Photonuclear Cross Sections in Aluminum and Magnesium

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Cross-section curves have been measured as functions of photon energy for the reactions $Al^{27}(\gamma, n)Al^{26}$, $Mg^{24}(\gamma, n)Mg^{23}$, $Mg^{25}(\gamma, p)Na^{24}$, and $Mg^{26}(\gamma, p)Na^{25}$. These curves exhibit the peaked shape characteristic of photonuclear reactions, the maximum cross sections being 8.1, 9.8, 14.8, and 19.3 millibarns respectively. The (γ, p) peak positions occur about 2 Mev higher than those of the (γ, n) reactions, and their cross sections as indicated above are considerably larger. It is shown that these peaked shapes result from a peaking of the photonuclear absorption cross sections. The larger values of the (γ, p) peak positions and cross sections may be explained as resulting from a direct interaction between high energy photons and nuclear protons.

I. INTRODUCTION

IN 1947 Hirzel and Waffler[1] reported that the ratio of (γ, p) to (γ, n) reaction cross sections in medium heavy nuclei was much larger than would be predicted by the statistical theory of Weisskopf.[2,3] Their experiments were performed with γ-rays from the $Li^7(p, \gamma)Be^8$ reaction, having energies of 14.4 and 17.6 Mev; these photon energies are lower than those at which the maximum (γ, p) cross sections occur.[4] Schiff attempted to explain this anomaly by assuming that only a selected set of nuclear levels become populated in photonuclear reactions.[5] Such "regular" level densities lead to disagreement with experimental photoproton energy distributions.[6,7] Recently Courant[8] has proposed a theory of direct photoelectric excitation of nucleons which gives fair agreement with the Hirzel and Waffler ratios of (γ, p) to (γ, n) cross sections.

Aluminum and magnesium are light elements which have low potential barriers against proton emission. On the other hand they are sufficiently heavy that one might expect to predict the qualitative if not the quantitative features of the (γ, p) and (γ, n) yields from statistical theory. Halpern and Mann[4] have measured the cross-section curve for the reaction $Al^{27}(\gamma, p)Mg^{26}$ as a function of photon energy, and Diven and Almy[6] have investigated the photoproton energy distribution from this reaction. Toms and Stephens[9] have measured the same quantities for the reaction $Mg^{25}(\gamma, p)Na^{24}$ and also the photoproton energy distribution from natural magnesium. In the present work we have measured cross-section curves for the reactions $Al^{27}(\gamma, n)Al^{26}$, $Mg^{24}(\gamma, n)Mg^{23}$, $Mg^{25}(\gamma, p)Na^{24}$, and $Mg^{26}(\gamma, p)Na^{25}$.

II. EXPERIMENTAL PROCEDURE

Three of the products of the reactions reported here have short half-lives. That of Al^{26} was determined in this experiment to be 6.49 ± 0.10 seconds, in good agreement with the best previous value of 6.3 seconds.[10] The half lives of Mg^{23} and Na^{25} are 11.6 seconds and 60 seconds respectively. It was therefore necessary to make a rapid transfer of the aluminum and magnesium samples from the betatron irradiation position to a counter.

At first a "swing" apparatus was set up, in which a sample was clamped at the end of a wooden arm in the irradiation position. Upon release at the end of an irradiation, the arm swung down positioning the sample above an end-window counter in a lead castle. At the same time the counter voltage was raised to the operating level and a time-stamping recorder was switched on. With this arrangement the activation curve for the $Al^{27}(\gamma, n)Al^{26}$ reaction was obtained.

The apparatus was then modified into a "dropping" device. A vertical brass tube held cylindrical samples which dropped around a cylindrical counter at the end of an irradiation, the other equipment remaining unchanged. With this arrangement activation curves were measured for the $Mg^{24}(\gamma, n)Mg^{23}$ and $Mg^{26}(\gamma, p)Na^{25}$ reactions.

The fourth reaction, $Mg^{25}(\gamma, p)Na^{24}$, gives a product having a half-life of 15 hours. Such activities were counted with standard equipment after thin magnesium disks had been irradiated and the short-lived activities had decayed.

