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Development of the low-cost multi-channel analyzer system for γ -ray spectroscopy with a PC sound card

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A low-cost multi-channel analyzer (MCA) system was developed using a custom-build interface circuit and a PC sound card. The performance of the system was studied using γ -ray spectroscopy measurements with a NaI(Tl) scintillation detector. Our system successfully measured the energy of γ -rays at a rate of 1000 counts per second (cps). © 2013 American Association of Physics Teachers.
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I. INTRODUCTION

The digitization of analog signals is one of the most important processes in modern physics experiments. The process can be divided into two steps: (1) digitization and (2) data sorting. The first step is performed by an analog-to-digital converter (ADC) and the second step is usually carried out on a computer (PC). A multi-channel analyzer (MCA) is frequently used for this purpose since it provides both functions in one module.

One useful application of MCAs is γ -ray spectroscopy. It is an important experimental method in nuclear physics and a good subject for undergraduate education. However, the equipment required for γ -ray spectroscopy is usually very expensive and few students have the opportunity to perform this type of measurements.

Figure 1 shows a block diagram of a simple system that can be used for γ -ray spectroscopy. When γ -rays pass through the scintillator (SCINTI), they interact with the material and the scintillator emits photons. A photomultiplier tube (PMT) is connected to the scintillator and converts the photons into electrical signals. An interface amplifier (AMP) reshapes the signals before sending them to the MCA system.

Our low-cost MCA development was motivated by our desire to expose our undergraduate students to γ -ray spectroscopy.¹ We developed a MCA system using a PC sound card with a 16-bit 44.1-kHz sampling ADC. Our goal was to develop a system with a resolution of more than 10 bits, able to handle count rates up to 1000 counts per second (cps).

In the following Sections, we will describe the hardware and software of our MCA system. Results of performance measurements with a pulse generator and a simple γ -ray detector are presented.

II. MULTI-CHANNEL ANALYZER SYSTEM

The performance of our system was compared with that of a reference system. The signal flow for both systems is shown in Fig. 2. A peak-sensing ADC, using the Computer Automated Measurement and Control (CAMAC) standard, was used as our reference. Table I summarizes the properties of both systems. Although the reference system can handle higher count rates, provides better resolution, and supports more channels, typical student experiments do not require sixteen channels and the ability to handle 10,000 cps. The two channels provide by our system are sufficient for most undergraduate experiments. By using a spare PC, our system costs less than 200 dollars.

Our system consists of an amplifier, a sound card, and a computer. The interface amplifier shapes and amplifies the detector signals to make them suitable for the ADC in the sound card. The sound card digitizes the input signals with a sampling rate of 44.1 kHz. The analysis program extracts the peak height from the digitized waveform while the peak-sensing ADC of the reference system records the peak amplitude of the input signal.

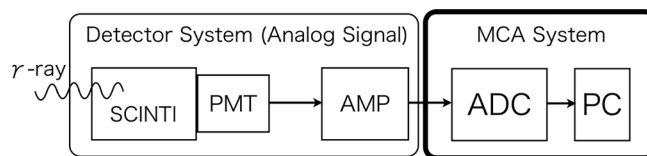


Fig. 1. Block diagram of a simple setup for γ -ray spectroscopy measurements.

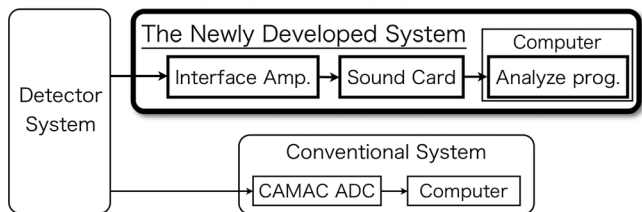


Fig. 2. Diagram of signal flow in our system and in a conventional CAMAC system used as a reference.

