Identification of Charged Particles by Multiplying Circuit

By

Masakatsu SAKISAKA*, Kazuo KOBAYASHI* and Koji YOSHIDA*

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A pulse multiplying circuit for charged particle identification according to

$$(E+E_0+k\cdot dE/dx)\times dE/dx \qquad E_0,\, k:\ \text{const}$$

was made, in which a squaring circuit using eighteen diodes was devised. The E and dE/dx pulses, due to the incidence of charged particles, were given by a semiconductor detector and a proportional counter of gas flow type, respectively.

The charged particles of low energies from D+d, T+d, Li+d and Be+d nuclear reactions were sorted by this circuit. A test for carbon ions was also done. The apparent separation ratios were as follows:

$$p:t:\alpha:\mathrm{C}\approx 1:2:9:60$$

1. Introduction

It has been essential to sort charged particles emitted by nuclear reactions. The various methods of particle identification have been reported. Among them, the electronic $E\times dE/dx$ method has been widely developed[1)–7)], which is based on the following principle.

When a particle of mass M, charge z and energy E passes through a thin medium of thickness dx, its energy is lost in the medium by a small amount of dE. Then non-relativistically

$$E\times dE/dx \propto Mz^2\, ln\,(4mE/MI) \qquad (1)$$

is satisfied, where m and I are electron mass and mean ionization energy of medium atom, respectively.

Since the change of the log term in (1) is small for large E range, the product $E\times dE/dx$ is nearly proportional to Mz^2, a constant characteristic for particle, and so the particle selection becomes easy. However, at low energies, the product varies seriously with E and this makes it difficult to identify low energy particles.

* Department of Nuclear Engineering.

Stokes[3] has corrected this defect practically by introducing the product

$$(E+E_0+k\cdot dE/dx)\times dE/dx \tag{2}$$

where E_0 and k are constants. Though the use of this product has extended the selectable energy range, the applicability to the particles of a few to several MeV in energy has not been reported. So we examined it experimentally for protons, tritons and alpha particles induced by low energy nuclear reactions, using a new multiplying circuit. An experiment for the identification of Po$-\alpha$ particles and carbon ions was also done.

2. Electronic Circuits

In radiation measurements, we usually treat voltage pulses which are amplified proportionally to energies given to a radiation detector. Therefore the product (2) is converted to an expression of voltage signals

$$(V+V_0+K\cdot \Delta V)\times \Delta V = V_{\rm out}, \tag{3}$$

where V and ΔV are proportional to E and dE/dx respectively. V_0 and K are constants which correspond to E_0 and k. The block diagram to obtain $V_{\rm out}$ is shown in Fig. 1, which is an analog computer of the equation

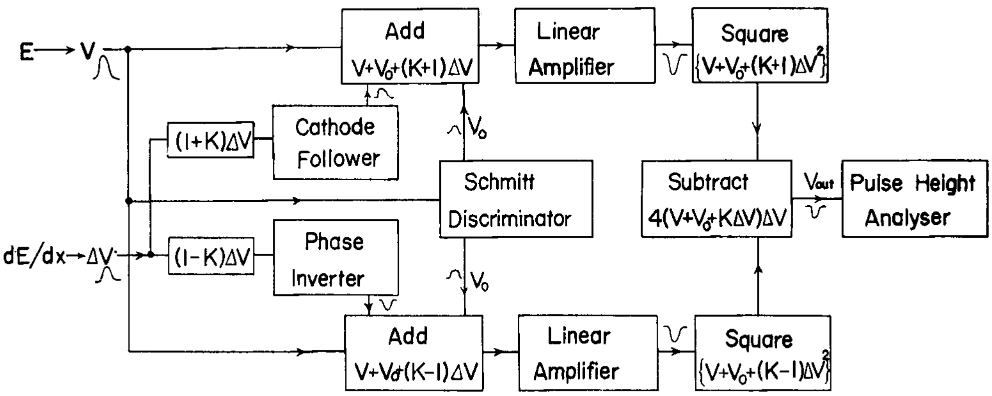

Fig. 1. Block diagram of pulse multiplying circuit for charged particle identification.

$$\{V+V_0+(K+1)\Delta V\}^2-\{V+V_0+(K-1)\Delta V\}^2 = 4(V+V_0+K\cdot \Delta V)\times \Delta V. \tag{4}$$

The electronic components will be described below.

