Undergraduate cosmic ray muon decay experiments with computer interfacing

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The physics departments of a consortium of higher education in Western Massachusetts, the Five Colleges Incorporated, are developing an advanced undergraduate laboratory course. The participating institutions are Amherst College, Mount Holyoke College, Smith College, and the University of Massachusetts. The course is designed to expose students to a variety of state-of-the-art equipment that would normally exceed reasonable financial commitments and faculty expertise of a single institution. The course is divided into experimental modules, one of which is the cosmic ray muon decay module developed at Smith College. The module is designed to investigate the dependence of the muon lifetime as a function of the medium in which it decays. Useful background information and a description of the module is given in this article.

INTRODUCTION

As early as 1941 the subatomic particle known as the muon was found to exist in abundance as a secondary particle in cosmic ray air showers.[1] This natural source of muons is readily exploited in a study of decay processes characterized by exponential half lives. More specifically we are looking at those decay processes with half-lives that operate on time scales of 10^{-7} to a few times 10^{-6} s. In modeling the sources of cosmic ray muons, we assume they are produced by interactions high in the earth's atmosphere. Time dilation of special relativity keeps the muons young until they reach the earth's surface. Then, if a muon with sufficiently low energy enters a detector it will be stopped and observed to decay. As the particle enters the detector, usually a scintillator or a Cerenkov device, a burst of photons is produced. The photons are detected and the signal amplified by a photomultiplier tube that triggers a start pulse in the detector timing electronics. The decay of the particle is associated with a second burst of photons. These photons initiate the stop pulse. The event's start-stop interval carries thestatistical uncertainty of the half-life decay. In this manner an ensemble of decay events is collected from which the correct lifetime can be extracted.

I. MUON DECAY MODES

In more traditional studies[2] the lifetime of the muon is investigated with interests focused on the free decay time seen in the reactions

$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e ,$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e ,$$

which have half-life times of approximately 2.2 μs. The free decay of the muon is not, however, the only process by which the muon can vanish.[3] The μ^- component of the muon flux appears to the stopping substance much like a heavy electron, and it soon acquires an orbit about one of the nuclei. The μ^- rapidly cascades to the ground level where it is subject to nuclear capture. The muon's Bohr radius in this ground state, r_0, is given by the expression

$$r_0 = (\hbar/e)^2(1/Zm_r) ,$$

where m_r is the reduced mass of the muon and nuclei and Z is the number of protons in the nucleus.

The common undergraduate exercise of comparing the muon orbital radius with the radius R_n of a nucleus is rich in pedagogical value. Here the nuclear radius is a function of the number of nucleons A and can be calculated with the expression[4]

$$R_n = R_0 A^{1/3} ,$$

if R_0 is taken as 1.2 $\times 10^{-13}$ cm. Fmm Fig. 1 and the quantum mechanical picture of probability densities for the muon about this radius, it is evident that the muon spends some fraction of its time in the nucleus. As the Z value of the capturing atomic structure increases, competing processes for the muon disappearance become increasingly more important. The processes of interest involve the nuclear capture of the muon:

$$\mu^- + p \rightarrow n + \nu_\mu .$$

Figure 2 summarizes the decay lifetimes as a function of Z. For low values of Z, less than about 6, free decay dominates the decay process. In the intermediate region of Z greater than 6 the nuclear capture processes become increasingly important, and this region is principally associated with Fermi transitions. Note the Z^4 dependence

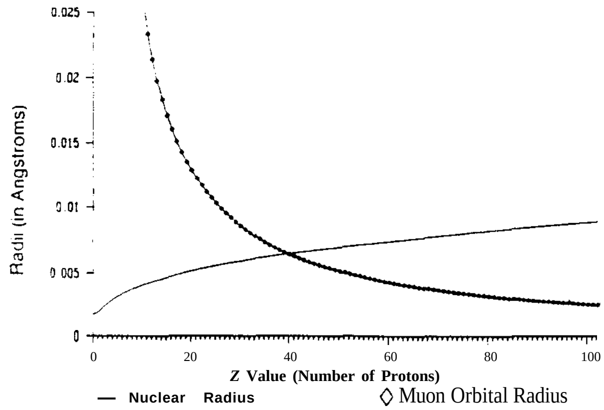

FIG. 1. Comparison **of radii for the nucleus and muon ground state orbit as a function of Z. Note crossover near Z = 40.**

of the decay lifetime in this region. The Z^4 dependence can be understood to be a product of two factors. The first is the Z dependence of the number of protons in the capturing nuclei, while a Z^3 dependence is derived from the probability density of the ground state hvdmgenic wave equation[5] for the muon and its overlap with the nucleus. In the region where Z is slightly greater than 40 the muon spends virtually all its time in the nucleus, and the Z dependence vanishes as the interaction is dominated by the nuclear capture process associated with Gamow-Teller transitions and has a half-life near 78 ns.

