Measurement of the $C^{12}(p, \gamma)$ and $C^{12}(d, n)$ Effective Cross Sections for Low Energy Bombarding Particles

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In this experiment a tube electrometer capable of measuring effective cross sections down to $\sim 10^{-31}$ cm^2 was used. This instrument is only slightly sensitive to the shape of the energy spectrum of the emitted particles. It yields absolute values directly and permits one to determine the sign of the radioactive emission. It can moreover be used to measure small as well as large radiation intensities without alteration of the geometry or the recording apparatus.

The values of the yields for the reactions $C^{12}(p, \gamma)$ and $C^{12}(d, n)$ in thick targets in the energy range 300-400 kev agree satisfactorily with the shape of the analogous curves at energies above 400 kev as presented in Refs. 7 and 8. The measured cross section for the $C^{12}(p, \gamma)$ reaction in the 300 kev range is in good agreement with the value computed for this energy from the extrapolation formula.

WHEN carbon is bombarded with protons and deuterons, radioactive nitrogen is formed as a result of the following reactions:

$$C^{12} + H^1 \rightarrow N^{13} + Q\,(\gamma); \tag{1}$$

$$N^{13} \rightarrow C^{13} + \beta^+ + \nu; \tag{1a}$$

$$C^{12} + H^2 \rightarrow N^{13} + n + Q; \tag{2}$$

$$N^{13} \rightarrow C^{13} + \beta^+ + \nu. \tag{2a}$$

Many experimenters have studied reaction (1) as to the yield of N^{13} and γ-rays. It has been established that two resonance peaks exist in the energy range 0.380 to 1.700 mev. The first resonance occurs at $E_p = 456 \pm 2$ kev[1]. The width of the resonance is $\Delta E_p = 35$ kev. For the second peak, E_p 1.697 ± 0.012 mev[2] and $\Delta E_p = 74 \pm 94$ kev. In Ref. 2, furthermore, two excitation levels for N^{13} were determined from the resonances in the proton energies, these being at 2.83 ± 0.018 and 3.53 ± 0.027 mev.

Measurements of the upper limit of the β^+-spectrum[3] indicated that $E_\beta = 1.202 \pm 0.005$ mev. The positron spectrum has a simple Fermi distribution[4]. According to many sources, the half-life period of N^{13} (reaction 1a) is about 10 minutes.

As Bethe has shown[5], reaction (1) is the first stage in the carbon cycle, and the results of research on it have great importance for astrophysical applications. It is especially important to obtain experimental cross sections near $E_p \sim 30$ kev.

On the basis of the Breit-Wigner dispersion equation for a single level the resonance data given above may be used for computing cross sections at low energies. However, in this case the results may prove questionable because of the considerable extrapolation from the resonance energy, since resonances at higher energy may greatly increase the cross section, and the simple dispersion equation for one level may not hold true in regions far from resonance. On the other hand, this extrapolation will simply be ruled out if resonances exist in the energy region of 10-40 kev.

To check these possibilities, Hall and Fowler[6] have investigated reaction (1) at proton energies of the order of 100 kev. The measured cross section is about two times smaller than the calculated one. It is equal to 1.0×10^{-34} cm^2 for an energy of 96 kev, and increases to $(8.5 \pm 1) \times 10^{-34}$ cm^2 at 128 kev. The excitation curves of activity in carbon bombarded with deuterons with energies ranging from 380 to 900 kev, which are presented in Refs. 7 and 8, indicate that as the deuteron energy increases there is a steady increase in N^{13} emission. For deuterons in the energy range from 0.7 - 1.9 mev[9] measurement of the positron yield from N^{13} disintegration revealed five resonance maxima at 0.92, 1.16, 1.30, 1.74 and 1.82 mev. These resonances were also obtained in measurements of the neutron yield.

The purpose of the present investigation was to determine the effective cross sections of reactions (1) and (2) for bombarding particles in the 300-400 kev energy region by measuring the positrons emitted in the disintegration of N^{13} nuclei. The study of reaction (1) permits an interesting comparison of the effective cross sections obtained in the experiment with those computed from the extrapolation formula. One may consider the measurement of the absolute yield and cross section of reaction (2) in an energy region close to the threshold as another important result.