A. The interface amplifier

The interface amplifier consists of a CR-(RC)⁷ shaping circuit and is also known as a semi-Gaussian amplifier.² Figure 3 shows a circuit diagram of the CR-(RC)⁷ amplifier. The linear Pulse Code Modulation (PCM) standard defines the sampling rate and resolution of PC sound cards. Modern PC sound cards record audio data with a sampling frequency of 44.1 kHz and a resolution of 16 bits (signed).

The bandwidth of the interface amplifier was designed to be under 20 kHz since the bandwidth of the sound card covers frequencies up to 20 kHz, which is the limit of audibility. Several samples of a digitized waveform are required in the analysis program to achieve good resolution. This requires a pulse width of at least 100 μ s to match the 44.1 kHz sampling rate (22.7 μ s per sample). The time constants of the differentiation and integration circuits were chosen as CR = 15 μ s to satisfy the above requirement. The sound card captures signals with amplitudes up to ± 2 V; this covers the typical range of nuclear physics electronics. Therefore, the gain of our amplifier was designed to be ~ 1 . The coarse gain of the system can be adjusted by changing the feed back resistance (R_g) of the operational amplifiers. The dynamic range can be fine tuned by adjusting the recording level of the sound card.

The parameters of the interface amplifier are listed in Table II. The impulse response was calculated using PSpice (Cadence Design Systems, Inc.) which is simulation software for electronic circuits. The results of the simulations, shown in Fig. 4, indicate that the bandwidth requirement is satisfied with these parameters. Eight operational amplifiers (op-amps) are used for the interface amplifier. Each LF353 (National Semiconductor Corp.) chips has two individual op-amps. These chips do not require any complicated adjustments.³

The amplifier parameters depend on the type of the detector system used and may need to be adjusted for other detector systems to achieve optimum performance. In general, gain adjustments (R_g) are sufficient.

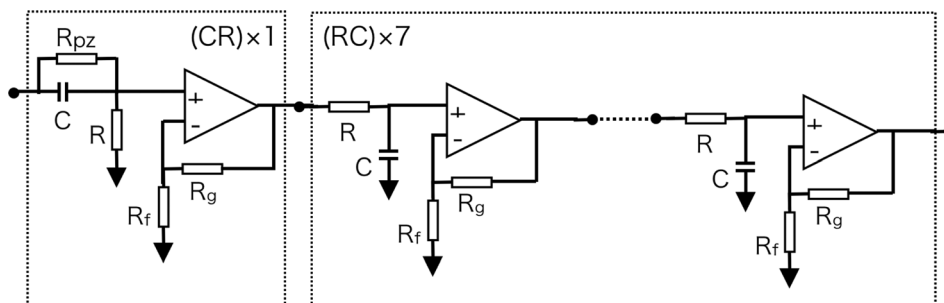


Fig. 3. Circuit diagram of the interface amplifier.

Table I. Properties of our system and the CAMAC reference system.

	Developed	Reference
Dynamic range	± 2 V	2.5 V
Resolution	10 bit	12 bit
Rate	<1000 cps	<10,000 cps
Number of channels	2	16
Cost of the ADC	\$100	$\sim \$4,000$ – $\$6,000$
Cost of the system	\$200	$\sim \$10,000$

B. The sound card

The output signal of the interface amplifier is connected to the PC sound card through a standard RCA pin jack connector. Table III lists the characteristics of the sound card we used. By using the left and right channels of the stereo signal, two signals can be digitized.

Although any internal sound card can work, an external sound card with a USB interface was used to reduce internal noises, mainly clock noise, from the computer. The data were recorded with a standard PC (AMD Athlon64 FX-60 Dual Core 2.6 GHz, 4 GB RAM, Windows XP) using software which captures the sampled pulse height information in ASCII format. Any standard sound capture program which supports WAV format can be used if the header information is adequately handled. We developed a simple program with the freely available cross platform audio API, OpenAL, for this purpose.⁵

C. The analysis program

In order to achieve good resolution, the analysis program applies a least chi-square fitting method to the sampled waveform. The waveform describes the pulse shape at the output of the interface amplifier. The data is fitted with the waveform template shown in Fig. 5 and is characterized by three parameters: “level shift,” “peak time,” and “amplitude.”