The instrumentation for these experiments usually involves expensive discriminators and time-to-amplitude converters in the form of nuclear instrumentation modules (NIM) The NIM equipment transfers decay time information to a multichannel analyzer. The increasing availability and decreasing cost of high-speed electronics and microprocessors now pmvide a vehicle for small institutions to study the shorter decay times associated with the nuclear capture of the muon. In Sec. II we will present one such system.

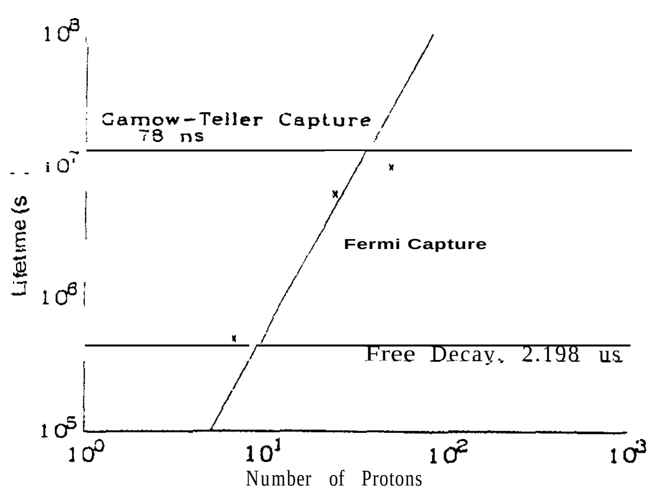

FIG. 2. Plot **of the Z dependence of muon lifetime. Observed lifetimes are marked with an X.**

II. EXPERIMENTAL APPARATUS AND COMPUTER INTERFACING

The detection and recording apparatus described here consists of a water Cerenkov detector sampled by a simple circuit. The circuitry is interfaced with an IBM PC (Fig. 3) through a Metrabyte[6] parallel port inserted within.

In order to study the range of the Z dependence of the nuclear capture, the water Cerenkov detector was run with distilled water and then with different nitrates, barium ($Z = 56$) and calcium ($Z = 28$), dissolved in the water to provide heavy nuclei with which the nuclear capture processes can take place. Barium and calcium nitrate were selected for their low cost and low toxicity. It was found that the calcium tended to become turbid if the acidity of the solution was not kept high ($pH < 3$).

Located within the Cerenkov vessel was a 5 in. hemispherical photomultiplier tube, PMT (Thorn EMI model: 989181, with its photocathode held at ground and partially immersed into the solution. The signals from the anode of the photomultiplier tube are sampled by the circuitry

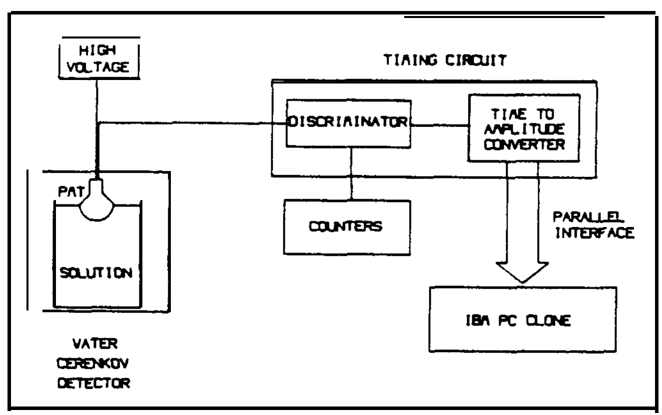

FIG. 3. Block diagram of the detector.

shown in Fig. 4. Here a start pulse created by the passage of a cosmic ray muon into the Cerenkov detector gates a 20 MHz clock to a series of counters. The gate is turned off by the detection of a muon decay observed as a delayed, second event pulse fmm the PMT. If no decay pulse is observed within a 12 μs window, the counters are reset and the start pulse is recorded as a singles event. The singles rates are, in turn, used to calculate the statistical accidental rate R_a, which is the phenomenon of having two unrelated events in the time window and given by

$$R_a = R_s^2 \Delta t T_r ,$$

where R_s is the singles rate, Δt is the 12 μs time window, and T_r is the total run time.