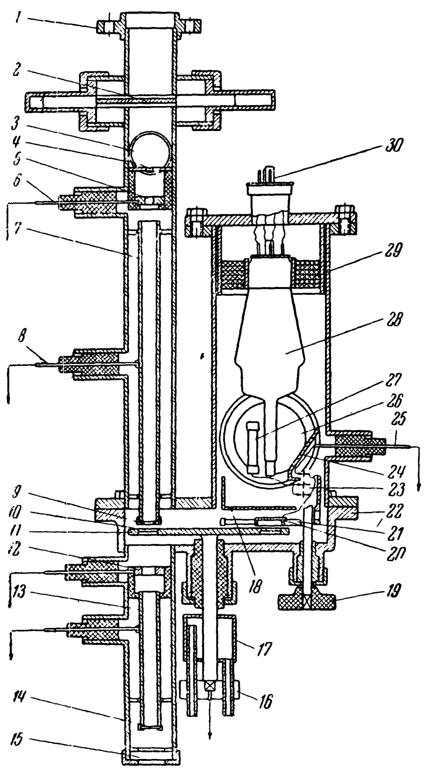

FIG. 1. Diagram of the apparatus. *1* – flange, *2* – gate diaphragm, *3* – window for observing the beam, *4,9* – diaphragms, *5, 12* – retaining diaphragms, *6* – outlet for tapping diaphragms, *7* – upper cylinder, *8* – outlet for measuring the current to the cylinder, *10* – target, *11* – disc with twelve targets, *13* – lower cylinder, *14* – screen, *15, 26* – windows, *16* – knob for turning the disc, *17* – tank for cooling the disc, *18, 24* – shields, *19* – switch knob, *20* – collecting electrode, *21* – amber insulation, *22* – apparatus housing, *23* – switch contacts, *25* – outlet for circuit calibration, *27* – (R_0) leakage resistor, *28* – EM-3 tube, *29* – rubber shock absorber, *30* – socket for cable tapping.

APPARATUS

The protons and deuterons were accelerated in the electrostatic generator of the Physico-Technical Institute, Academy of Sciences, Ukrainian SSR. A rotor voltmeter, calibrated with the resonance peaks of the $F(p, \gamma)$ reaction ,was used to measure the voltage to an accuracy of 0.5%.

The experiments were conducted with atomic and molecular beams of hydrogen and deuterium. Before the experiments were undertaken, the beams were analyzed. The current was measured with a current integrator.

The method used in the investigation was based on the quantitative determination of the β-activity of the reaction products accumulated in the target. At the present time this method is the only one that allows the measurement of very small effective reaction cross sections (in principle down to 10^{-35} cm^2). Thick targets of natural carbon were used in the experiments. The positrons were recorded with a tube electrometer, assembled with an EM-3 electronic tube, which was placed in a vacuum.

A diagram of the apparatus is shown in Fig. 1. The basic parts of the apparatus are the following: a) Faraday cylinder – *7*, which was used in a dual capacity: first, to measure the current passing through it to make sure it was not entering through the side walls of the cylinder; secondly, to permit the introduction through lead *8* of a retarding potential for stopping the electrons knocked out of the target by the beam; b) collecting electrode (collector) – *20*, which was used to collect the positrons emitted by the target; c) disc with twelve targets – *11*, which could be revolved with the aid of turning knob *16* to place the targets under the beam. The same device was used to move the targets under the collector. All of these operations were performed from outside, without disturbing the vacuum; d) electrometer switch – *23*, used for connecting the collector to the grid of the tube, for grounding the collector and grid, and also for admitting the voltage from its source to the collector during calibration of the circuit.

In this same apparatus there was an electronic tube, which was connected by a cable to a balance circuit (Fig. 2). Power for the circuit was supplied by acid batteries with a capacity of 120 amp-hr. Zero displacement in the circuit was practically non-existent. Before starting an experiment the circuit was calibrated; after the completion of the experiment this calibration was checked. The circuit sensitivity was $\sim 5 \times 10^{-5}$ V/fission. The indicator used was a mirror galvanometer of the *M*-21 type with a sensitivity of 5×10^{-10} A/mm/m. The charge sensitivity of the circuit was 7×10^{-16} coulomb/fission.

