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COINCIDENCE METHOD APPLIED TO ION BEAM MEASUREMENT

By Stanley Fultz and M. L. Pool

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SUMMARY

A coincidence Geiger counter system was constructed for the absolute measurement of the activity of radioactive substances made in a cyclotron. The average beam current in the cyclotron can be calculated from the number of disintegrations per second observed, the half-life of the radioactive substance, and the reaction cross section.

INTRODUCTION

A possible method for measuring the current of an ion beam in an accelerator would be to measure the absolute thick target yield for a known reaction caused by the ions, and from this to calculate the average current. Such a method has been applied to measurements of the ion current in The Ohio State University cyclotron, and details of it are contained in the following report.

The absolute measurement of the activity induced in the target material cannot be made without complete quantitative information on the manner by which the nucleus disintegrates; that is, full knowledge of the quantum energies and intensities of the gamma rays emitted and of those processes occurring in cascade is required. With this, the coincidence method can be intelligently applied. The basis for computing the source strength from measurements of coincidence rate and individual counting rates is given below.

This investigation was conducted at The Ohio State University Research Foundation under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics.

ANALYSIS

Calculation of Absolute Source Strength

As an example of the calculation of absolute source strength (reference 1) a case is considered where the nucleus disintegrates by emission

of a beta particle and the new nucleus has an excited state which gives rise to a gamma ray immediately afterwards. (The disintegration of Au^{198} is such a case.)

The activated target foil is placed between two end-window Geiger counters, which are connected to scaling circuits for measuring the individual counting rates and to a coincidence mixer which is used to measure the rates at which pulses occur simultaneously. A piece of light plastic material may be placed in front of the window of one of the counters in order to keep out all the beta rays. This counter acts as the gamma counter, while the other is the beta counter.

The count rate in the gamma counter q_γ will depend on the efficiency of the counter e_γ and on the strength of the source Q.

$$q_\gamma = Qe_\gamma \tag{1a}$$

$$q_\beta = Qe_\beta \tag{1b}$$

Similarly the true coincidence rate q_c is given by:

$$q_c = Qe_\beta e_\gamma \tag{2}$$

However, the electronic coincidence mixer has a finite resolving time. (The resolving time is the maximum time within which two individual randomly related pulses will be registered as a single pulse.) It is therefore necessary to correct for the coincidences originating from randomly related pulses:

$$q_r = 2\tau q_\beta q_\gamma \tag{3}$$

Here q_r is the random coincidence rate, and 2τ is the resolving time of the mixer where τ is the average pulse width of the pulses passing from the pulse-shaping circuits to the mixing tube.

Letting q_m be the measured coincidence rate, then q_c is:

$$q_c = q_m - 2\tau q_\beta q_\gamma - q_k \tag{4}$$

where q_k is the cosmic-ray coincidence rate.

The efficiency of the counter for detecting gamma rays can now be found by taking the ratio of true coincidence rate to the beta-ray count rate, thus:

$$e_\gamma = \frac{Qe_\gamma e_\beta}{Qe_\beta} = q_c \Big/ q_\beta \tag{5}$$

Having e_γ, Q, the absolute disintegration rate of the source, can easily be found:

$$Q = \frac{Qe_\gamma}{e_\gamma} = q_\gamma \Big/ e_\gamma \tag{6}$$

Thick sources can be used for these measurements, provided that no appreciable attenuation of the gamma rays occurs for those gamma rays being measured. The position of the beta counter and the self-absorption of the beta rays in the source do not affect the calculations of source strength, since the count rates for beta rays cancel out.

It is also possible to measure the absolute disintegration rate by comparing the source with a known standard. Only the gamma rays are used in such a case, and again the quantum energies and intensities of these radiations must be known, both for the standard and the unknown. Of equal importance is a knowledge of the manner in which the efficiency of the counter changes with quantum energy. If the gamma counter be constructed by placing a Lucite plate in front of the window counter, this efficiency will vary linearly with quantum energy over a considerable range. The ratio of the absolute source strength of the unknown Q_x to the source strength of the standard Q_s is given by:

$$Q_x \Big/ Q_s = (e_\gamma)_s q_x \Big/ (e_\gamma)_x q_s \tag{7}$$

where q_x and q_s are individual count rates of the unknown and the standard obtained for identical geometrical conditions, that is, for the same shape and area of the sources and the same distance from the counter.