The waveform template was prepared in advance of the measurements and may be different for different experiments. In this experiment, our goal is to do γ -ray spectroscopy with a NaI(Tl) scintillation counter and the waveform template must thus describe the shape of the NaI(Tl) pulse. A pulse generator was used to make the template. The rise and fall times of the pulse generator were set to 500 ns and 10 μ s, respectively, to simulate the shape of the PMT signals after the pre amplifier. A digital oscilloscope (Tektronix, TDS 3052B) was used to capture the output signals of the interface amplifier. Thirty generated waveforms were captured by the oscilloscope and their average was used to

Table II. Parts and parameters of the interface amplifier.⁴

Capacitor (C), ceramic condenser	3 nF
Resistance (R), metal-film resistor	5 k Ω
Pole zero feedback (R_{pz}), metal-film	5 k Ω
Feedback resistance (R_f), metal-film	2.1 k Ω
Gain adjust resistance (R_g), metal-film	1 k Ω
Operational amplifier	LF353

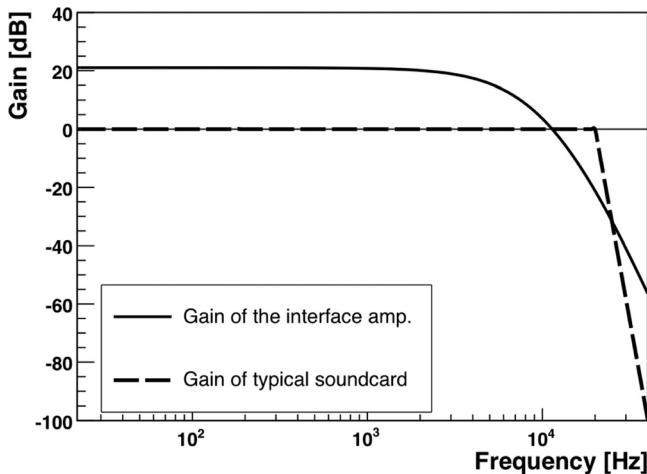


Fig. 4. Simulation of the frequency responses of the interface amplifier (solid line) and gain of a typical sound card (dashed line).

Table III. Properties of typical soundcard.

Soundblaster Digital music PX (Creative tech. LTD.)	
Connection	USB (External Connection with Computer)
Sampling rate	44.1 kHz
Band width	20 kHz
Resolution	Signed 16 bit
Full Scale	$\pm 2V_{rms}$

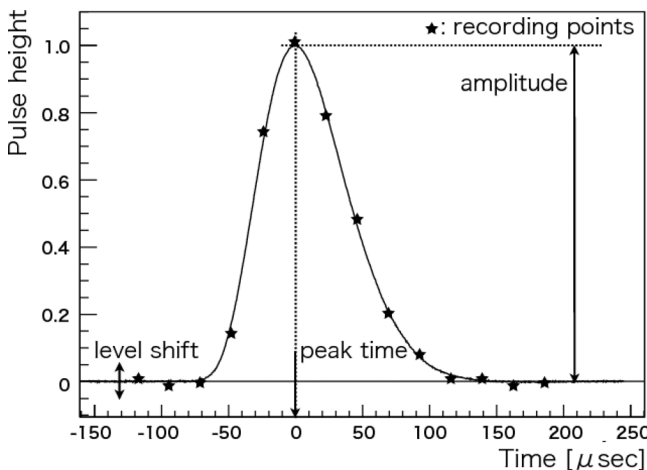


Fig. 5. The waveform template used for chi-square fitting.

generate the waveform template. A reader who has no digital oscilloscope can use a Gaussian function as the waveform template though this may result in reduced resolution.