These activation curves were normalized to the known $Cu^{63}(\gamma, n)Cu^{62}$ activity[11] at 22 Mev by irradiating similar cylindrical samples of aluminum, magnesium, and copper in the dropping apparatus. It was necessary to correct such activities for self-absorption of beta-particles in the samples. The corrections for the Cu^{62} activity have been measured in this laboratory for cylindrical geometry by Mr. R. G. Baker, and those for the Al^{26} activity were measured by the dropping tech-

[1] O. Hirzel and H. Waffler, Helv. Phys. Acta **20**, 373 (1947).
[2] V. F. Weisskopf and D. H. Ewing, Phys. Rev. **57**, 472 (1940).
[3] J. M. Blatt and V. F. Weisskopf, *The Theory of Nuclear Reactions*, Technical Report No. 42, Laboratory for Nuclear Science and Engineering, Massachusetts Institute of Technology.
[4] J. Halpern and A. K. Mann, Phys. Rev. **83**, 370 (1951).
[5] L. I. Schiff, Phys. Rev. **73**, 1311 (1948).
[6] B. C. Diven and G. M. Almy, Phys. Rev. **80**, 407 (1950).
[7] P. R. Byerly, Jr., and W. E. Stephens, Phys. Rev. **83**, 54 (1951).
[8] E. D. Courant, Phys. Rev. **82**, 703 (1951).
[9] M. E. Toms and W. E. Stephens, Phys. Rev. **82**, 709 (1951).
[10] H. Bradner and J. D. Gow, Phys. Rev. **74**, 1559 (1948).
[11] Johns, Katz, Douglas, and Haslam, Phys. Rev. **80**, 1062 (1950).

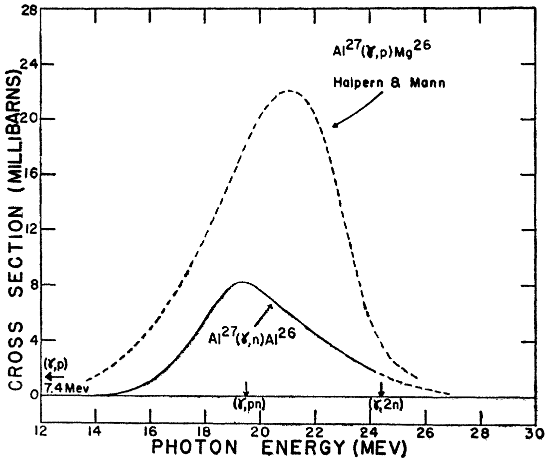

FIG. 1. Cross-section curves for the reactions $Al^{27}(\gamma, n)Al^{26}$ (solid line) and $Al^{27}(\gamma, p)Mg^{26}$ (dotted line, as measured by Halpern and Mann). The arrows indicate thresholds for possible competing reactions.

nique. It was assumed that the self-absorption corrections for the activities produced in magnesium were the same as those for Al^{26}.

The resulting activation curves were analyzed by the photon difference method[12] to obtain the photonuclear cross sections as functions of photon energy. These cross sections are plotted as the solid lines in Figs. 1, 2, 3, and 4.

III. DISCUSSION

In Fig. 1 are plotted the cross-section curves for the reactions $Al^{27}(\gamma, n)Al^{26}$ (solid line) and $Al^{27}(\gamma, p)Mg^{26}$ (dotted line, as measured by Halpern and Mann[4]). This is the only case reported here in which both the (γ, p) and (γ, n) cross-section curves have been measured for the same parent isotope. The curves exhibit the peaked shape characteristic of photonuclear reactions. In the general case such peaks can be thought of as resulting from "cascade" competition, in which a second nucleon can be emitted at higher excitations leaving a different residual nucleus not detected in the experiment, or as resulting from a "resonance" absorption of photons as predicted by Goldhaber and Teller,[13] and by Levinger and Bethe.[14]

These two possibilities are implicit in a general probability equation

$$\sigma(a, b) = \sigma_c(a) G_c(b),$$

in which the cross section for an (a, b) reaction, $\sigma(a, b)$, is set equal to the product of the probabilities for the capture of particle a and the emission of particle b. In statistical theory $\sigma_c(a)$ is the cross section for the formation of a compound nucleus and $G_c(b)$ is the probability that such compound nucleus will decay via the "channel" b. A peaked cross section could therefore result from a peaking of either factor or of some fortuitous combination of the two factors.