Calculation of "The Yield Curve"

The intensity of the ion-beam current can be found by establishing the relation between the nuclear cross section for producing the

observed activity in the target material, and the absolute amount of activity produced. This relation involves the excitation function for the reaction, and the range-energy relation for the ions (incident particles) in the target material.

Using the following notation

$\sigma(\bar{E})$ average cross section for reaction when energy of incident particles is between E and $E + dE$; values of $\sigma(\bar{E})$ are obtained from excitation function for reaction (reference 2)

$\bar{E}$ average energy of bombarding particles in traversing thickness dx of target during bombardment

n total number of particles incident on target during bombardment

N number of atoms per square centimeter of target foil

dN^* number of atoms activated in a thickness dx of target material

$$dN^* = Nn\sigma(\bar{E})\ dx \tag{8}$$

This is frequently written as

$$dN^* = \frac{Nn\sigma(\bar{E})\ dE}{dE/dx} \tag{9}$$

Then the total number of activated atoms produced is:

$$N^* = \sum Nn\sigma(\bar{E})\delta x(\bar{E}) \tag{10}$$

where $\delta x(\bar{E})$ denotes the finite interval of range which corresponds to a fixed loss of energy (say 0.5 Mev) of the bombarding particles of average energy $\bar{E}$ in that finite interval. The total activity is thus obtained by numerically integrating over the products of $\sigma(\bar{E})$ and $\delta x(\bar{E})$ at equal successive increments of energy, up to the (maximum) energy of the ion beam. From N^* the thick target yield can now be calculated:

$$dN^*/dt = \lambda N^* \tag{11}$$

where λ is the decay constant. Then to express the source strength in millicuries (for zero time):

$$Q_o = (dN^*/dt)\Big/\left(3.7 \times 10^7\right)$$

The number of particles corresponding to 1 microampere-hour is 2.26×10^{16}. Putting $n = 2.26 \times 10^{16}$,

$$Q_o(\bar{E}) = \frac{2.26 \times 10^{16}}{3.7 \times 10^7} \lambda N \sum \sigma(\bar{E})\delta x(\bar{E}) \tag{12}$$

millicuries per microampere-hour. The thick target yield is $Q_o(\bar{E})$ when the bombarding ions are monoergic, of energy E. Plots of $Q_o(\bar{E})$ for Au^{198}, Co^{60}, and Na^{24} are given in figure 1. In these calculations the energy interval used was 0.5 million electron volts; see figure 2.

To obtain a measurement of ion beam the activity of the target foil is first measured. Let this be Q_o' millicuries at zero time, as calculated from coincidence measurements (equations (4), (5), and (6)), and let the time of bombardment be T hours. The average current in the ion beam during the bombardment will be:

$$i = Q_o'/Q_oT$$

microamperes where Q_o is obtained as in equation (12).

TEST PROCEDURE

Measurement of Beam Energy

A measurement of the beam energy can be obtained by observing ratios of the activities induced in several different target materials, when these are bombarded by ion beams of identical energy, intensity, and type. Such control on the ion beam is best effected by use of a rotating target by which targets can be moved into the beam as often as desired and accurately timed.

Let $Q_o'(a)$ and $Q_o'(b)$ be the activities measured in foils of materials "a" and "b," corrected to zero time. Seek the energy for which

the ratio $Q_o'(a)/Q_o'(b)$ is in best agreement with $\lambda_a N^*(a)/\lambda_b N^*(b)$. The latter ratio can be found from yield curves as in figure 1. As an example, the following activity ratios were observed for the materials cobalt, sodium, and gold bombarded with deuterons in The Ohio State University cyclotron: Co/Au = 1.96 (±0.16) × 10^{-1}; Na/Au = 2.08 (±0.11) × 10^3. From figure 1 the following ratios are obtained:

Ratio	Energy (Mev)				
	8.00	8.25	8.50	8.60	8.75
Co/Au	0.293	0.238	0.192	0.181	0.160
Na/Au	3930	3100	2400	2240	1940

The best agreement between experimental and calculated ratios appears to occur at about 8.60 million electron volts. This energy is therefore attributed to the ion beam.

Calculation of Beam Current

Having ascertained the energy of the beam from ratios of the activities produced in thick targets of different materials, its current can now be found. To do this merely note the bombardment time and calculate the millicuries produced per hour of bombardment. Then compare this with the millicuries which would have been produced for 1-hour bombardment in a beam of 1-microampere current, at the energy calculated. The latter activity is obtained from figure 1.

