The scintillation pulse distributions from cosmic rays, from a Co^{60} source, and from the radioactive contamination of the aircraft are shown in Fig. 1. A Co^{60} calibration curve was taken after each data run; and all pulse heights are referred to the peak of the differentiated Co^{60} curve which corresponds to a Compton electron energy of ~1.0 Mev. Over a limited range, therefore, the scale for pulse height on Fig. 1 may be used as energy in Mev.

The total pulse distribution, obtained during a flight at 2000 feet, was assumed to be due to the contamination of the aircraft and was used to correct the data. This was justified on the basis of G-M tube data regarding the total cosmic-ray intensity (ionizing and gamma) at 2000 feet and introduces an error of less than 10 percent in the evaluation of the contamination.

The relatively short airborne time and low counting rate yielded a small number of counts with resultant poor statistics, as shown by the extensions of the data points in Fig. 1. These extensions are based solely on the probable error due to statistical variations.

Very brief investigation with a G-M tube guard ring around the scintillation detector indicated that pulses due to the ionizing component were in the region above 0.8 units of pulse height (0.8 Mev), whereas the region for energies below ~0.8 Mev probably consists primarily of pulses due to gamma-rays created in the atmospheric cascade process. Since the pulse distribution for a mono-energetic source (Co^{60}) rises much more slowly at small pulse heights than does the cosmic-ray distribution, it is concluded that many cosmic gamma-rays are spread over a broad energy range in the vicinity of 0.5 Mev.

The shape of the distribution above slit position 0.8 (0.8 Mev) is probably a result of nonlinear crystal response[2] in combination with an ionizing particle energy spectrum obeying an inverse power law. There is some indication that the curve has a peak in the region above 1.7 units. Most of the pulses above 0.8 Mev are due to cosmic-ray electrons which, it is estimated,[3] constitute 80 percent of the total ionizing intensity at 30,000 feet and 50° geomagnetic latitude. These electrons give up energy to the anthracene by ionization and the formation of bremsstrahlung.

Using the formula of Bloch,[4] it may be shown that electrons with energies above 5 Mev will lose about 2 Mev by ionization in 0.5 inch of anthracene. This energy loss is almost independent of the incident energy and would account for a peak in the distribution above 1.7 units.

For very high energies, the bremsstrahlung process would become increasingly important, and partial capture of the resultant radiation would contribute to pulses above 2 units. There is, of course, no reason to expect a linear relation between pulse height and incident electron energy once bremsstrahlung becomes important (even if the electron is stopped in the crystal), unless the crystal is large enough to capture all of the secondary gamma-rays.

Investigations are being continued in an effort to obtain more information about the cosmic-ray background and the various processes contributing to the scintillation spectrum.

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* This work was done under contract with the United States Department of the Air Force.

[1] To be described elsewhere.

[2] The linearity of the pulse height *versus* energy curve for low energies in anthracene has been studied by J. I. Hopkins, Phys. Rev. **78**, 643 (1950).

[3] Montgomery, *Cosmic Ray Physics* (1949), p. 131.

[4] W. Heitler, *Quantum Theory of Radiation* (1944), pp. 217 ff.

Radiations from Zr^{89}

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The Zr^{89}, produced by $\mathrm{Y}(d, 2n)$ in the M.I.T. cyclotron, decays with a half-life of 79.3 hours. Figure 1 shows the momentum distribution of the particles emitted from Zr^{89} as measured with a thin lens magnetic beta-ray spectrometer. The conversion line has an energy of 910 kev, whereas the continuum of positrons has an end point of 905 kev on a conventional Fermi plot. No beta-gamma coincidences nor x-gamma coincidences have been found. No gamma-gamma coincidences except those due to annihilation radiation have been found. The conversion coefficient has been estimated as 0.5 percent.

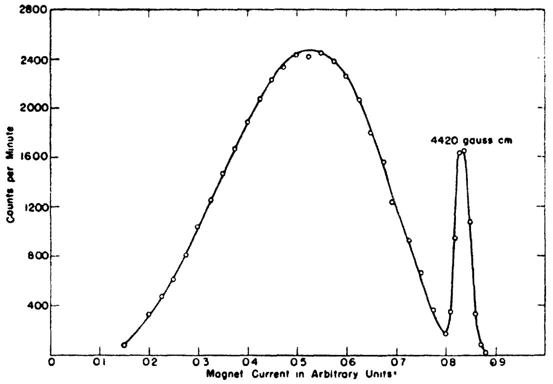

FIG. 1. Momentum spectrum of Zr^{89} particles.

From the results of this research, the level emitting the conversion electrons has a lifetime considerably greater than the resolving time of the coincidence circuit used (10^{-7} sec). This is in agreement with the high conversion coefficient found. It is not known whether the conversion takes place in Zr or Y.