Given the capacity of the collector, the ballistic sensitivity of the circuit, and the measured galvanometer deflection, one can find the quantity of charge that was collected by the collector. From the charge determined in this manner it is possible to find the cross section of the reaction under investigation.

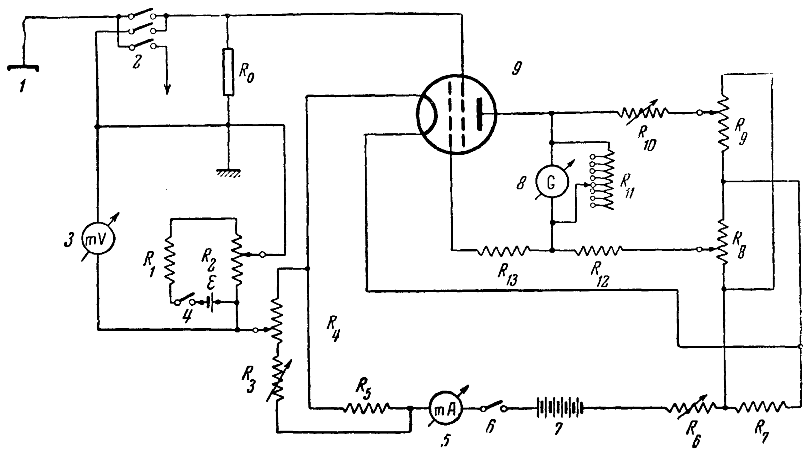

FIG. 2. The balance circuit. *1* – collecting electrode, *2* – electrometer switch, *3* – mV-meter, model 0.5, type M-15; *4* – calibration switch; *5* – mA-meter, max. 150 mA, type M-15; *6* – switch for circuit power supply; *7* – 12-volt accumulator battery; *8* – mirror galvanometer; *9* – EM-3 electronic tube; $\mathcal{E}$ – 1.5-volt dry cell; R_1 – 100 Ω; R_2, R_6 – 10 Ω; R_3 – 20 Ω; R_4, R_8, R_9 – 1000 Ω; R_5 – 30 Ω; R_7 – 45 Ω; R_{10} – resistance box to 10,000 Ω; R_{11} – galvanometer shunt (0.1; 1; 10; 100; 1000; 2500; 4000Ω); R_{12} – 2000 Ω; R_{13} – 4000 Ω; R_0 – 5×10^{10} Ω.

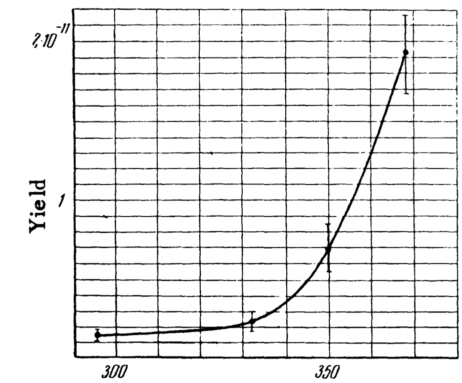

FIG. 3. N^{13} yield from the $C^{12}(p, \gamma)$ reaction.

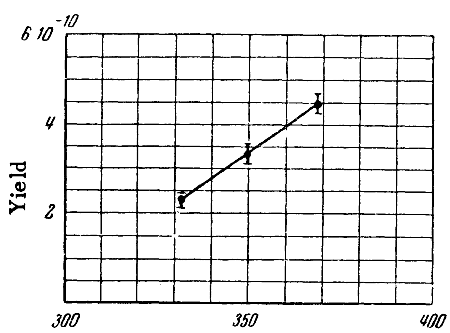

FIG. 4. N^{13} yield from the $C^{12}(d, n)$ reaction.

