corresponding to capture of protons of energy 53 to 75 Mev. Thus one expects, if the yield of Na^{24} is to vary slowly above 70 Mev as is observed,[2] that noncapture processes should become important above 75 Mev. A similar argument can relate the slow variation with energy in the C^{11} reaction above 40 Mev[5] to the observed departure of the C^{11} recoil range (Fig. 1) from its maximum value at approximately the same energy.

In order to calculate the actual nuclear excitation, W, from the recoil data of Fig. 1 a knowledge of the angular distribution of the recoil fragments is necessary. In the case of noncapture excitation, followed by isotropic emission of particles, the nuclear excitation is given by

$$W=W_m(2\gamma\cos\theta-\gamma^2), \quad (1)$$

where W_m is the relative kinetic energy in the center-of-mass system before collision, $\gamma=v_r/v_c$ is the ratio of the nuclear recoil velocity to the velocity of the center of mass, and θ is the nuclear recoil angle. Over the velocity range of this experiment the range varies approximately linearly with velocity, so that

$$N_r/N_t=\langle R\cos\theta\rangle_{Av}/t\simeq R(\langle v_r\cos\theta\rangle_{Av})/t, \quad (2)$$

where $R=R(v)$ is the range of the recoil fragment in the target foil whose total thickness is t. Placing $\theta=0$ in Eq. (1) gives the upper limit to W for a given γ. From the data of Fig. 1 this upper limit is approximately 80 Mev in the Na^{24} reaction and 55 Mev in the C^{11} reaction when $W_m=90$ Mev in both cases. If $\langle\cos^2\theta\rangle_{Av}$ is taken as 0.75, W becomes 50 Mev for C^{11} and 65 Mev for Na^{24}. Measurements of the angular distribution of nuclear recoils in photographic plates or cloud chambers would enable a more precise value of W to be calculated.

* Assisted by the joint program of the ONR and AEC.
† Present address: Cavendish Laboratory, Cambridge, England.
[1] R. Serber, Phys. Rev. **72**, 1114 (1947).
[2] Norton M. Hintz, Phys. Rev. **83**, 185 (1951).
[3] J. Knipp and E. Teller, Phys. Rev. **59**, 659 (1941).
[4] V. Weisskopf, Phys. Rev. **52**, 295 (1937).
[5] Aamodt, Peterson, and Phillips, unpublished University of California Radiation Laboratory Report No. 1400 (1951).

(γ, α) Reactions on Li^7, O^{16}, and $Br^{79,81}$

H. NABHOLZ, P. STOLL, AND H. WÄFFLER*
Swiss Federal Institute of Technology, Zürich, Switzerland
(Received April 14, 1952)

IN light as well as in middle-weight nuclei, (γ, α) reactions have exceedingly small cross sections ($\approx 10^{-29}$ cm^2). Therefore, an investigation of these processes needs a highly sensitive detecting device. The nuclear emulsion turned out to be very suitable to a study of (γ, α) reactions in the above mentioned elements, since emulsions can easily be loaded with lithium, and oxygen as well as bromine, form a great part of the emulsion itself.

1. Li^7.—200μ Kodak NT 1a plates loaded with lithium have been exposed to the ~6.13 Mev gamma-rays from the $F^{19}(p, \alpha)O^{16}+\gamma$ reaction at a bombarding energy of ~430 kev. About 600 events consisting of an α-particle ($E\cong 1.5$ Mev) and a triton ($E_T\cong 2$ Mev) emitted in opposite directions have been observed in 30 cm^2 of the emulsion. They belong to the reaction

$$Li^7(\gamma, \alpha)T^3(Q=-2.51 \text{ Mev}).$$

From the geometry of the arrangement, the number of tracks counted, and the absolute intensity of the gamma-rays measured according to the method of Fowler *et al.*,[1] the cross section has been determined to be

$$\sigma[Li^7(\gamma_{6.13}, \alpha)]=(2.65\pm 1.0)\times 10^{-29} \text{ cm}^2.$$

The angular distribution (350 tracks) of the tritons with respect to the incident gamma-rays is given by

$$J(\theta)=1-(0.1\pm 0.09)\cos\theta.$$

This result is in qualitative agreement with the following assumptions: $Li^7(^2P_{\frac{3}{2}}^-)$ absorbs in its ground state EQ and MD radiation. Both kinds of transitions lead to a $^2P_{\frac{1}{2}}^-$ state and accordingly to an isotropic distribution. From an admixture of ED absorption there results a $^2P_{\frac{3}{2}}^+$ state, which together with the $^2P_{\frac{1}{2}}^-$ state causes a $\cos\theta$ interference term in the angular distribution.