The energy thresholds for (γ, pn) and $(\gamma, 2n)$ reactions in Al^{27} are indicated by arrows in Fig. 1. The $(\gamma, 2n)$ threshold is too high to have affected the turnover of the cross-section curves through an influence on G_c. The (γ, pn) threshold occurs at the (γ, n) peak position and below the (γ, p) peak position. Since Halpern and Mann measured proton yields, their cross-section curve is the sum of the cross sections for the reactions $Al^{27}(\gamma, p)Mg^{26}$, and $Al^{27}(\gamma, pn)Mg^{25}$. However the greater part of their curve must have been due to the (γ, p) reaction alone for the following reasons: Diven and Almy found, using 20.8-Mev x-rays, that the aluminum photoproton energy distribution was peaked at 4 Mev. Those (γ, pn) reactions in which a proton is first emitted, followed by neutron emission from the residual nucleus, would therefore have only a small cross section below 23 Mev. The alternative case, in which a neutron is emitted first, followed by proton emission from the residual nucleus, also should have only a small cross section for a few Mev above threshold due to the kinetic energy of the initial neutron. Thus the (γ, pn) reaction would be unimportant where the (γ, p) cross section turns over.

In Table I are listed the energy thresholds for the emission of neutrons, protons, and alpha-particles, both singly and in combination, from the four parent nuclei considered in this paper. The reaction $Al^{27}(\gamma, \alpha)Na^{23}$ has a low threshold and could affect the turn-over of the (γ, n) and (γ, p) cross-section curves, but (γ, α) cross sections are much less than a millibarn in very light elements[15] and are about a millibarn or less in medium heavy elements.[15,16] The (γ, α) cross-sections peak at 18 Mev in carbon and oxygen and at 23 Mev in copper and rubidium.[16] It is therefore probable that (γ, α) reactions

TABLE I. Thresholds (Mev) for competing reactions in magnesium and aluminum. A few values are experimental results; the rest have been computed from mass values (mostly from Bethe[a]).

Reaction	Parent isotope Mg^{24}	Mg^{25}	Mg^{26}	Al^{27}
(γ, n)	16.2[b]	7.1[c]	10.1[c]	14.0[b]
(γ, p)	12.3	11.5[b]	14.0[b]	7.4
(γ, α)	9.5	9.0	11.7	9.5
$(\gamma, 2n)$	29.5	23.3	17.2	24.4
(γ, pn)	22.8	17.9	23.2	19.5
$(\gamma, n\alpha)$	26.3	16.6	21.2	21.3
$(\gamma, 2p)$	20.6	22.1	23.6	21.4
$(\gamma, p\alpha)$	22.4	21.8	27.2	19.1
$(\gamma, 2\alpha)$	14.2	17.2	21.3	20.8

[a] H. A. Bethe, *Elementary Nuclear Theory* (John Wiley and Sons, Inc., New York, 1947).
[b] McElhinney, Hanson, Becker, Duffield, and Diven, Phys. Rev. 75, 542 (1949).
[c] Sher, Halpern, and Stephens, Phys. Rev. 81, 155 (1951).

[12] A. G. W. Cameron and L. Katz, Phys. Rev. **83**, 883 (1951); Can. J. Phys., November, 1951 (to be published).

[13] M. Goldhaber and E. Teller, Phys. Rev. **74**, 1046 (1948).
[14] J. S. Levinger and H. A. Bethe, Phys. Rev. **78**, 115 (1950).
[15] C. H. Millar and A. G. W. Cameron (to be published).
[16] R. N. H. Haslam and H. M. Skarsgard, Phys. Rev. **81**, 479 (1951); Haslam, Smith, and Taylor, Phys. Rev. Nov. 15 (in press).

have a negligible effect on the (γ, p) and (γ, n) cross section maxima.