As an example, results are presented for a set of bombardments (using deuterons as the bombarding particles) which were carried out in The Ohio State University cyclotron. In two of these cases a rotating target was used in order to obtain ratios of the activities produced in different materials by the same beam.

Date	Target	Yield		Beam current (μamp)
		Measured (millicurie/hr)	Calculated (millicurie/μamp-hr)	
Dec. 7	Co	1.10 (±0.04) × 10^{-3}	0.49 × 10^{-3}	2.35 (±0.09)
Dec. 22	Au	8.5 (±0.4)	2.7	3.15 (±0.15)
Jan. 5	Au	7.37 (±0.35)	2.7	3.00 (±0.16)
Jan. 5	Co	.134 (±0.05)	.49	2.74 (±0.10)
Jan. 18	Au	4.07 (±0.10)	2.7	1.51 (±0.07)
Jan. 18	Na	8500 (±0.22)	6000	1.42 (±0.04)

A minimum of five coincidence measurements were made on each activated foil. Where possible, gamma-gamma coincidences were measured since fewer errors can arise from scattering effects than in the case of beta-gamma coincidences. The isotopes Na^{24} and Co^{60} are suitable for gamma-gamma coincidence measurements. The Au^{198} foils were measured by beta-gamma coincidences and also by comparing the gamma rays with those of a calibrated Co^{60} source. Good agreement between the two methods was obtained in all cases. In the bombardments of January 5 and January 18, the currents obtained from two materials for the same cyclotron run can be compared. It can be seen from the above table that the values obtained for the current in the deuteron beam are in agreement within their probable errors. A cover plate with a narrow slot was used for the January 18 bombardments, so the activated area of target was reduced. This accounts for lower beam current in comparison with previous bombardments. In general the current of a deuteron beam of moderate energy (up to 16 Mev, say) can be measured to about ±5 percent if the excitation functions used in computing them are those given in reference 2. This has been confirmed verbally by Dr. D. C. Peaslee. (The curve for gold in reference 1 must be reduced by the factor 10 on the ordinate scale.)

Calculation of $\delta x(\overline{E})$

To calculate the range increment which corresponds to a fixed loss of energy (0.5 Mev, say, as in fig. 2) at various energies, it is first necessary to obtain the range-energy relation for the bombarding ions in the target material. For deuterons this can be readily found by converting the curves given by Bethe and Livingston (reference 3) for protons in air over to those for deuterons in air, then to deuterons in the target material. Thus, having the range-energy relation for the deuterons in the target material, the range increment which corresponds to a fixed loss of energy, at any (average) energy can easily be found. A simpler way, however, is merely to plot this increment as a function of energy, for the case of deuterons in air, then convert the range-increment values over to the target material using the expression:

$$\delta x(\overline{E})_{targ} = \frac{B_{air}}{B_{targ}} \times \frac{\text{Number air atoms/cc}}{\text{Number target atoms/cc}} \times \delta x(\overline{E})_{air} \tag{13}$$

where B is the stopping number for the materials.

$$B = Z \log_e \frac{(2mv^2)}{I} \tag{14}$$

and I is the average ionization potential of the material.

The calculation of B can become both difficult and tedious. However, only a ratio of these quantities is of interest, and so only the relative stopping power S is of concern:

$$S = \frac{B_{targ}}{B_{air}} \tag{15}$$

Measurements of S have been made for many materials by several investigators. However, there does not seem to be much recent information available, based on measurements made using higher energy incident particles. Those of Mano were obtained by use of alpha particles of the natural radioactive elements and are therefore averages over energies of all these particles emitted by the particular substance used and are therefore also confined to low energies. Bethe has shown that S is energy dependent, and in order to use it correctly it must be considered as a function of energy $S(\bar{E})$. However, this dependence becomes less significant for elements of low atomic number and consequently in these cases the data of Mano are probably all right. In the case of gold, however, it is necessary to observe the energy dependence. For the above calculations, the $S(\bar{E})$ values for gold were obtained from Bethe and Livingston (reference 3) while the S values for cobalt and sodium are 2.45 and 1.35, respectively. In order to calculate $S(\bar{E})$ from equations (14) and (15), a value for the average ionization potential I must be obtained. This offers some difficulty. It is discussed by Clarke and Irvine (reference 4).

