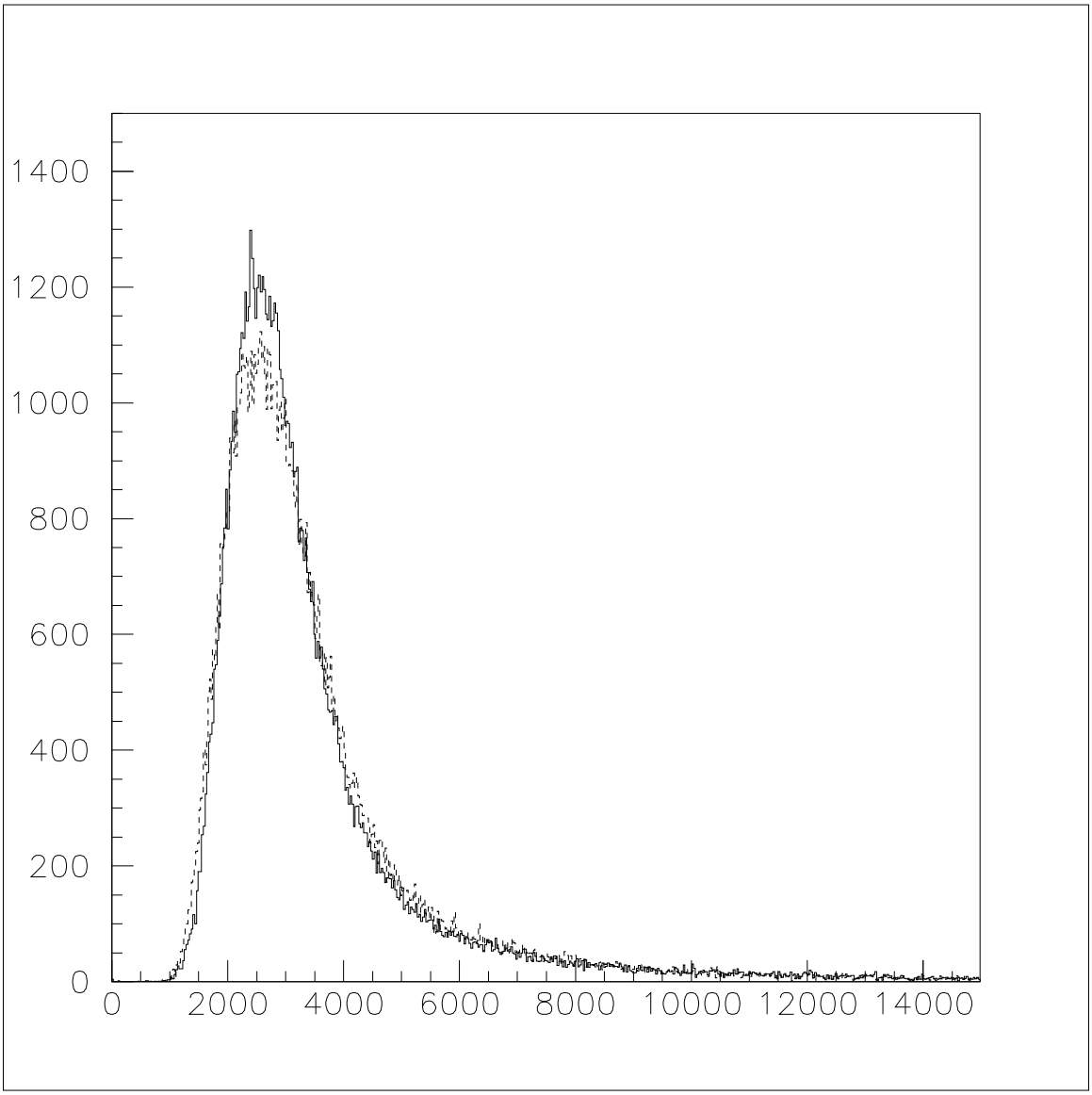

Figure 7: Energy-loss distributions for minimum-ionizing particles in 2 cm of P10 at 23.9°C and 1 bar. The cluster-model distribution has been scaled in energy to match the peak from Geant using W=29.8 eV. The cluster-model result (solid line) is still somewhat narrower than that of the Geant PAI algorithm (dashed line).