Other possible reactions, $(\gamma, n\alpha)$, $(\gamma, 2p)$, $(\gamma, p\alpha)$, and $(\gamma, 2\alpha)$, which might offer "cascade" competition to the (γ, n) and (γ, p) reactions, have energy thresholds near the cross-section maxima in Fig. 1. The cross sections for such reactions should be very small for a few Mev above threshold since the first particle to emerge is likely to have several Mev of kinetic energy. (γ, d) reactions have energy thresholds 2.2 Mev lower than (γ, pn) thresholds. However, the combined (γ, d) and (γ, pn) cross sections in the neighboring nucleus S^{32} are much smaller[17] than the (γ, p) cross sections in Al^{27}.

From the above considerations we conclude that the turn-over of the two cross-section curves in Fig. 1 is due to a peaking of σ_c rather than G_c, in accord with the theories of resonance dipole absorption of photons.[13,14]

It should also be noted in Fig. 1 that the (γ, p) cross section is much greater than the (γ, n) cross section in the neighborhood of 20 Mev. However, in this case,

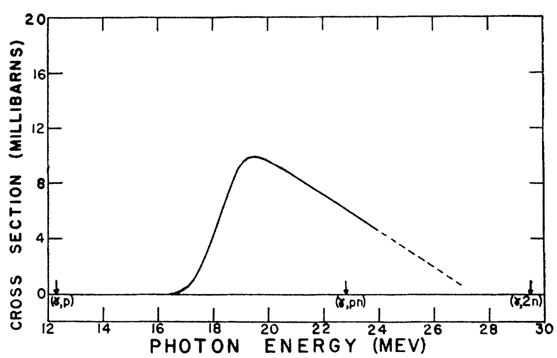

FIG. 2. Cross-section curve for the reaction $Mg^{24}(\gamma, n)Mg^{23}$. The arrows indicate thresholds for possible competing reactions.

the (γ, p) energy threshold is 6.6 Mev below the (γ, n) threshold. The result is therefore consistent with statistical theory.

Figure 2 shows the cross-section curve for the $Mg^{24}(\gamma, n)Mg^{23}$ reaction. The peak cross section is approximately equal to that for the $Al^{27}(\gamma, n)Al^{26}$ reaction. Considerations similar to those above show that the turn-over of this reaction also cannot be explained in terms of competition. It is interesting to note that the curve rises very steeply to the peak due to the high (γ, n) threshold, and that the peak occurs at nearly the same photon energy as does that for the $Al^{27}(\gamma, n)Al^{26}$ reaction. The (γ, p) threshold is in this case also much lower than the (γ, n) threshold, and if the total photonuclear absorption cross section is to be approximately equal to that for aluminum, the (γ, p) cross sections would have to be much larger than the (γ, n) ones in the neighborhood of the peak.

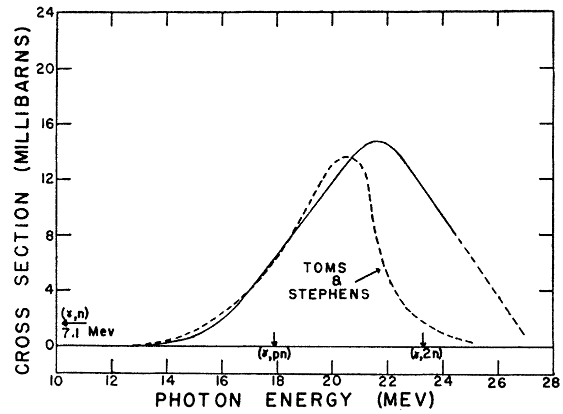

FIG. 3. Cross-section curves for the reaction $Mg^{25}(\gamma, p)Na^{24}$. The dotted line is the determination by Toms and Stephens. The arrows indicate thresholds for possible competing reactions.

