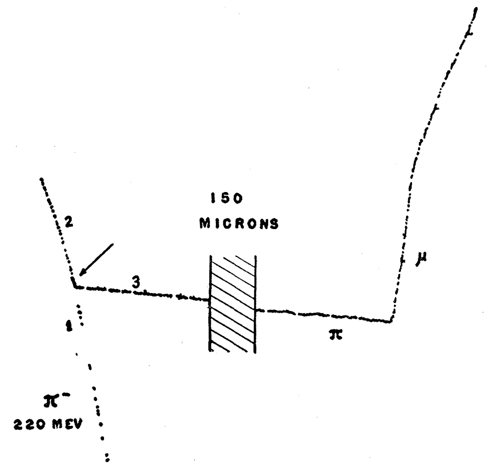

FIG. 1. A projection drawing of a negative π-meson interaction in a photographic emulsion. A positive π meson (track 3) was produced in the collision with a light nucleus.

after 2900 microns. The μ-meson track from the $\pi-\mu$ decay is 610 microns long. A decay electron is observed from the end of the μ-meson track. The event is interpreted as the production of a positive π meson by a negative π meson by a double charge exchange reaction:

$$\begin{aligned} \pi^- + p \text{ (in a nucleus)} &\rightarrow \pi^0 + n, \\ \pi^0 + p \text{ (in the same nucleus)} &\rightarrow \pi^+ + n. \end{aligned} \tag{2}$$

A very crude estimate of the probability per nuclear interaction of positive π-meson production by negative π mesons can be made from the number of π^- meson stars and $\pi-\mu$ decays. A π meson of energy less than about 20 Mev from an interaction will on the average stop in the stack of plates. A lower limit of the probability that a positive π meson of energy less than about 20 Mev will be produced in an interaction is estimated from the ratio of the

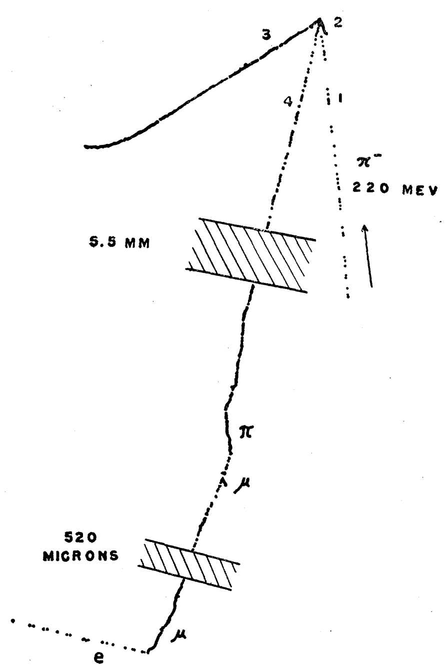

FIG. 2. A projection drawing of a negative π-meson interaction is shown above. A positive π meson (track 4) was produced in the collision.

number of π^+ to π^- times the probability of finding a π^- meson of energy less than 20 Mev from an interaction,

$$(36/415)\times(20/4160)\cong 4\times 10^{-4}.$$

The author is grateful to Professor H. L. Anderson for the use of the facilities of the University of Chicago cyclotron. The author is indebted to Mr. A. Rosenfeld and Mr. J. Orear for their assistance with the exposures and for many helpful discussions. Many discussions with Dr. G. Takeda were helpful.

* Supported in part by the Research Committee of the graduate school from funds supplied by the Wisconsin Alumni Research Foundation.

[1] W. F. Fry, Phys. Rev. **91**, 130 (1953); **84**, 385 (1951). W. F. Fry and George R. White, Phys. Rev. **90**, 207 (1953).
[2] W. F. Fry, Nuovo cimento **10**, 490 (1953); Phys. Rev. **85**, 676 (1952).