2. O^{16}.—200μ Kodak NT 1a plates have been irradiated by the 17.6-Mev gamma-rays from the $Li^7(p, \gamma)$ reaction. Figure 1 shows the energy-distribution of 600 α-particle tracks measured in 15 cm^2 of emulsion. As follows from the well-known masses of O^{16}, C^{12}, and He^4, the peak at 7.8 Mev corresponds to the $O^{16}(\gamma, \alpha)$ reaction leading to the ground state of the rest nucleus C^{12}. Since the first excited state of C^{12} lies at ~4.5 Mev, a second maximum at ~4.4-Mev α-particle energy could be expected from the 17.6-Mev gamma-line. This maximum would partially interfere with the 5.7-Mev α-particles from the 14.8-Mev gamma-line present in the lithium gamma-ray spectrum, as well as with polonium contamination tracks (5.3 Mev) always present in the emulsion. But since the number of α-tracks between 4 and 6 Mev is only 25 percent of the number of those between 7 and 9 Mev, one can say that the predominant part of the $O^{16}(\gamma_{17.6}, \alpha)$ transitions leads to the ground state of the C^{12} nucleus. From a comparison of the number of tracks which belong to this peak with the number of "carbon stars" arising from the reaction $C^{12}(\gamma, \alpha)2\alpha$, the following cross section ratio results:

$$\sigma[O^{16}(\gamma_{17.6}, \alpha)]/\sigma[C^{12}(\gamma_{17.6}, \alpha)]=0.82\pm 0.1.$$

A new determination of the carbon cross section has been made recently.[2] The result is $\sigma[C^{12}(\gamma, \alpha)2\alpha]=1.7\pm 0.3\times 10^{-28}$ cm^2 for γ-rays from lithium. Assuming this new value tentatively as correct, we get after a correction for the three Li γ-ray lines (17.6; 14.8; $\approx$12.5 Mev) an absolute value of the oxygen cross section:

$$\sigma[O^{16}(\gamma_{17.6}, \alpha)]=(1.8\pm 0.5)\times 10^{-28} \text{ cm}^2,$$

which is in agreement with a former determination.[3]

3. $Br^{79,81}$.—An interpretation of the peak at 10.2 Mev in the α-particle distribution is not possible by a (γ, α) process on one of the light elements of the emulsion, as calculations with the well-known masses show. Only bromine and silver remain. But the emission probability for an α-particle of 10 Mev from a silver

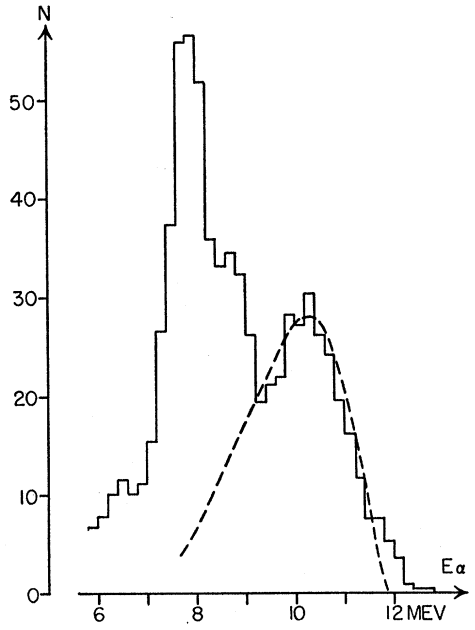

FIG. 1. α-particle distribution in a nuclear plate exposed to lithium gamma-rays. Block-diagram: experimental distribution; dashed curve: theoretical α-particle distribution for bromine.