In Fig. 3 are plotted two determinations of the cross-section curve for the $Mg^{25}(\gamma, p)Na^{24}$ reaction. The solid line gives the results of the present experiment and the dotted line gives those of Toms and Stephens.[9] The two curves are in good agreement up to 20 Mev, both in relative shape and absolute cross section, but above that energy a serious discrepancy sets in. For Mg^{25} the (γ, n) threshold lies considerably lower than the (γ, p) threshold, yet the (γ, p) peak cross section is only slightly smaller than that for the $Al^{27}(\gamma, p)Mg^{26}$ reaction. The $Mg^{25}(\gamma, n)Mg^{24}$ peak cross section could not be much greater than those of the previously discussed (γ, n) reactions if Mg^{25} is to have the same total photonuclear absorption cross section as Al^{27}.

The threshold for the $Mg^{25}(\gamma, pn)Na^{23}$ reaction is only 17.9 Mev. Since Toms and Stephens found the photoproton energy distribution from both natural magnesium and from Mg^{25} to peak at 4 to 5 Mev, it is evident that for photon energies in the neighborhood of 22 Mev a considerable portion of the (γ, p) residual

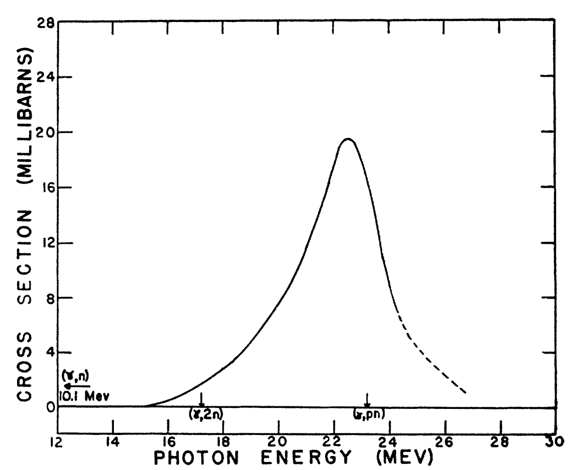

FIG. 4. Cross-section curve for the reaction $Mg^{26}(\gamma, p)Na^{25}$. The arrows indicate thresholds for possible competing reactions.

[17] L. Katz and A. S. Penfold, Phys. Rev. **81**, 815 (1951); **83**, 169 (1951); and L. Katz and A. G. W. Cameron, Can. J. Phys., November, 1951 (to be published).

TABLE II. The characteristic features of the photonuclear cross-section curves reported here plus some others determined for the same region of the periodic table.

Reaction	Peak energy (Mev)	Peak cross section (barns)	Peak width (Mev)	Integrated cross section (Mev-barns)
$Al^{27}(\gamma, n)Al^{26}$	19.2	0.0081	4.7	0.045
$Al^{27}(\gamma, p)Mg^{26}$ [a]	21.2	0.022	5.4	0.12
$Mg^{24}(\gamma, n)Mg^{23}$	19.4	0.0098	5.8	0.057
{$Mg^{25}(\gamma, p)Na^{24}$	21.7	0.0148	6.0	0.10
{$Mg^{25}(\gamma, p)Na^{24}$ [b]	20.5	0.0137	3.9	0.056
$Mg^{26}(\gamma, p)Na^{25}$	22.6	0.0193	3.3	0.085
$P^{31}(\gamma, n)P^{30}$ [c]	19.5	0.0167	6.5	0.129

[a] Reference 4. [b] Reference 9. [c] Reference 17.

nuclei will be left sufficiently excited to emit a neutron, thus removing such nuclei from detectability in the experiment. It is probable that much of the "reduction" in the (γ, p) maximum cross section is due to this cascade competition of the (γ, pn) reaction.

Figure 4 shows the cross-section curve for the $Mg^{26}(\gamma, p)Na^{25}$ reaction. The maximum cross section is nearly equal to that for the $Al^{27}(\gamma, p)Mg^{26}$ reaction, even though the (γ, n) threshold is 3.9 Mev lower than the (γ, p) threshold. The only multiple reaction with a threshold low enough to offer competition to the (γ, p) reaction near the peak is $Mg^{26}(\gamma, 2n)Mg^{24}$. It is likely that this reaction would be mainly effective in lowering the (γ, n) cross-section curve, and that it would not have much effect on the (γ, p) cross-section turn-over. The $Mg^{26}(\gamma, n)Mg^{25}$ reaction cross section near the peak is again probably not very different from those of the previous cases.