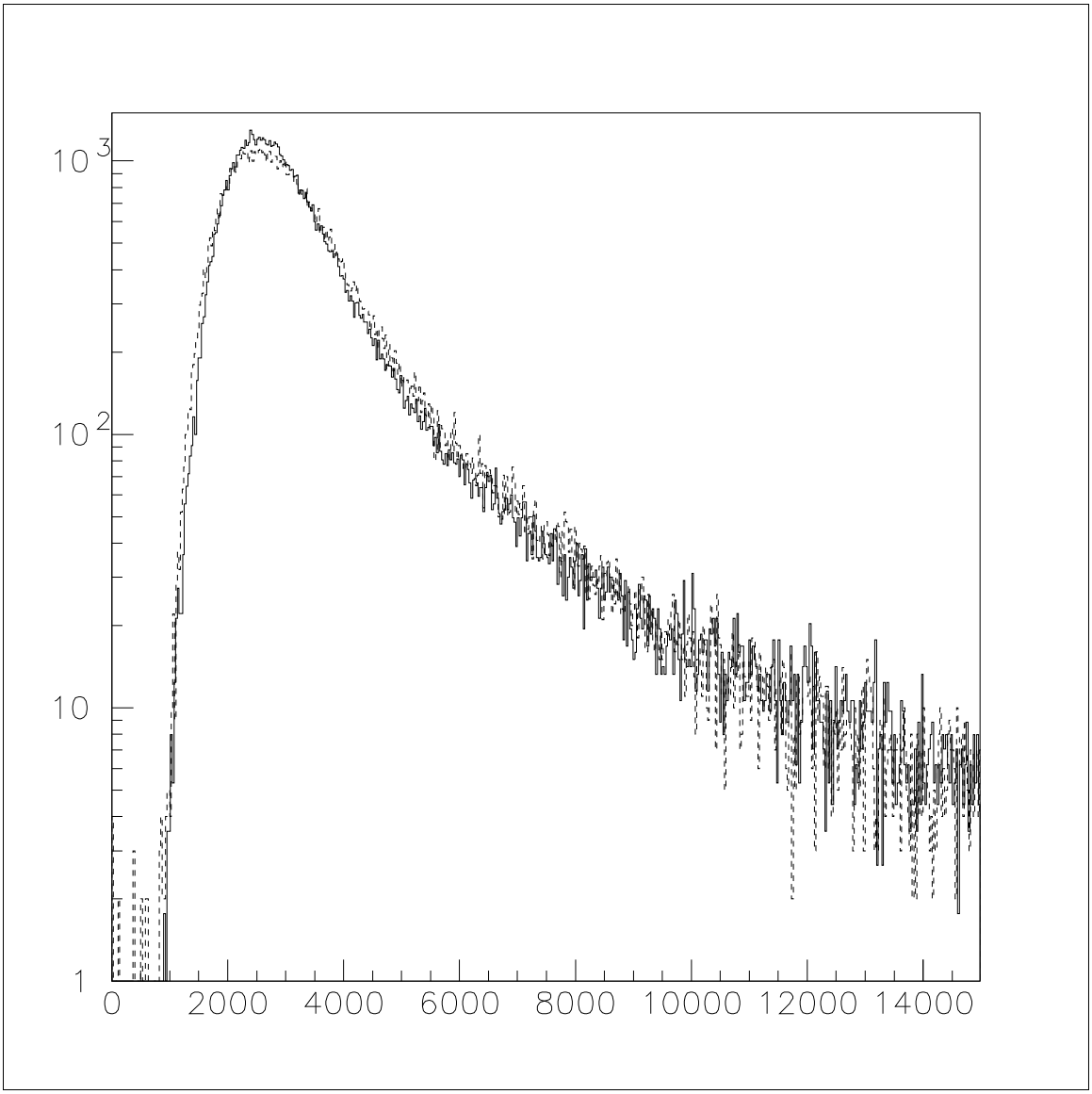

Figure 8: Same as Fig. 7, but plotted on a log scale.