2.1. Circuits of $(1+K)\Delta A$, $(1-K)\Delta V$ and V_0

The ΔV pulse is fed to two voltage dividers as show in Fig. 2. The five terminals of each divider are so connected by a rotary gang-switch that $(1+K)\Delta V$ and $(1-K)\Delta V$ signals are simultaneously obtained from the left and

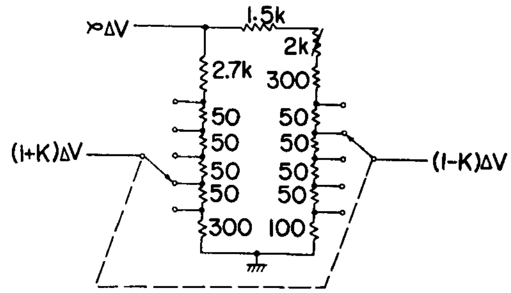

Fig. 2. Circuits of $(1+K)\Delta V$ and $(1-K)\Delta V$.

right output terminals. Here, the K values are chosen as 0, 1/6, 1/3, 1/2 and 2/3.

The V_0 circuit is a Schmitt discriminator which is triggered by an input pulse V of larger than 4.5 V. Thus a signal of constant amplitude V_0 is given.

2.2. Adding and subtractiug circuits and amplifier

The adding circuit of $V+V_0+(K-1)\Delta V$ or $V+V_0+(K-1)\Delta V$ is a network composed of three equal resistances 15 kΩ and capacitances 0.01 μF, which is based on the Millman's theorem just as shown in Fig. 3. On the other hand,

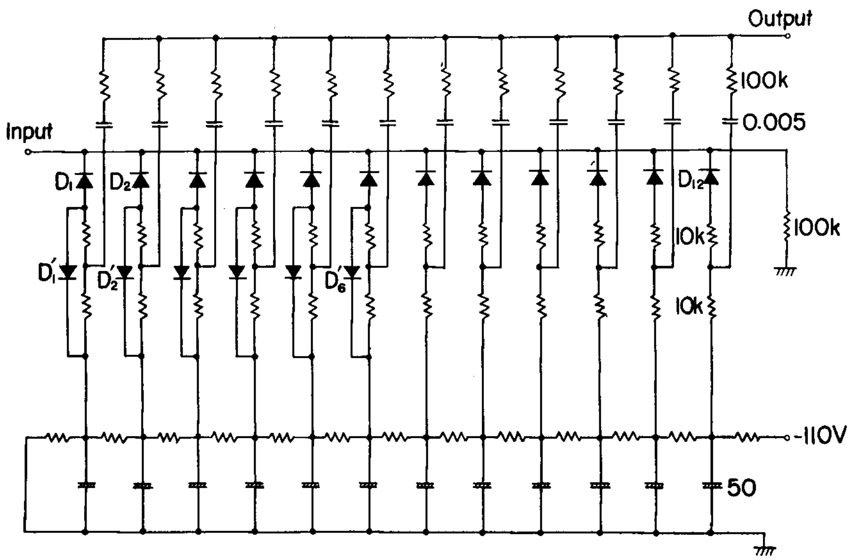

Fig. 3. Squaring Circuit.

the subtracting circuit is a differential amplifier using a 12AU7 tube.

Since the amplitude of the sum pulse from the adding circuit becomes smaller than 5 V, a linear amplifier of gain 20 is necessary, which is a negative feed-back amplifier using a 12AU7 and a 6CL6. The output signal is sent to the next squaring circuit through a 6CL6–cascade White cathode follower of output impedance ~9 Ω, because the input impedance of the squaring circuit is as low as 1~2 kΩ.