The parallel interface between the circuitry and the IBM PC downloads the event information into the microprocessor memory using an assembly language program. A histogram of the number of decay events versus the delay time quantized by the 20 MHz sampling of the circuit is collected. The data is analyzed by a nonlinear (grid

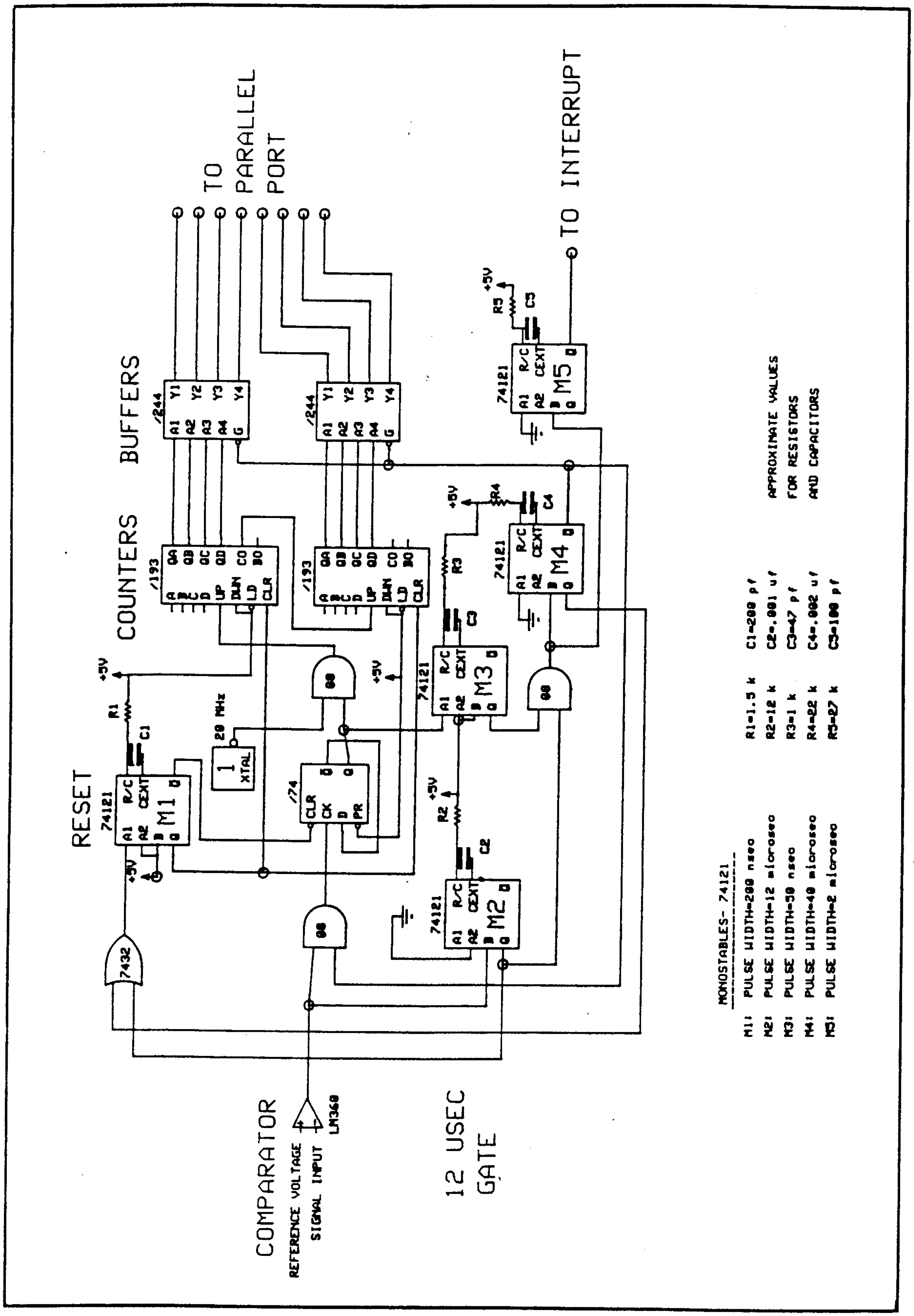

FIG. 4. Circuit diagram of the timing circuit's electronics.