In our analysis program, we set a proper threshold level to discriminate true γ -ray signals from electronic noise. If a sample of the captured data is higher than this threshold level, the signal is treated as a real signal. The program then searches for the peak position. After the waveform is selected, a least chi-square fitting is carried out with the waveform template. The chi-square fit is performed using the freely available Minuit package of the CERN program library (CERNLIB) and ROOT.⁶

III. PERFORMANCE MEASUREMENTS

Figure 6 shows a schematic diagram of the test setup of our system. We measured the resolution and the linearity of the system with a pulse generator at low count rates. The overall system performance was studied with γ -ray measurements with a NaI(Tl) scintillation counter. The rate stability of the system was also determined.

A CAMAC peak-sensing ADC (Hoshin C008) was used as our reference system.⁷ This ADC has 16 inputs, 12 bit resolution, and better than 1 least significant bit (LSB) linearity. A shaping amplifier (Ortec 671) was used to shape the PMT signals. The shaping time was set to 10 μ s and the output pulse height was adjusted to be less than 2 V, the range of the ADC.

The analysis program was compiled using a g++ compiler. It processes 10,000 events in 90 s on a PC with a 2.0 GHz intel Core 2 Duo processor with 2 GB of memory.

A. Pulser tests

A research pulser (Ortec 448) was used to study the resolution and linearity of the system. It generates a unipolar pulse with a long term stability of 15 ppm over 24 h. The repetition rate of the pulser was set at 20 Hz. The rise and fall times were set to 500 ns and 10 μ s, respectively. This produces a pulse with a shape similar to the pulse generated by the pre-amplifier.

The width of the measured peaks is plotted in Fig. 7 as function of pulse height. The peak width (σ) is defined as the standard deviation of the peak:

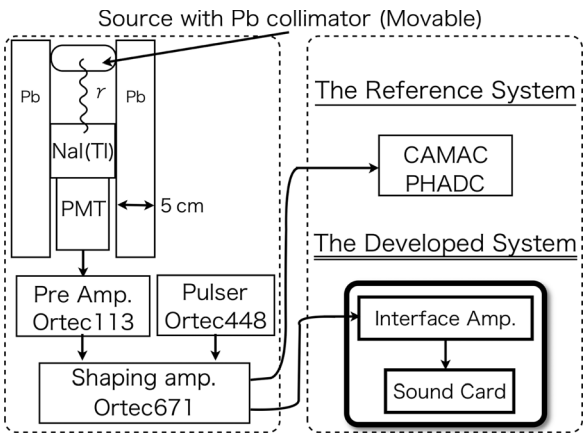


Fig. 6. Schematic diagram of the experimental setup of the radioactive source measurements.

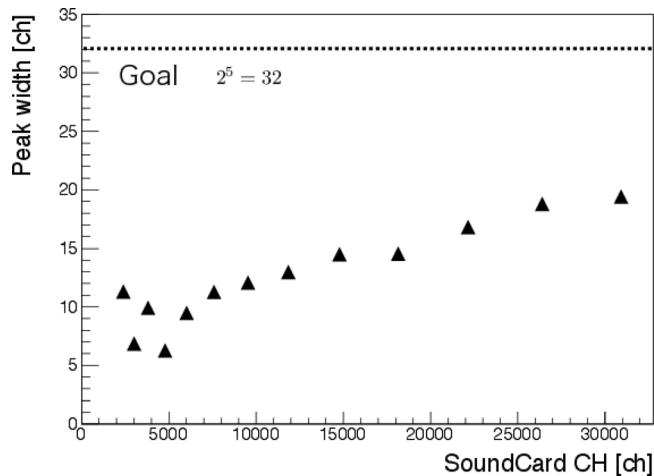


Fig. 7. Standard deviation of the pulser peaks as function of the peak centroid.

$$\sigma^2 = \frac{1}{N-1} \sum_{i=1}^N (x_i - \mu)^2, \quad (1)$$

where N is the total number of samples and μ is the mean of the peak. Our goal was to develop a system with 10-bit