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Cross Sections and Q-Values for the $\mathrm{C}^{13}+\mathrm{D}^2$ Reactions*

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The energy of the reaction products from the disintegration of C^{13} by deuterons has been analyzed with the 16″ double-focusing magnetic spectrometer. The emitted particles, identified by their mv/Ze value and pulse size in the scintillation proportional counter, correspond to the reactions (1) $\mathrm{C}^{13}(d, \alpha)\mathrm{B}^{11}$, (2) $\mathrm{C}^{13}(d, p)\mathrm{C}^{14}$, and (3) $\mathrm{C}^{13}(d, t)\mathrm{C}^{12}$.

The targets were prepared by depositing C^{13} on thin tantalum strips by heating the tantalum in an atmosphere of $\mathrm{CH_3I}$ vapor, enriched to 61 percent C^{13}. The thickness of the targets, estimated from the energy spread of the outgoing particles, was approximately 50 kev for the incident deuterons. The deuteron beam of 1006±1 kev from the van de graaff generator was controlled with an electrostatic analyzer calibrated against the $\mathrm{Al}^{27}(p, \gamma)\mathrm{Si}^{28}$ resonance at 993.3±1 kev.[1]

The calibration of the magnetic spectrometer with Po alpha-particles and the experimental procedure has been described previously.[2] No correction for surface contamination layers has been made, since a magnetic analysis of the elastically scattered deuterons showed these layers to be negligibly small. Appropriate relativistic corrections have been made. Our results are $Q_1 = 5.164 \pm 0.006$ Mev; $Q_2 = 5.940 \pm 0.004$ Mev; and $Q_3 = 1.310 \pm 0.003$ Mev. The probable errors include statistical errors as well as all known systematic errors, the most significant being the uncertainty in the angle of observation, 89.3±0.2 degrees. These values are in good agreement with those obtained recently by Buechner and his collaborators:[3] $Q_1 = 5.160 \pm 0.010$ Mev; $Q_2 = 5.948 \pm 0.008$ Mev; and $Q_3 = 1.310 \pm 0.006$ Mev. The agreement between independent measurements of the $C^{13}(d, \alpha)B^{11}$ Q-value is particularly fortunate, since this reaction is of critical importance in determining the mass of the nuclei lighter than B^{11} in terms of O^{16}. A mass table based on these accurately determined Q-values is being prepared for publication.

In addition to the ground-state transitions, a group of alpha-particles was observed which we have tentatively identified with the $C^{13}(d, \alpha)^*B^{11}$, leaving B^{11} excited by 2.107±0.017 Mev above the ground state. The Q-value for this reaction is 3.057±0.016 Mev. The existence of this lowest excited state in B^{11} has been previously reported by Bateson[4] and by Buechner and Van Patter[5] from a study of the $B^{10}(d, p)B^{11}$ proton groups.

The method of obtaining nuclear reaction cross sections from thick target spectra has been described previously.[6] Following this procedure, we find for 0.99-Mev deuterons a differential cross section at 90 degrees of 7 millibarns/steradian for $C^{13}(d, \alpha)B^{11}$, 2 millibarns/steradian for $C^{13}(d, t)C^{12}$. The high energy protons from $C^{13}(d, p)C^{14}$ were able to pass completely through the ZnS phosphor screen of the scintillation counter, producing a non-uniform pulse height distribution and making the counter efficiency uncertain, so that we are not able to give a value for this cross section.

We wish to thank Mr. John D. Seagrave for preparing the C^{13} targets; a detailed description of his targets will appear elsewhere.

* This work was assisted by the joint program of the ONR and AEC.

[1] Herb, Snowdon, and Sala, Phys. Rev. **75**, 246 (1949).
[2] Whaling and Li, Phys. Rev. **81**, 150 (1951).
[3] Strait, Van Patter, Buechner, and Sperduto, Phys. Rev. **81**, 747 (1951).
[4] W. O. Bateson, Phys. Rev. **80**, 982 (1950).
[5] Buechner and Van Patter, Phys. Rev. **79**, 240 (1950).
[6] Snyder, Rubin, Fowler, and Lauritsen, Rev. Sci. Instr. **21**, 852 (1950).

The Angular Dependence of Scattering and Reaction Cross Sections

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THE general expression for the differential scattering or reaction cross sections for an unpolarized beam in terms of the scattering matrix has been given in the literature.[1] However, the practical evaluation of this expression runs into difficulties as soon as some of the particles involved have intrinsic spins. In that case, one must average over the spin directions in the incident channel and sum over the spin directions in the outgoing channel. The resulting sums over vector addition (Clebsch-Gordan) coefficients are quite tedious to evaluate directly. However, one should think that all sums over magnetic quantum numbers are essentially geometrical in character and can therefore be performed without a detailed knowledge of the particular collision process (of the elements of the scattering matrix). We wish to point out that this is indeed correct and leads to an explicit expression for the scattering or reaction cross sections free of all sums over magnetic quantum numbers. This explicit form has the additional advantage that it expresses the cross sections directly as sums of Legendre polynomials, with coefficients which are manifestly real numbers. The necessary formalism has been developed by Racah[2] in connection with the theory of complex atomic spectra.