2. 3. Squaring circuit

Giannelli and Stanchi[6] have reported a new multiplying circuit by combining a logarithmic network with an anti-logarithmic network. Wahlin[7] has devised a similar circuit by two logarithmic networks. The nonlinear properties of these networks have been achieved by adding pulses from many diodes which are biased by different voltages. Referring to their results, we have made a squaring circuit by twelve diodes and supplementary six diodes as shown in Fig. 3.

When a negative signal (−5~−100 V) from the preceding amplifier is supplied to twelve diodes of $D_1, D_2, \cdots$ and D_{12}, some of them flow currents since the signal amplitude exceeds the bias voltages. This causes pulses at the 10 kΩ resistances connected in series with the diodes and these pulses are added at the output terminal. If the bias voltages are adequately given, an approximately square relation between the input and output is obtained as illustrated in Fig. 4.

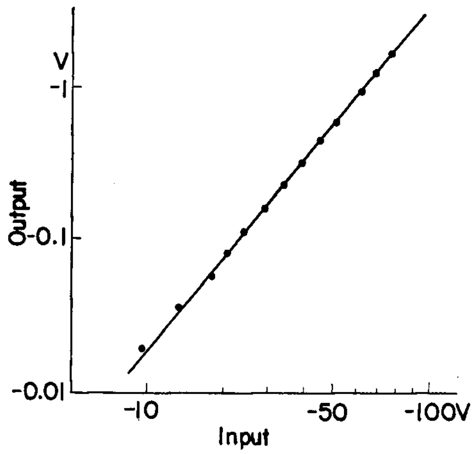

Fig. 4. Property of the squaring circuit.

The six diodes of D_1', D_2', $\cdots$ and D_6' are used to eliminate small backward pulses induced by the signal input.

2. 4. Properties of Multiplying Circuit

The multiplying circuit should have the property represented by the relation (3). This was examined by supplying various test pulses from a conventional pulse generator. Fig. 5 (a) is an illustrative result of ΔV *vs* V_{out} where V and V_0 are chosen as parameters, while (b) in the same figure is the relation between V and V_{out} for various K's. Since each curve is linear enough within the deviation of 2%, the present computer seems satisfactory for our experimental purpose of particle selection.

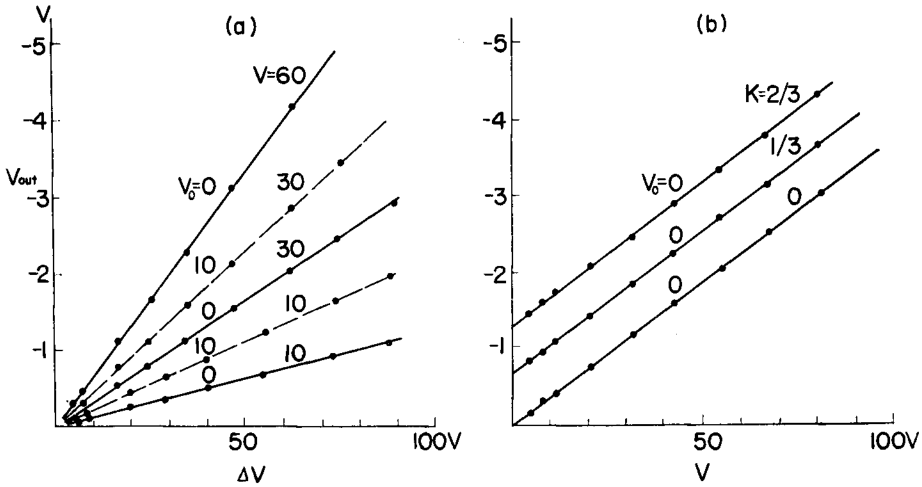

Fig. 5. Illustrative properties of the pulse multiplying circuit.