Confirmation of Method

As a means of confirming the above method for calculation of ion-beam currents, a comparison was made between calculated thick target yields (fig. 1) and figures published recently for other cyclotrons of widely different energies. In the table below are listed experimental results from a report privately circulated by Dr. Joseph G. Hamilton of the University of California at Berkeley.

Isotope obtained	Cyclotron energy (Mev)	Yield (millicuries/μamp-hr)	
		Published	Calculated
Na^{24}	6.0	6.1 (±?)	2.8
Co^{60}	6.0	.00007 (±?)	.00013
Au^{198}	6.0	.000086 (±?)	.00011
Na^{24}	16	10 (±?)	12

Although the methods by which the source strengths were measured at these places are not known, fair agreement is obtained between the published and the calculated values. The discrepancies which occur are probably mostly due to errors in measurement.

APPARATUS

The coincidence circuit used for the above experiments was of simple design and is shown schematically in figure 3. In essence, it consists of two multivibrator-type pulse-shaping circuits feeding a Rossi pair of triodes. The resolving time of the circuit will depend on the widths of the pulses from these circuits as well as on the bias on the output tube for the mixing circuit. Changing this also changes the amount of overlap of the pulses, which is required for triggering the output tube.

The resolving time of the circuit can therefore be varied in two ways, namely, by changing the pulse width or by changing the amount of overlap. For most reproducible results it is desirable to have the overlap small, so that resolving time should be varied by varying the widths of the pulses in each of the channels. This can be done by changing resistances and capacitances in the "one-kick multivibrator" circuits.

CONCLUDING REMARKS

The coincidence method outlined above seems to be a very satisfactory one. The method is applicable to all substances for which a decay scheme has been worked out. For deuteron bombardments above 10 million electron volts, gold would be a more suitable target than elements of lower atomic number.

The Ohio State University Research Foundation
Columbus, Ohio, January 20, 1951

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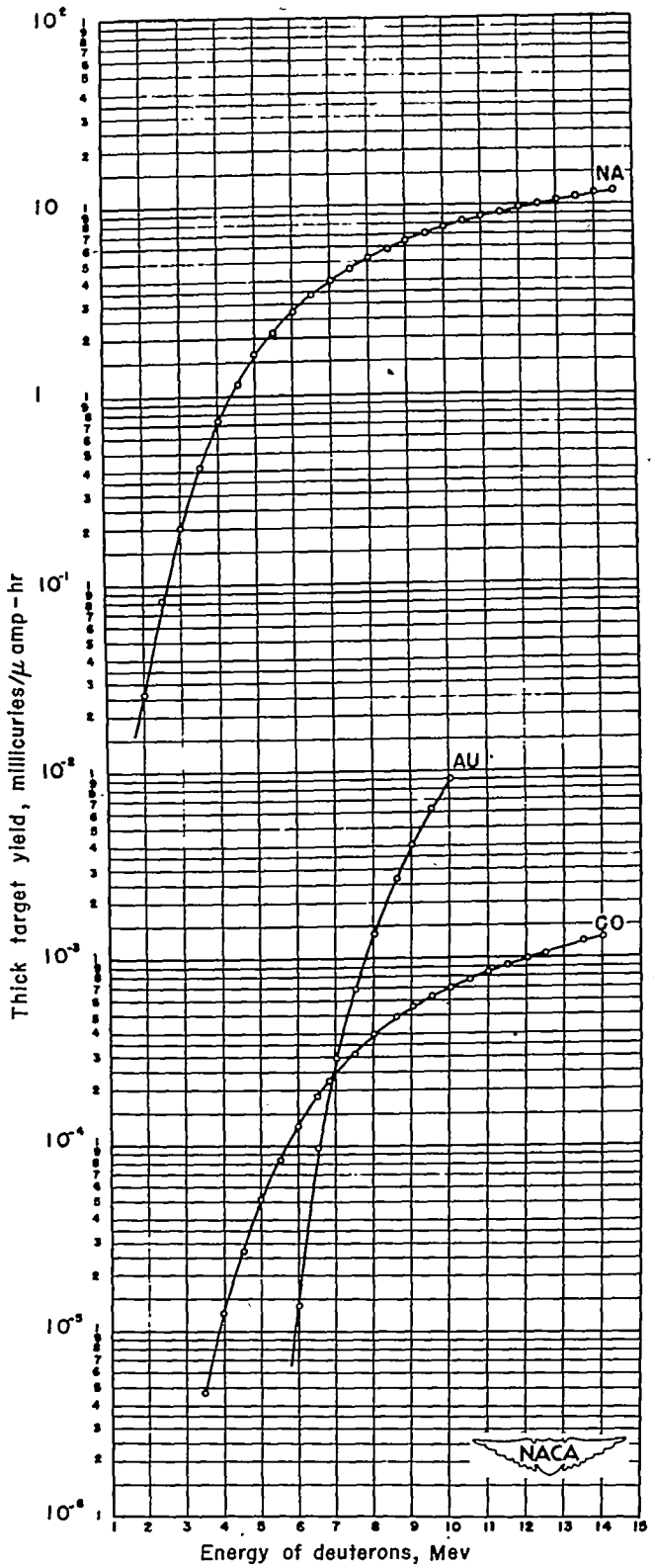