The characteristics of the above cross-section curves are listed in Table II, together with those for the $P^{31}(\gamma, n)P^{30}$ reaction.[17] Values of the photonuclear cross sections for the four new curves reported here are given at one-Mev intervals of photon energy in Table III.

It may be seen in Table II that the (γ, n) cross-section maxima occur at nearly equal photon energies, and that the (γ, p) cross-section maxima are also at approximately equal energies but are about 2 Mev higher than those of the (γ, n) reactions. Moreover,

TABLE III. Values of the photonuclear cross sections in magnesium and aluminum at one-Mev intervals of photon energy. The cross sections are in millibarns.

Photon energy (Mev)	Reaction $Mg^{24}(\gamma, n)Mg^{23}$	$Mg^{25}(\gamma, p)Na^{24}$	$Mg^{26}(\gamma, p)Na^{25}$	$Al^{27}(\gamma, n)Al^{26}$
14	—	0.2	—	—
15	—	0.7	0.05	0.2
16	—	1.9	0.5	1.1
17	0.4	3.9	1.4	2.8
18	4.3	6.5	2.8	5.6
19	9.4	9.1	4.8	8.0
20	9.6	11.8	7.5	7.6
21	8.5	14.1	11.6	6.0
22	7.2	14.5	17.8	4.4
23	5.9	12.2	18.2	3.1
24	4.6	9.4	9.1	2.0
25	3.3	6.6	4.3	1.1
26	1.9	3.6	2.3	0.5

the (γ, p) maximum cross sections are nearly all higher than the (γ, n) maximum cross sections. The lowest (γ, p) peak cross section, for the reaction $Mg^{25}(\gamma, p)Na^{24}$, is slightly less than the highest (γ, n) peak cross section, for the reaction $P^{31}(\gamma, n)P^{30}$. However, the latter reaction occurs in a slightly heavier element where the potential barrier for protons is higher than in magnesium and aluminum and where the total photonuclear absorption cross section is expected to be larger,[13,14] and it has been shown above that the former reaction has its peak cross section reduced by competition with the (γ, pn) reaction.

The (γ, p) maximum cross sections are remarkably independent of wide variations in photonuclear thresholds and of the odd-odd, odd-even, and even-even characteristics of the residual nuclei. This is contrary to the predictions of the statistical theory and therefore indicates that photonuclear excitation does not usually produce true compound nuclei. Furthermore, the fact that the emission of protons is the predominant mode of nuclear de-excitation despite the presence of the potential barrier indicates that the principal interaction of high energy photons is with nuclear protons.

Such an interaction readily explains the difference between the (γ, p) and (γ, n) peak energy positions. The average proton, after being excited in the nucleus, probably suffers a few collisions before making its escape. In some cases a true compound nucleus is probably formed, from which the emission of neutrons is easier than that of protons, but in most cases a nucleon will escape before thermal equilibrium can be established. As the initial excitation of the nuclear proton is increased, its mean free path in nuclear matter also increases and it has a larger remaining energy after a given number of collisions. The percentage of protons which escape before the formation of a compound nucleus therefore increases with the energy of excitation. Hence the (γ, n) cross-section curve will turn over below the peak of the total photonuclear absorption cross-section curve (which is also the peak of the (γ, p) cross-section curve).

Courant[8] has proposed that individual nucleons may be excited by a dipole absorption of high energy photons. In this process the nuclear protons are assigned an effective charge eN/A and the nuclear neutrons one of $-eZ/A$. This would give both protons and neutrons nearly the same probability for excitation. While such a process leads to larger (γ, p) to (γ, n) cross-section ratios than would be predicted by statistical theory, the (γ, p) maximum cross sections should still be smaller than those of the (γ, n) reactions. We therefore conclude that the excitation probability for nuclear neutrons is much less than is assumed in this theory.

IV. CONCLUSIONS

Cross-section curves as functions of photon energy have been measured for the reactions $Al^{27}(\gamma, n)Al^{26}$, $Mg^{24}(\gamma, n)Mg^{23}$, $Mg^{25}(\gamma, p)Na^{24}$, and $Mg^{26}(\gamma, p)Na^{25}$.