3. Identifications of Charged Particles

3.1. *dE/dx* and *E* counters

To select charged particles from nuclear reactions, it is necessary to obtain both *dE/dx* and *E* signals simultaneously for a given particle. Therefore we used a counter system of a proportional counter (*dE/dx*) and a semiconductor detector (*E*) which were arranged close to each oter.

The proportional counter is a cylindrical type of effective length 50 mm and the central wire is 0.05 mm in diameter. The charged particles are injected coaxially to the counter and the window for particle entrance is 4 mm in diameter which is covered by a mylar foil of 0.45 mg/cm^2 in thickness. A mixture of argon (90%) and methane (10%) is supplied continuously at the pressure of 49 mmHg. The resolution for Po$-\alpha$ particles was about 6%.

The *E* counter is a semiconductor of Au surface barrier type, whose depletion layer is about 200 μ in thickness and the surface diameter is 5 mm. The resolution for Po$-\alpha$ particles was measured as 1.5%.

The counter assembly was arranged in a vacum scattering chamber for nuclear reaction measurements.

3.2. Light particle identification

Light particles of low energies were produced by nuclear reactions. A magnetically analysed beam of deuterons, which were accelerated up to 0.2 or 0.3 MeV in energy by a Cockcroft-Walton type accelerator, bombarded a deuterium, tritium, lithium or beryllium target at the center of the scattering chamber. The counter system was placed at 90° or 135° with respect

Table 1. Nuclear reactions and emitted particles

Reaction	Deuteron energy (MeV)	Angle (°)	Particle and energy (MeV)
D(d, p)t	0.2	90	p: 3.07 t: 1.06
T(d, n)α	0.2	90	α : 3.48
^{6}Li(d, α)α ^{6}Li(d, p)^{7}Li ^{7}Li(d, α_1)^{5}He(α_2, n)	0.2	135	α : 10.5 p: 4.39 {α_1 : 7.39, ~5 {α_2 : continuous up to ~7
^{9}Be(d, p)^{10}Be ^{9}Be(d, t)2α ^{9}Be(d, α)^{7}Li	0.3	90	p: 1.33, 4.39 {t: 1.39, 3.50 {α : continuous α : 1.52, 4.38, 4.69

to the beam and detected the charged particles. The nuclear reactions used and the emitted particles are tabulated in Table 1.

Fig. 6 (a) and (b) are the V_{out} spectra of the multiplying circuit applied to protons, tritons and alpha particles from D+d and T+d reactions. It is seen that the separation can be improved by adjusting k and E_0. The V_{out} for Li+d reaction is shown in (d) of the figure. Considering the spectrum of (b), it is clear that protons and alpha particles are emitted from this reaction. The proton- and alpha-gated $E(V)$ spectra are shown by the broken and thin solid lines respectively in (c) of Fig. 6, and their sum agrees well with the ungated spectrum expressed by

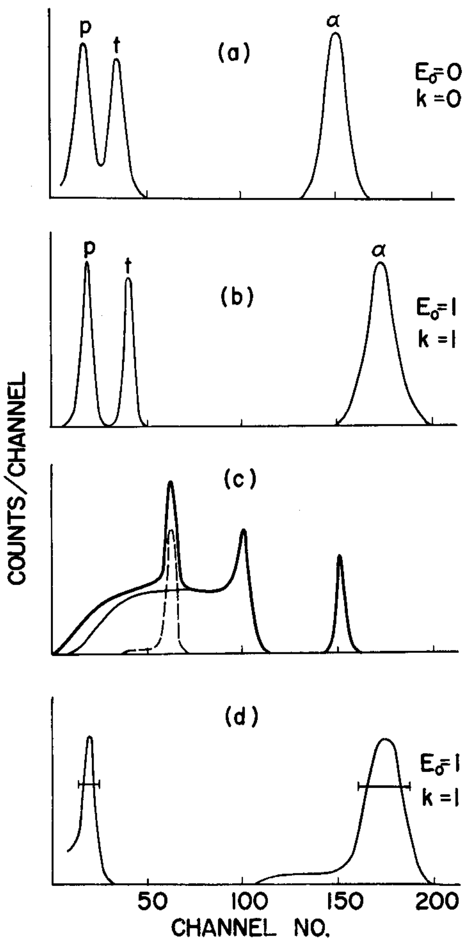

Fig. 6. Pulse height distributions of V_{out} and V.
(a), (b) and (d) are the V_{out} spectra, but (c) shows the distribution of the V pulses. Horizontal bars are the widths of the gate windows.

the heavy solid line, except a part of low energy.