Figure 1.- Yield curves for isotopes of sodium, gold, and cobalt.

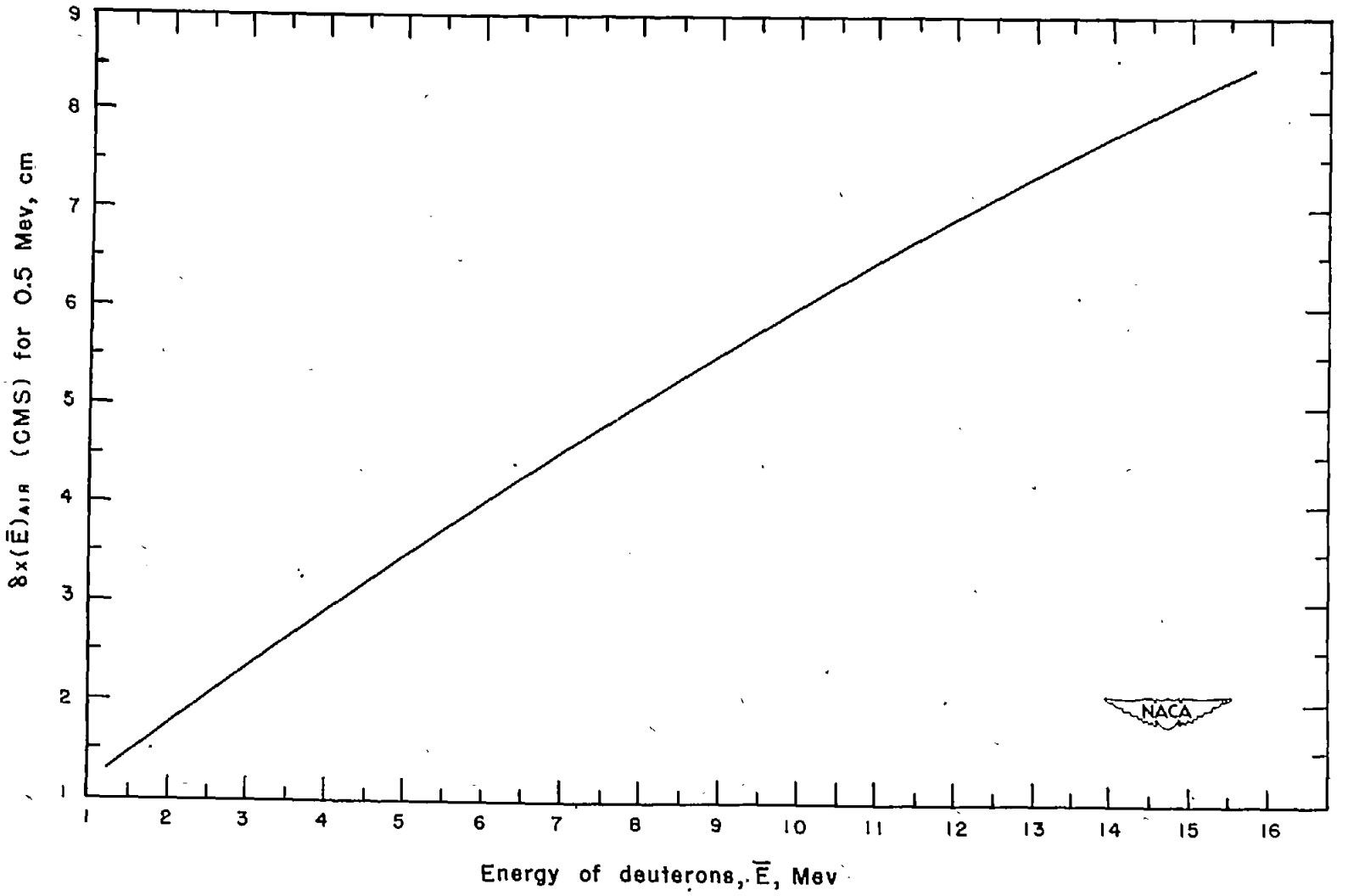

Figure 2.- Energy of deuterons for an energy loss of 0.5 million electron volts.