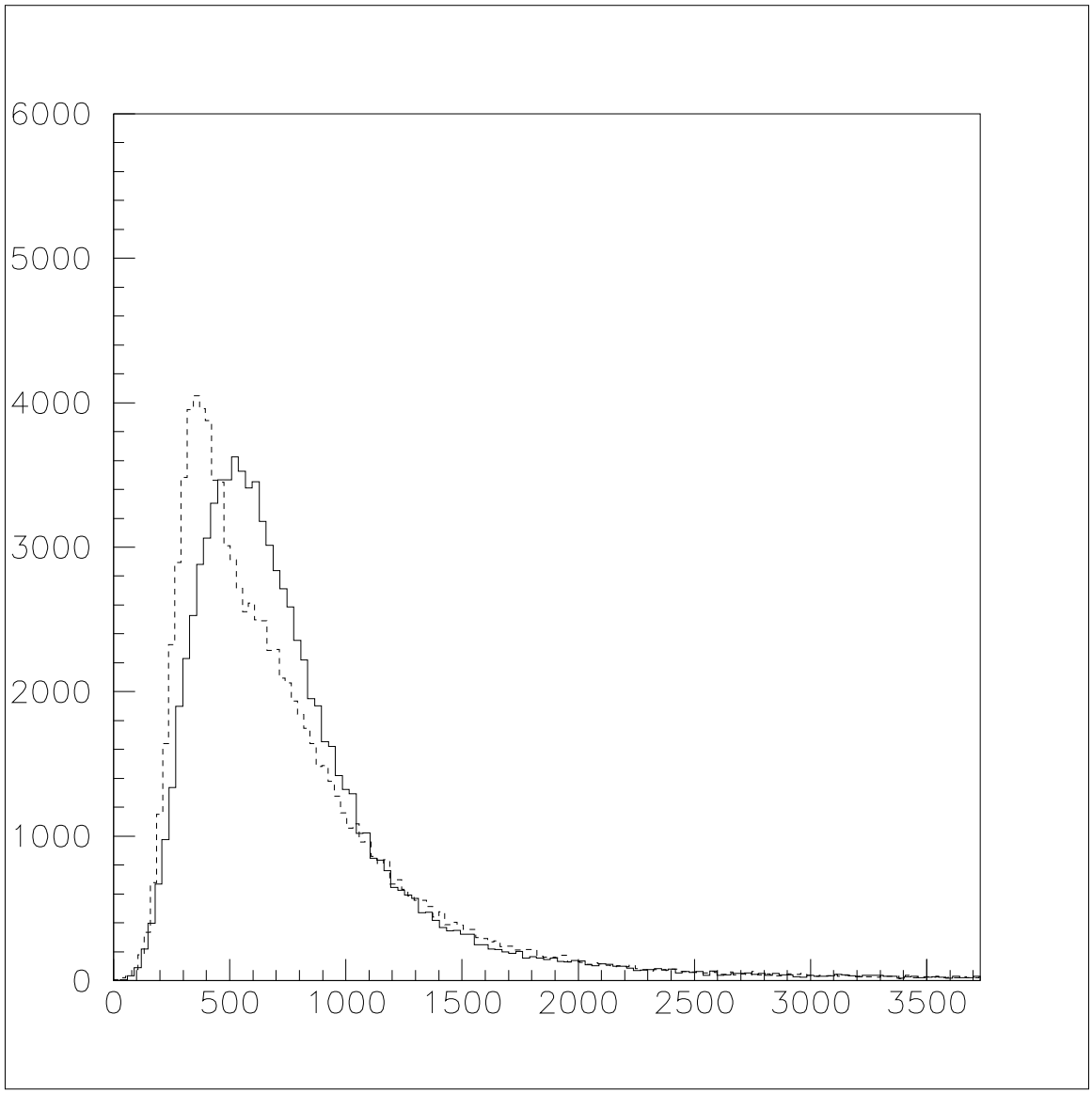

Figure 9: Energy-loss distributions for minimum-ionizing particles in 0.5 cm of P10 at 23.9°C and 1 bar. The cluster-model distribution (solid line) has been scaled in energy using W=29.8 eV. The Geant PAI results (dashed line) show the influence of the argon L-shell in the peak region.