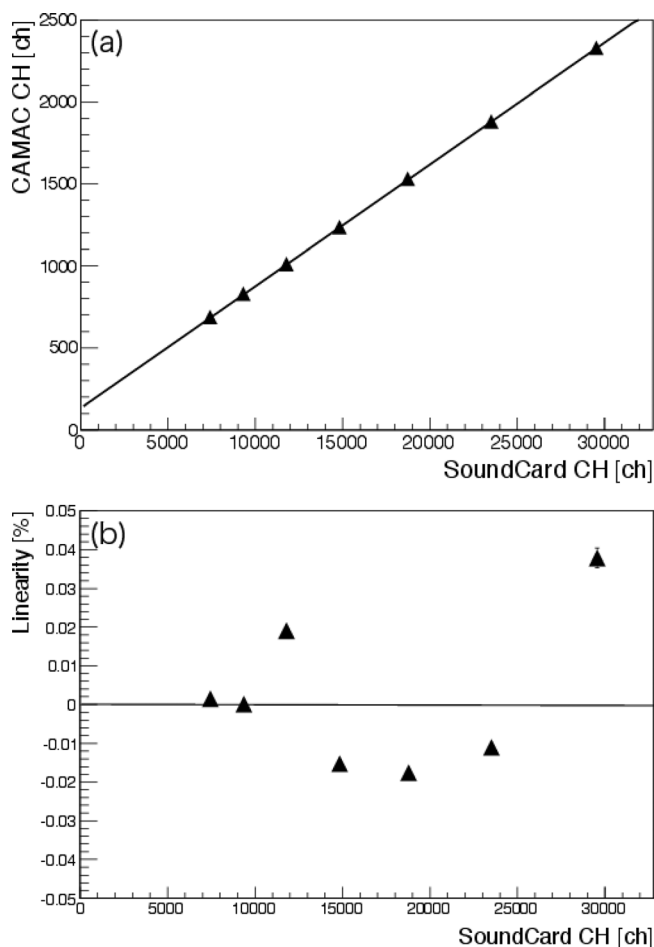


Fig. 8. (a) The correlation between the peak centroids obtained with our system and with the CAMAC reference system. The line shows the result of a linear fit to the data. (b) The residuals from the linear fit as function of the peak centroid measured with our system.

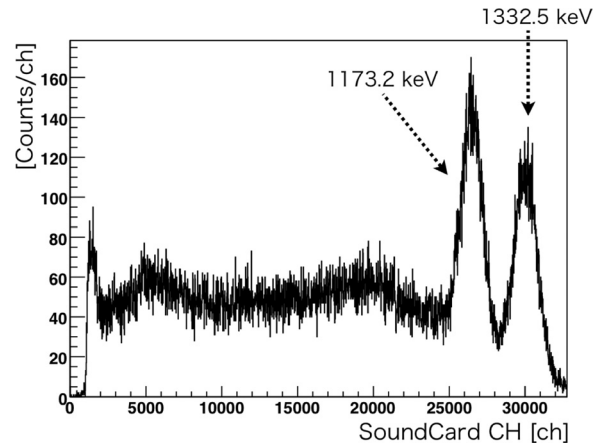


Fig. 9. ^{60}Co γ -ray spectrum acquired with our system.

resolution over the entire range; i.e., the system must be able to detect differences of $1/2^{10} = 1/1024$ of full scale. The sound card has 16 bits for a range from -2 V to $+2\text{ V}$ (full scale) and 15 bits for positive inputs. A 10-bit effective resolution requires the peak widths to be less than 5-bits wide (32 channels). Figure 7 shows that the peak widths are less than 32 channels over the entire range.

The linearity of the system was examined using the CAMAC system as a reference. Figure 8(a) shows the correlation between the mean values (μ) of the peaks measured by our system and those obtained with the reference system.