Similar experiments were done for the particles from Be + d reaction and the V_{out} spectrum showed three peaks which were attributable to protons, tritons and alpha particles. The proton-, triton- and alpha-gated $E(V)$ spectra were in good coincidence with the particles and their energies shown in Table 1. Thus the present multiplying circuit is applicable to the identification of charged particles of a few to several MeV energy range.

3. 3. Heavy particle identification

Heavy particles are different from light particles because heavy ions of MeV range decrease their mean charges as well as energies when passing through medium material. Therefore the present network seems inadequate for heavy particle identification. However, since a coarse compensation of the charge change would be done practically by adjusting k and E_0, we have applied the circuit to the separation of alpha particles and carbon ions.

Carbon ions of 9.7 MeV energy were obtained by the third sub-harmonic acceleration of $^{12}C^{2+}$ ions with the 106 cm cyclotron in Kyoto University. The extracted ions were introduced directly to the dE/dx and E counter system described above. But the entrance window was covered by two semicircular mylar foils of about 0.2 and 0.5 mg/cm^2 in thickness. Thus the carbon ions of ~9 and ~7 MeV in energy could be injected in the system simultaneously. The gas pressure of the dE/dx proportional counter was also reduced to 16 mmHg.

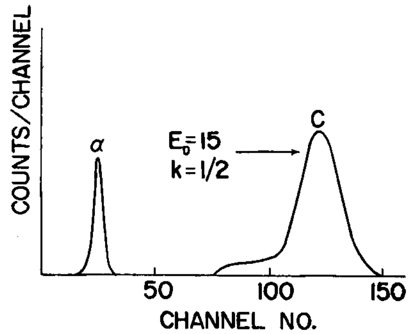

Fig. 7. V_{out} spectra for alpha particles and carbon ions. The spectrum for alpha particles is obtained for E_0 = 4 MeV and K=1.

Fig. 7 shows the V_{out} spectra for Po$-\alpha$ and carbon ions, the apparent separation ratio being about 1 : 7.

4. Discussions

The product (2) is a practical expression that corrects a large variation of the log term in (1). Since k is a constant that compensates the energy loss in the dE/dx counter, k~1 would be reasonable for any particle if dE is not so large. This was confirmed experimentally because the well resolved V_{out} spectra could be obtained when k~1.

On the other hand, E_0 affects seriously the convergence of the product outputs. From the numerical calculations of $(E+E_0+\frac{1}{2}dE/dx)\times dE/dx$ for our

Table 2. Optimum E_0

Charged particle	Proton	Triton	Alpha particle	Carbon ion
E_0 (MeV)	1	1.5	3.5	~15

counter system, the optimum E_0 values were derived as shown in Table 2, which also agreed well with the experimental observations. This means that the best separation for different particles can not be given by an uniquely defined E_0. Therefore the separation ratios seen in Figs. 6 and 7 are not obtained under the ideal condition for each particle--they are apparent.

Table 2 indicates that larger E_0 is necessary as ion mass increases, but the V_{out} spectrum for heavy ions has a poor resolution as seen in Fig. 7. This is because the product (2) does not contain the essential correction for the change of ion charge.

The present multiplying circuit and counter assembly have proved to be an excellent property of particle identification for light particles. The separation for heavy ions would be promisingly improved if an electronic device for the compensation of charge change is added to the circut. The apparent separation ratios for protons, tritons, alpha particles and carbon ions were approximately 1:2:9:60.

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