The final result can be written most simply in terms of the quantities $Z(l_1J_1l_2J_2, sL)$ defined as follows:

$$Z(l_1J_1l_2J_2, sL) = (2l_1+1)^{\frac{1}{2}}(2J_1+1)^{\frac{1}{2}}(2l_2+1)^{\frac{1}{2}}(2J_2+1)^{\frac{1}{2}} \times W(l_1J_1l_2J_2, sL)s(l_1, l_2)_{L00}, \quad (1)$$

where W is the coefficient defined by Racah,[2] and $s(l_1, l_2)_{L00}$ is a vector addition coefficient in the notation of Wigner and Eisenbud.[1]

The differential cross section for a process leading from channel s to channel s' can then be written as follows:

$$d\sigma^{ss'} = (k_s)^{-2} \sum_{L=0}^{\infty} B_L^{ss'} P_L(\cos\theta) d\Omega_{s'}, \quad (2)$$

where $P_L(\cos\theta)$ is the Legendre polynomial defined in the usual way, and the coefficients $B_L^{ss'}$ are related to the scattering matrix $u_{sl;\,s'l'}{}^J$ of reference 1 as follows:

$$\begin{aligned} B_L^{ss'} = {} & (-)^{j_{s'}-j_s}[4(2j_s+1)]^{-1} \sum_{J=0}^{\infty} \sum_{l=|J-j_s|}^{J+j_s} \sum_{l'=|J-j_{s'}|}^{J+j_{s'}} \\ & Z(lJlJ, j_sL)Z(l'Jl'J, j_{s'}L)\,|\delta_{ss'}\delta_{ll'} - i^{l+l'}u_{sl;\,s'l'}{}^J|^2 \\ & + (-)^{j_{s'}-j_s}[2(2j_s+1)]^{-1} \sum_{J_1}\sum_{l_1}\sum_{l_1'} \Big(\sum_{J_2 \geq J_1} \sum_{l_2 \geq l_1} \sum_{l_2' \geq l_1'} \Big)' \\ & i^{-l_1+l_1'+l_2-l_2'} Z(l_1J_1l_2J_2, j_sL)Z(l_1'J_1l_2'J_2, j_{s'}L) \\ & \times \text{Real Part of } [(\delta_{ss'}\delta_{l_1l_1'} - i^{l_1+l_1'}u_{sl_1;\,s'l_1'}{}^{J_1})^* \\ & \times (\delta_{ss'}\delta_{l_2l_2'} - i^{l_2+l_2'}u_{sl_2;\,s'l_2'}{}^{J_2})], \end{aligned} \quad (3)$$

where the prime on the last three sums of the second term means that those terms are excluded for which all three inequalities become equalities, i.e., for which $J_2 = J_1$, $l_2 = l_1$, and $l_2' = l_1'$ simultaneously.

While one could hardly claim that (3) is a very simple expression, it is appreciably simpler than the one given in reference 1, since six sums over magnetic quantum numbers have been eliminated. Furthermore, it is satisfying that the rules about the limitations of the complexity of angular distributions[3] can be shown to follow from (3) by the use of Racah's selection rule for nonvanishing W-coefficients. All terms in (3) are manifestly real with the exception of $i^{-l_1+l_1'+l_2-l_2'}$ in the second sum of (3). This term, however, is also real because of the parity selection rule according to which l_1-l_1' and l_2-l_2' are either both even or both odd. Equation (3) simplifies considerably for a resonance reaction going through one and only one level of the compound nucleus. In that case the scattering matrix can be factored. This special case was considered already by Myers,[4] who failed to give explicit expressions for the Racah coefficients, however. The simplifications are only minor in the case of resonance scattering because of the interference between resonance and potential scattering. The formalism developed here is adequate for the description of scattering or reactions induced by neutral particles and for reactions or inelastic scattering of charged particles. In the case of elastic scattering of charged particles the series (2) contains the coulomb scattering and hence converges extremely slowly. It is possible, however, to subtract out the coulomb scattering to get a usable expression.

Further work in this connection is in progress and will be reported later in more detail. In particular, we are going to give recursion relations and tables of the Racah coefficients W and the Z-coefficients defined by (1). We would like to thank Dr. Stuart Lloyd of the University of Illinois for some valuable discussions in connection with the Racah coefficients.

[1] E. P. Wigner and L. Eisenbud, Phys. Rev. **72**, 29 (1947); see Eqs. (33), (35), and (42). We shall use their notation in this letter.
[2] G. Racah, Phys. Rev. **61**, 186 (1942); **62**, 438 (1942).
[3] C. N. Yang, Phys. Rev. **74**, 764 (1948).
[4] R. D. Myers, Phys. Rev. **54**, 361 (1938).

Study of Low Energy Gamma-Radiations Emitted from Pa^{231} and U^{234}

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MACKLIN AND KNIGHT[1] observed, with a Geiger counter, a low energy gamma-radiation from a thin source of U^{234}, an α-emitter. By absorption of this radiation in Al, they showed