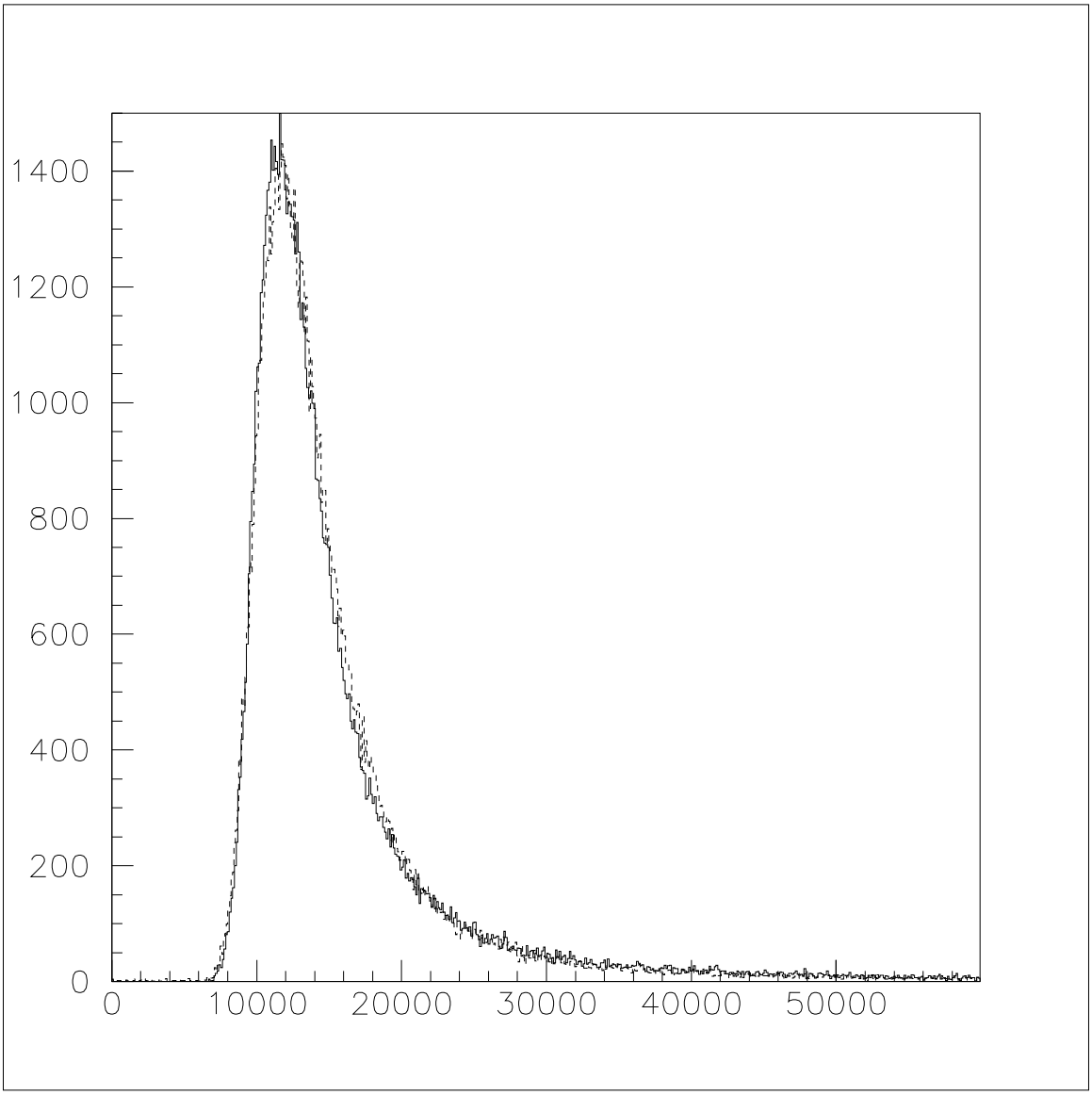

Figure 10: Energy-loss distributions for minimum-ionizing particles in 8 cm of P10 at 23.9°C and 1 bar. The cluster-model distribution (solid line) has been scaled in energy using W=29.8 eV. The Geant PAI results (dashed line) are in good agreement.