nucleus excited at 17.6 Mev is about 1000 times smaller than for a bromine nucleus under the same conditions. (This is calculated by means of the statistical theory of nuclear reactions.) Therefore, one can safely ascribe the overwhelming number of α-particles at 10 Mev to the $Br^{79,81}(\gamma, \alpha)$ reaction. Under this assumption, the cross section for both bromine isotopes relative to that of the $C^{12}(\gamma, \alpha)2\alpha$ reaction has been computed to be

$$\sigma[Br^{79,81}(\gamma_{17.6}, \alpha)]/\sigma[C^{12}(\gamma_{17.6}, \alpha)]=0.51\pm0.05. \quad (1)$$

This value may be compared with the result calculated according to statistical theory. From the mass formula one gets $E_b(Br^{81})-E_b(Br^{79})=0.5$ Mev for the difference of the α-particle binding energies in Br^{79} and Br^{81}. The α-particle distribution (see Fig. 1) gives immediately $E_b(Br^{79})=5.7$ Mev. Since the neutron binding energies are also known for both bromine isotopes, namely, 10.6 and 9.95 Mev for Br^{79} and Br^{81}, respectively, the theoretical cross section ratios $(\gamma, \alpha)/(\gamma, n)$ can be calculated. The result is $\approx 8\times10^{-4}$ for Br^{79} and 3×10^{-4} for Br^{81}. With these values and the experimental cross section ratios $\sigma[Cu^{63}(\gamma, n)]/\sigma[Br^{79}(\gamma, n)]$ and $\sigma[Cu^{63}(\gamma, n)]/\sigma[Br^{81}(\gamma, n)]$ given by Wäffler,[4] we obtain

$$\sigma[Br^{79,81}(\gamma_{17.6}, \alpha)]/\sigma[Cu^{63}(\gamma_{17.6}, \alpha)]=4.2\times10^{-4}. \quad (2)$$

To get the absolute value of $\sigma[Br^{79,81}(\gamma_{17.6}, \alpha)]$ we put $\sigma[Cu^{63}(\gamma, n)]=10^{-25}$ cm^2.

Experimental value $\sigma[Br^{79,81}(\gamma_{17.6}, \alpha)]=(1.2\pm0.5)\times10^{-28}$ cm^2.

Theoretical value $\sigma[Br^{79,81}(\gamma_{17.6}, \alpha)]=4\times10^{-29}$ cm^2.

This theoretical value is obtained for $r_0=1.3\times10^{-13}$ cm in the nuclear radius formulas; with $r_0=1.5\times10^{-13}$ cm the theoretical cross section increases by a factor of about 6. Our results demonstrate, therefore, that in the present case statistical nuclear theory gives the correct magnitude for the ratio $(\gamma, \alpha)/(\gamma, n)$.

From the level distribution of the residual nucleus, the energy distribution of the emitted α-particles can be calculated. The dotted curve in Fig. 1 shows the theoretical distribution, based on the level density formula $\omega(E) \propto \exp\{2[a(A)\cdot E]^{\frac{1}{2}}\}$ with $a(A)=2.7$ Mev^{-1} as given by Blatt and Weisskopf.[5]

As one may learn from the figure, the calculation based on the above-mentioned assumptions is in satisfactory agreement with the experiment.

* Now at the University of Zürich, Zürich, Switzerland.

[1] Fowler, Lauritsen, and Lauritsen, Revs. Modern Phys. **20**, 236 (1948).
[2] H. Glättli *et al.* (to be published).
[3] H. Wäffler and S. Younis, Helv. Phys. Acta **22**, 614 (1949).
[4] H. Wäffler and O. Hirzel, Helv. Phys. Acta **21**, 200 (1948).
[5] J. M. Blatt and V. Weisskopf, unpublished ONR Technical Report No. 42 (1950).

A Fast Neutron Spectrometer

L. E. Beghian, R. A. Allen, J. M. Calvert, and H. Halban
Clarendon Laboratory, Oxford, England
(Received March 11, 1952)

THE methods used so far to determine the energies of fast neutrons rely mostly on the measurement of the pulse-height spectrum of recoil protons (hydrogen-filled ionization chambers, organic scintillating crystals, photographic plates). The neutron energy spectrum is then determined from the recoil spectrum, the neutron-proton scattering cross section, and the angular distribution as a function of energy. All these techniques however have the common disadvantage of poor resolution and considerable difficulty in the interpretation of results.