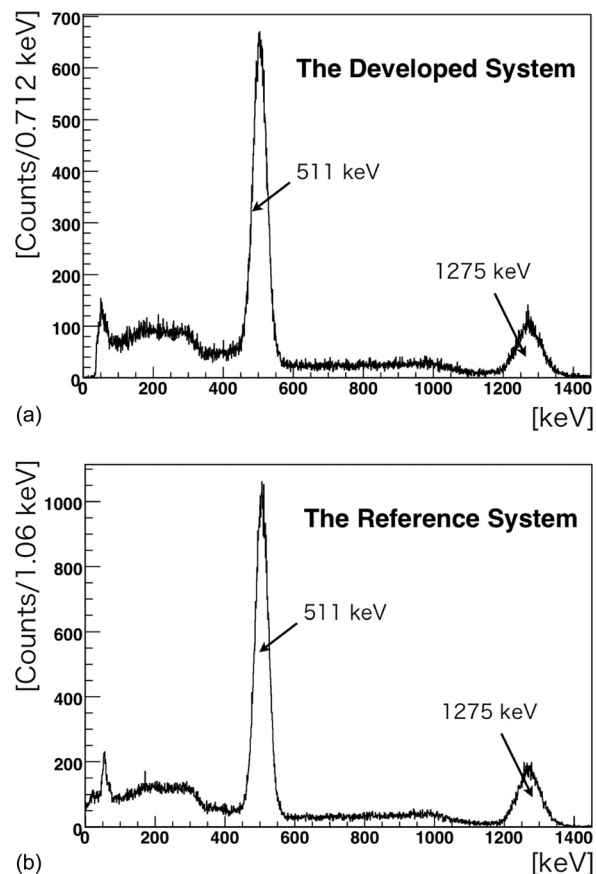


Fig. 10. ^{22}Na γ -ray spectra measured with our system (top) and with the reference system (bottom). The bin width corresponds to the width of one ADC channel for each system.

Figure 8(b) shows the residuals from the linear fit, normalized by the full scale of the ADC ($2^{15} - 1 = 32767$). It can be seen that these residuals are less than 0.05%. Since the linearity of the CAMAC reference system is $< 1/2^{12} \sim 0.024\%$, we conclude that the linearity of our system is better than 0.075% over the entire range.

B. Tests with radioactive sources

To demonstrate the performance of our system with γ -ray spectroscopy measurements, we used the setup shown in Fig. 6. The NaI(Tl) scintillation counter (Bicron 3H3/3L-X, $\phi 8 \text{ cm} \times 8 \text{ cm}$) was surrounded by 5-cm thick lead walls to reduce background radiation. A radioactive source was fixed to a 5 cm-thick lead block with a hole of radius 1 cm to collimate the γ -rays onto the center of the scintillation counter. The rate of γ -rays was adjusted by changing the distance between the source and the detector.

A ^{60}Co source was used for the energy calibration. Figure 9 shows a histogram obtained with the ^{60}Co source. The two peaks at ~ 26000 ch and ~ 30000 ch correspond to the 1173.2 keV and 1332.5 keV γ -rays emitted by the ^{60}Co source, respectively. The energy calibration of the system was performed using these two peaks and we obtained the following relation:

$$y[\text{keV}] = 0.044622 \cdot x[\text{ch}] - 8.8373, \quad (2)$$

where x is amplitude of the waveform captured by the sound card (in units of channel number) and y is γ -ray energy (in units of keV). The CAMAC reference system was calibrated using the same procedure.

Figure 10 shows the γ -ray spectra obtained with a ^{22}Na source and measured with our system (top) and with the CAMAC reference system (bottom). The ^{22}Na nucleus decays to an excited state of ^{22}Ne via a β^+ -decay process with the half-life of 2.6 years. The excited ^{22}Ne decays to the ground state and emits a 1275 keV γ -ray.⁸ The positron is stopped in the source, annihilates with an electron, and emits two 511 keV photons in opposite directions, as required by momentum conservation. The bin widths correspond to the energy range covered by one ADC channel of each system. The most intense peak, the annihilation peak, and the peak at higher energies are due to the 511 keV and 1275 keV photons, respectively. The count rate of the system for the measurement shown in this figure was 450 cps. A chi-square fitting procedure was applied to the 511 keV peaks of both system and the results were consistent within an accuracy of 0.25%.