These curves are plotted in Figs. 1 to 4 and numerical values are listed in Tables II and III.

The curves have the peaked shape characteristic of photonuclear reactions. In three of the four cases such cross-section turn-overs cannot be explained as resulting from a cascade competition with other photonuclear reactions but must be due to a peaking of the photonuclear absorption cross section.

The (γ, p) reactions peak at slightly higher photon energies than the (γ, n) reactions and their cross sections near the peak are considerably greater. These large cross sections are remarkably independent of wide variations in photonuclear thresholds and of the characteristics of the residual nuclei. These facts can be explained in terms of a primary interaction of high energy photons with nuclear protons.

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Radiation Reaction in Relativistic Motion of a Particle in a Wave Field

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An approximate solution of the equations of motion of Dirac's classical theory f pointlike particles is obtained for a particle in the field of a plane wave, under the assumption that the radiation reaction terms in these equations can be considered as small. The appearance of runaway terms in this solution is avoided by letting the interaction set in gradually. Considerable simplification is achieved by restriction to the domain of high relativistic energies where the transfer of energy and momentum from the wave to the particle appears to be mainly due to radiation reaction. A quantitative discussion of the conditions of applicability of the formulas obtained is made possible by the assumption that there is correspondence between a photon and a classical wave train of finite length. This assumption leads to the conclusion that the classical formulas can be valid for arbitrarily high energies. An estimate of a lower limit for the duration of the interaction between particle and wave train yields an expression which resembles formulas for lifetimes of unstable particles both in its dependence upon fundamental constants and in its increase with the energy involved in the process.

I. INTRODUCTION

THE transfer of linear momentum from a wave to a particle is usually considered as a typical quantum effect, particularly in the E.R.[1] domain. It is the primary purpose of this paper to show that in classical theory such momentum transfers can be accounted for as radiation reaction effects, and that correspondence can be established between relevant results of classical and quantum theory. The equations of motion of Dirac's classical theory of charged, pointlike particles in an electromagnetic[2] field are used as starting point and transformed in a way which simplifies the treatment of the motion of a particle under the influence of a plane wave (Sec. II). A solution of the transformed equations is worked out explicitly in a first approximation, under the assumption that the radiation reaction terms can be considered as small. Runaway terms in this solution are made to disappear by the device of letting the interaction set in gradually, but no attempt is made to prove the consistency of this procedure (Sec. III). Restriction to the E.R. domain leads to simple formulas which are not likely to depend upon any particular assumptions (Sec. IV).

A quantitative discussion of the conditions of applicability of the first approximation is made possible by the assumption that the particle absorbs the energy of a photon while interacting with a wave train of finite length. This leads to the conclusion that the first approximation is likely to be valid for arbitrarily high energies. At first sight such a conclusion seems surprising, since in the N.R. domain the relative order of magnitude of the radiation reaction terms is given by the expression $\frac{2}{3}e^2\omega/mc^3$ (ω angular frequency) which becomes larger than unity for photon energies $\hbar\omega > 205mc^2$. But radiation reaction makes the particle recede in the direction of incidence of the wave. This effect, though small, is cumulative, and can account for large momentum transfers in the E.R. domain. It leads to such a reduction of the frequency of the wave relative to the particle that, on the average, the ratio of the radiation reaction terms to the main terms in the equations of motion does not exceed the order of magnitude of the fine structure constant, $e^2/\hbar c \cong 1/137$ (Sec. V). Analogous results have been previously obtained in the quantum theory of radiation damping.[3]

The same assumptions lead to an estimate of a lower limit for the duration of the interaction between particle and wave train. The expression obtained for this limit

[1] E.R. for extreme relativistic, N.R. for nonrelativistic.

[2] P. A. M. Dirac, Proc. Roy. Soc. (London) **A167**, 148 (1938).

[3] For scattering of photons by charged, spinless particles, the case corresponding to the proposed semiclassical treatment, see E. Gora, Z. Physik **120**, 121 (1943). The present paper originated from an attempt to find a classical analog to the results obtained there.