In order to try to overcome these difficulties, a technique to select only recoil protons which have suffered a head-on collision has been developed. The simplest way of doing this is to measure coincidences between recoil protons produced in an organic scintillating crystal and a second crystal arranged to detect neutrons scattered at practically 90° to the primary neutron beam. In principle, the scattering angle could be defined by geometrical alignment of the two crystals relative to the neutron beam, but this would lead to an intolerably low over all sensitivity of the apparatus.

We have, therefore, adopted a time-of-flight method which selects only coincidences which are due to neutrons traveling from the first to the second crystal with energies less than 30 kev. It is thus clear that for a primary energy of several million volts, the recoil proton in C_1 carries away more than 99 percent of the primary energy which in turn is dissipated in scintillation energy. Hence by measuring the pulse-height distribution of such recoils by a multi-channel kicksorter, the neutron energy spectrum can be directly determined.

As shown in Fig. 1, the two crystals C_1 and C_2 are viewed by 14-stage photomultipliers (E.M.I. type 6262) whose outputs feed into a fast coincidence circuit of total resolving time 3×10^{-8} second. The pulse from C_1 is delayed by 3.5×10^{-8} second. Thus a coincidence will be favored if the time of flight of the scattered neutron from C_1 to C_2 (distance 6 cm) is between 2×10^{-8} and 5×10^{-8} second: i.e., if its energy is between 3×10^4 ev and 5×10^3 ev approximately.

For C_1, a stilbene crystal (1.5 cm diameter, 0.5 cm thick) is

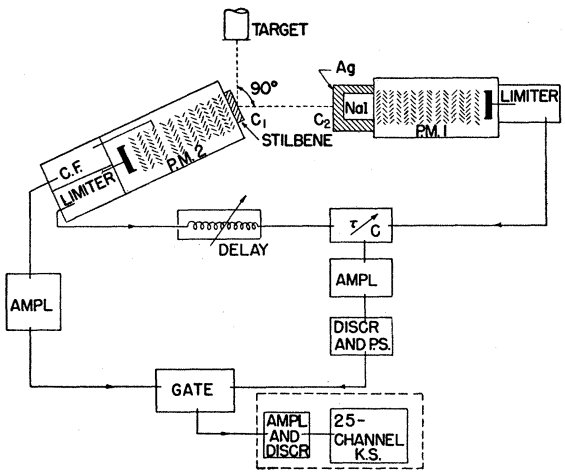

FIG. 1. Block diagram of spectrometer. C—coincidence unit; AMPL—amplifier; DISCR—discriminator; C. F.—cathode follower; P. S.—pulse shaper; K. S.—kicksorter; P. M. photomultiplier. Arrow indicates variable settings.

used. We find the scintillation energy for this is closely proportional to proton recoil energy [results to be published in Proc. Phys. Soc. (London)]. For C_2, a one-inch cube of NaI (Tl), surrounded by $\frac{1}{2}$ cm silver is used. The capture of neutrons by silver or iodine nuclei results in a γ-ray cascade which can then be detected by the crystal. The over-all efficiency of this combination for detecting neutrons of 3×10^4 ev is calculated to be about 6 percent from the known radiative capture cross sections. The pulse-rise time from sodium iodide is slow (0.25×10^{-6} second) for the present purpose; however, since proportionality of pulse height is not required from this crystal (it is anyhow limited to feed into the coincidence circuit), it is possible to operate on the initial portion of the leading edge of the pulse with a rise time of less than 10^{-8} second.

The output of the coincident circuit is amplified by a 5-megacycle bandwidth amplifier, and is then used to gate proportional pulses from C_1 (resolving time of gate 2×10^{-6} second). This insures that only those pulses from C_1 are selected for analysis which correspond to a head-on neutron-proton collision in the crystal, apart from a background due to random coincidences. The gated pulses are then analyzed by a multi-channel kicksorter. The normal output electrode of photomultiplier "C_1" cannot be used to supply the proportional pulses, since the output from this electrode has to be limited before being fed into the coincidence circuit. Instead, pulses from the 11th dynode are used since these have been found to be closely proportional to scintillation energy.