The rate dependence of the ratio of the peak areas and the shift of the peak positions were measured in order to evaluate the rate stability of the system. The peak area ratio R is

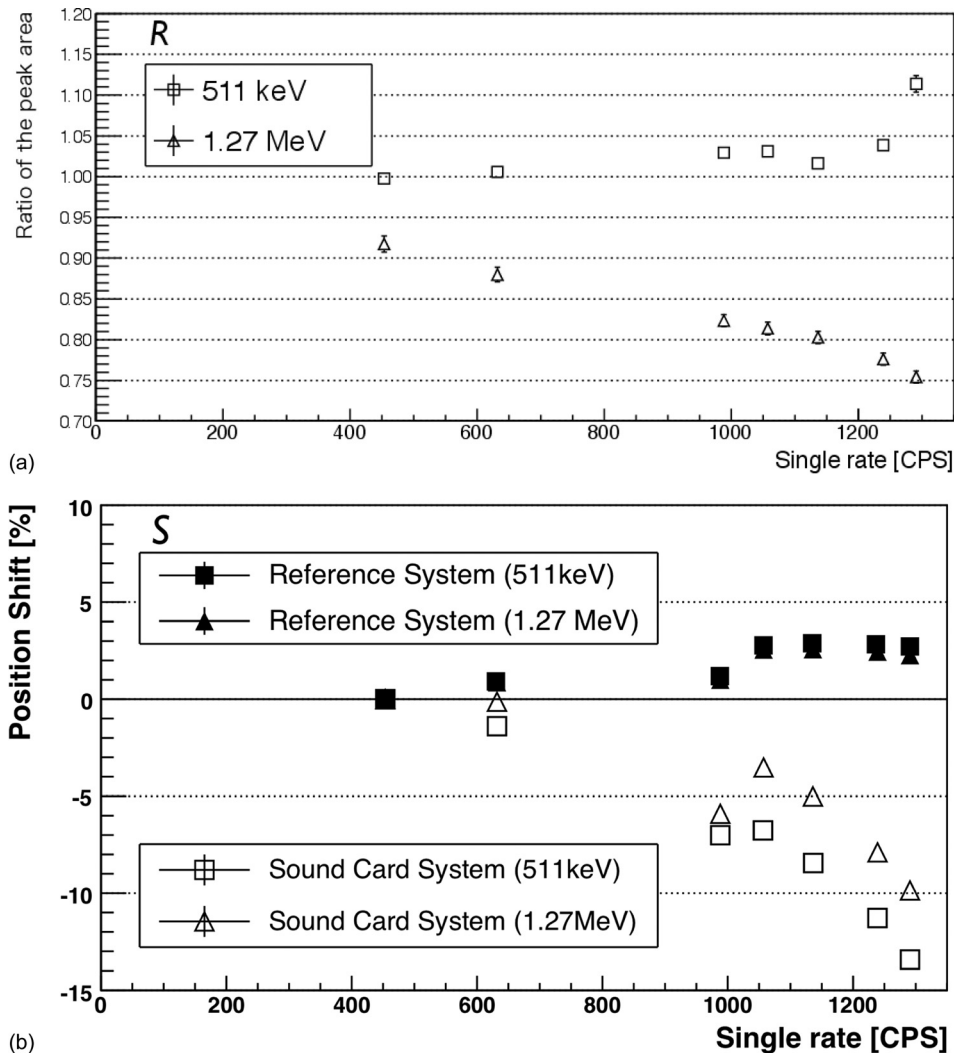


Fig. 11. The ratio of the peak areas R (top) and the peak position shift S (bottom).

defined as the ratio of the number of counts observed by our system to that obtained with the CAMAC system. For the 511-keV peaks at a count rate of 450 cps, R was determined to be $R = 0.998 \pm 0.005$. The peak shift S is defined as the difference of the position of the full-energy peaks at different count rates, relative to the position at the lowest count rate (450 cps).

Figure 11 shows the rate dependencies of the area ratio R (top) and the peak shift S (bottom), respectively. The value of R for the 1.273-MeV peak decreases when the singles rate increases. The area loss becomes 20% ($R = 0.8$) at 1200 cps. The 511-keV peak shows opposite tendency and the maximum difference is about 10%.