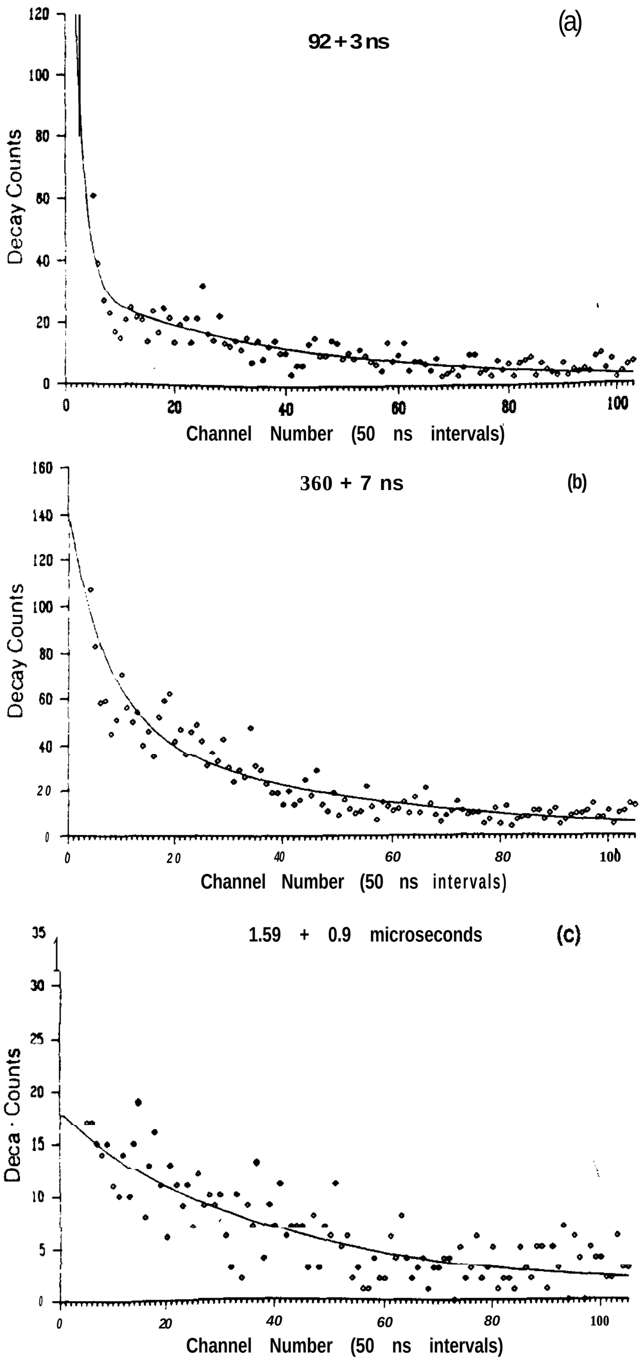

FIG. 5. Exponential curves fit to data for free decay and capture lifetimes of (a) barium, (b) calcium, and (c) water (oxygen).

search)[7] least-squares program, MUDECAY, written in BASIC. The algorithm fits two exponential curves to the data. Two curves are needed for the different populations of muons (μ^+ and μ^-). The first exponential is due to the μ^+ free decay with mean lifetime of $2.2\,\mu s$. The second exponential is due to the μ^- where the characteristic time constant is derived as follows.

The decrease in the μ^- population during the time interval dt is given by

$$dN = (\lambda_f + \lambda_c)N\,dt\,,$$

where λ_f and λ_c are the reciprocal mean free and mean capture lifetimes, respectively. The time constant for the combined processes is therefore

$$\tau = \tau_f \tau_c / (\tau_f + \tau_c)\,.$$

The background rate of accidentals is fixed by the singles rates, and a decay exponential that incorporates free and nuclear capture of the μ^- component of the muons is computed and displayed in Figs. 5(a)-5(c).

A symmetric fiducial volume of 10 to 15 kg of water and a singles rate of 1 min/cm^2 at 175 ft above sea level provided an ample number of events within a week per solution to identify the clear signature of the nuclear capture process.

III. CONCLUSIONS

The experiment as described can be easily developed at an equipment cost slightly under $1200. Students are exposed to the experimental methods of particle detection techniques and computer interfacing. A familiarity with relativistic effects from the Cerenkov radiation is gained, while an introduction to nuclear and particle physics via the nuclear capture of the muon is available. The astute student will recognize the flavor dynamics of the ($u \rightarrow d$) quark metamorphosis via weak interactions of leptons with quarks, while the young biophysicists interested in the hazards of cosmic ray irradiation will be impressed with the change in the singles rates when the water Cerenkov detector is emptied.

REFERENCES

1. B. Rossi, *Cosmic Rays* (McGraw-Hill, New York, 1964), p. 2.
2. A. Hall, D. Lind, and R. Ristinen, Am. J. Phys. 38, 1196 (1976).
3. T. Ward, M. Barker, J. Brenden, K. Komisarcik, M. Pickar, D. Wask, and J. Wiggens, Am. J. Phys. 53, 542 (1985).
4. J. D. McGervey, *Introduction to Modern Physics* (Academic, New York, 1983), p. 52.3.
5. Reference 4, p. 246.
6. Metrabyte Corporation, 254 Tosca Drive, Stoughton, MA 02072 ~5109.001.
7. P. Bevington, *Data Reduction and Error Analysis for the Physical Sciences* (McGraw-Hill, New York, 1969), p. 206.