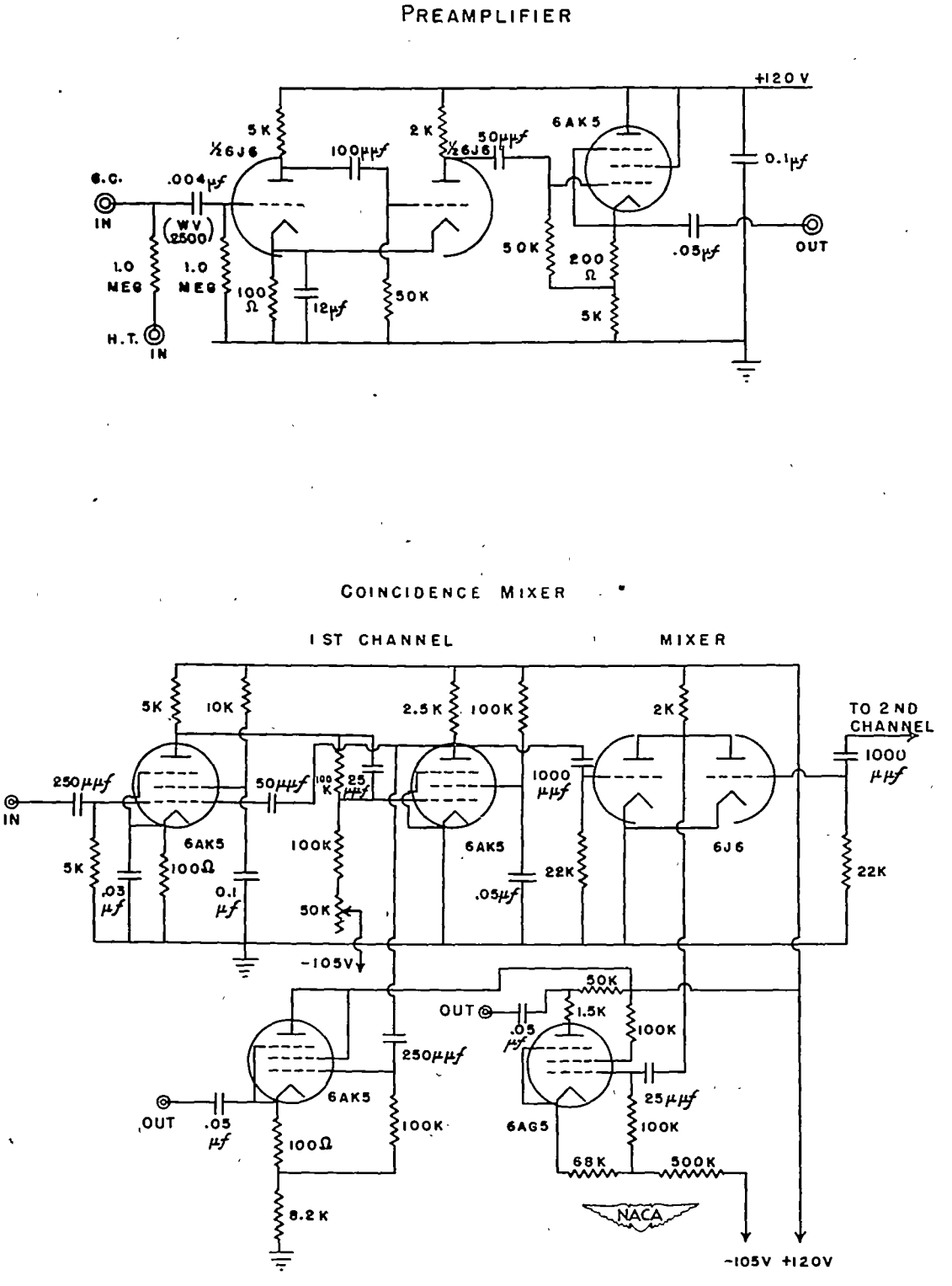

Figure 3.- Schematic diagram of coincidence and preamplifier circuits used in the experiments.

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