The value of S deviates from zero when the single rate is larger than 1000 cps and the peak shift can be limited to a few percent for a single rate less than 600 cps.

IV. SUMMARY AND CONCLUSION

A low cost multi-channel analyzer system was developed using a PC sound card and a simple interface circuit. The performance of the system was evaluated using a NaI(Tl) counter in a γ -ray experiment. At low count rates, the resolution and linearity are more than 10 bits and 0.075%, respectively. Up to count rates of 1000 cps, the peak shift and area changes are less than a few percent at low energies and up to 20% at higher energies. Our system shows sufficient performance for undergraduate experiments which require modest resolution with count rates less than 1000 cps. The count-rate limitations are due the interface amplifier. In order to have better performance at high count rates, a more

sophisticated interface amplifier with a baseline restorer would be necessary.

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¹Similar projects can be found in the sites: <<http://www.physics.usyd.edu.au/~marek/pr/index.html>> and <http://www.fusor.net/board/view.php?bn=fusor_neutrons&key=1281247740>.

²W. R. Leo, *Techniques for Nuclear and Particle Physics Experiments*, 2nd rev. ed. (Springer-Verlag, Berlin, 1994), p. 283.

³LF353 Wide Bandwidth Dual JFET Input Operational Amplifier General Description, (National Semiconductor), <<http://www.national.com/ds/LF/LF353.pdf>>

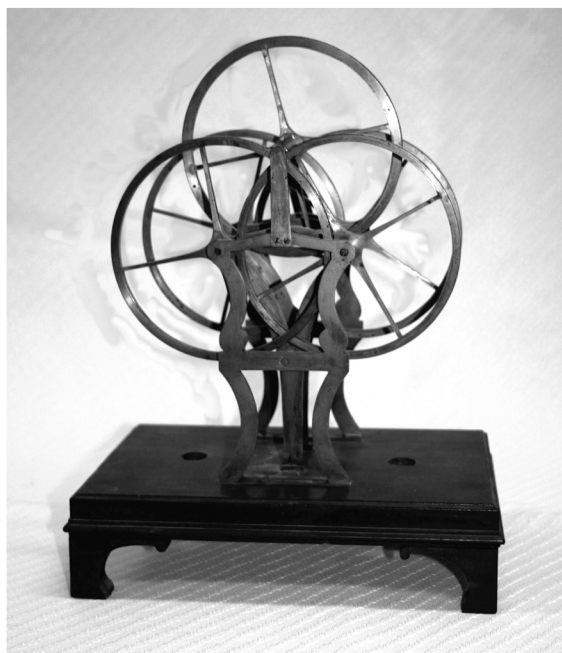
⁴RS Components web site, parts listed in Table 2 are available for example at the web site, <<http://www.rs-components.com/index.html>>

⁵OpenAL web site, libraries which we used in the data recording program and manual can be obtained from here, <<http://connect.creativelabs.com/openal/default.aspx>>

⁶ROOT web site, the analysis tool which we used in the analysis program can be downloaded from here and Minuit class is included in the ROOT package, <<http://root.cern.ch/>>

⁷Web site of Hoshin electronics co., ltd. where spec sheet of the reference ADC can be downloaded, <<http://www.kagaku.com/hoshin/index.html>>.

⁸R. B. Firestone *et al.*, *Table of Isotope*, CD-ROM Ed. (Wiley-Interscience 1996), p. 456 and p.1423.



Atwood's Machine

This device first appears in a chapter in The Rev. George Atwood's book, *A Treatise on the Rectilinear Motion and Rotation of Bodies, with a Description of Original Experiments Relative to the Subject*, published in 1784. At the heart of the device is a low-friction and small moment of inertia wheel, over which a light string passes with two almost equal masses attached to its ends. Originally it was used to study the properties of uniformly accelerated bodies; today it has become a staple problem to illustrate the use of Newton's second law. This example is at Hamilton College in Clinton, New York. (Notes and photograph by Thomas B. Greenslade, Jr., Kenyon College)