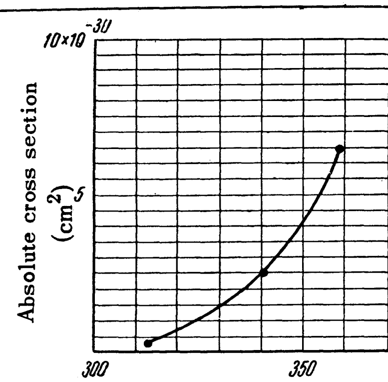

FIG. 5. $C^{12}(p, \gamma)$ cross section curve.

CROSS SECTION MEASUREMENTS

To determine the dependence of the cross sections of the $C^{12}(p, \gamma)$ and $C^{12}(d, n)$ reactions on the energy of the bombarding protons and deuterons, the β^+-activity of thick targets was measured.

The reaction yield for a given energy of the bombarding particles can be presented in the following form:

$$y = Ckn\lambda / N \cdot 1.6 \cdot 10^{-19} f\,(1 - e^{-\lambda t_1})\,(e^{-\lambda t_2} - e^{-\lambda t_3}),$$

where C is the capacity of the collector, k is the sensitivity of the circuit, n is the number of fissions from the galvanometer scale, λ is the disintegration constant, N is the number of particles bombarding the target during irradiation, f is the geometric factor, t_1 is the irradiation time of the target by the beam, t_2 is the time of onset of charge accumulation in the collecting electrode, and t_3 is the time of the cessation of accumulation. Before the yield was measured, the disintegration constant λ was determined, and the decay period of N^{13} was computed which, according to our data, proved to be 10.02 ± 0.1 min, in agreement with the findings of other authors.

Figures 3 and 4 show the yield curves for reactions (1) and (2). The ordinate indicates the yield, i.e., the number of positrons per particle bombarding the target, and the abscissa the energy of the bombarding particles in kilo-electron-volts.

From the yield curves one can determine the cross section by the familiar equation

$$\sigma = (dy/dE)(dE/dx)/n,$$

where dE/dx is the loss of energy by the bombarding particles in the target, y is the reaction yield and n is the number of nuclei per 1 cm^3. The quantities dy and dE are determined from the yield curve. Specific energy losses by the bombarding particles in the target are computed from the familiar Bethe formula.

Figure 5 shows the $C^{12}(p, \gamma)$ cross section curve. The value of the $C^{12}(p, \gamma)$ effective cross section is 0.30×10^{-30} cm^2 for an energy of 313 kev and grows to 6.4×10^{-30} cm^2 at 358 kev. The value of the $C^{12}(d, n)$ effective cross section is 0.8×10^{-28} cm^2 for an energy of 340 kev. The absolute errors in the determined cross sections do not exceed ±10%.

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Equilibrium Spectrum of Electrons and Photons with Account of Scattering

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An exact solution of the equation for the equilibrium spectrum of electrons and photons has been found with account of scattering, i.e., an expression is obtained for the angular and energetic distributions of particles at the shower maximum in heavy elements.

AN analytical expression for the "equilibrium" spectrum (integrated over the depth t *) of photons and electrons, which is valid for any dependence of the absorption coefficient of the photons $\sigma(E)$ on the energy, was first obtained in the work of Tamm and Belen'kii.[1] An analytical expression for the "equilibrium" spectrum, with account of the Rutherford scattering of the charged particles, was found by Belen'kii and Maksimov.[2] However, the equations in Ref. 2 for the equilibrium spectrum with account of scattering were solved approximately; making use of the method of adjoint equations,[3] it is possible to find their exact solution.

Let us write the basic equations of cascade theory with account of scattering:

$$\cos\vartheta \frac{\partial P}{\partial t} = L_1 [P(E_0, t, E, \vartheta), \quad (1)$$

$$\Gamma(E_0, t, E, \vartheta)] + \frac{E_k^2}{4E^2} \Delta_\vartheta P(E_0, t, E, \vartheta),$$

$$\cos\vartheta \frac{\partial \Gamma}{\partial t} = L_2 [P(E_0, t, E, \vartheta), \Gamma(E_0, t, E, \vartheta)].$$

* The depth t is measured in atomic units.