Far Ultraviolet Radiation from the Cornell Synchrotron*

P. L. HARTMAN AND D. H. TOMBOULIAN
Cornell University, Ithaca, New York
(Received July 17, 1953)

THE existing experimental studies[1-3] of the properties of the radiation due to transversely accelerated high-energy electrons have been confined to the visible and near ultraviolet regions of the spectrum. An attempt was therefore made to extend the region of observation to the vacuum ultraviolet. Since a grazing incidence spectrograph was available and could readily be modified for this purpose, it was decided to omit the observations in the Schumann region and to proceed directly with the exploration of the soft x-ray region (50A to 500A). The spectrograph was equipped with a lightly ruled 30 000-line grating whose radius of curvature was 154 cm. The grazing angle of incidence was set at 4.5° with a resulting calculated short-wavelength limit of 30A.

The spectrograph slit housing was connected to a porthole in the synchrotron "donut" by sections of tubing containing a vacuum gate-valve provided with a retractable quartz window. The latter was used only in the initial determination of the height and direction of the visible beam prior to positioning of the spectrograph. The valve served to isolate the spectrograph chamber from the "donut" of the synchrotron while the spectrograph was being pumped out. Upon evacuation of the spectrograph, the gate-valve was opened, allowing the radiation to pass through the evacuated interconnecting tube and fall directly upon the slit of the spectrograph.

The radiation is emitted tangentially from the electron orbit and is confined to a narrow cone centered on the instantaneous direction of the motion of the electron. The angular opening of the cone is of the order of 1/600 radian for a 300-Mev electron. This property demands that great care be exercised in aligning the axis of the spectrograph (line joining mid-points of grating and slit) with the axis of the cone of radiation. This adjustment was carried out by first observing through a theodolite the image of a visible spot of light at the orbit as reflected by a mirror placed opposite the quartz window located at the end of the porthole tube. The axial direction of the radiation in space was thus established and the spectrograph was slid into position so that its optical axis fell into coincidence with the direction of the light beam. The latter adjustment was also accomplished with the now fixed mirror and theodolite by sighting through them at two reference points fixed in the body of the spectrograph. The reference points were previously so located as to define the axis of the spectrograph. The final alignment was further verified by the use of a photocell placed within the spectrograph so as to detect the light from the central image when the usual trap for the central image was moved out of the way. The various runs reported here were exploratory in nature and were designed to determine whether the radiation could be detected within reasonable exposure times and, if so, to gain qualitative information concerning the intensity distribution and the possible existence of a short-wavelength limit to the continuous spectrum.[4] Hence, in all the exposures but one, the electrons were accelerated to the peak energy of the synchrotron (310 Mev) so that the spectrum corresponds to the integral of the instantaneous power spectrum over an acceleration cycle. In one run, by turning off the rf voltage early in the acceleration cycle, the maximum energy was lowered to 220 Mev. The exposure times, under the particular operating conditions of the synchrotron, were of the order of 30 minutes except for the low-energy run. With Ilford QI plates, good photographic densities were obtained with the above exposure times.

The following observations are derived by inspection of the photographic records dealing with various runs at the peak energy.

a. A strong continuum is present in the soft x-ray region, which for 310-Mev electrons appears to extend at least down to the instrumental short-wavelength cutoff which is observed to set in at about 55A.

b. The photographic negatives over the 50 to 400A spectral range show no marked density variations, with no sudden drop over the short-wavelength region available under the particular conditions of detection.

c. When thin metallic foils of Be and Al are introduced into the path of the undispersed radiation, the characteristic K and $L_{2,3}$ absorption edges of Be and Al, respectively, are strongly recorded in two orders. (The Be K edge is located at 110A, while the $L_{2,3}$ edge of Al is at 170A.)

d. For the 220-Mev run, the microphotometer trace shows a gradual but definite increase in density, from about 60A on, and attains a peak in the vicinity of 170A, diminishing gradually towards longer wavelengths.

The height of the recorded continuous spectrum here is much smaller than the height of images of line spectra photographed with the same highly astigmatic spectrograph. This characteristic is probably the result of the fact that the space distribution of the radiation is very different from that of conventional light sources.

Various tests have definitely established the absence of fogging of the spectral plates by gamma rays or other sources such as the light from the injector filament. An attempt will be made to carry out a photometric reduction of the plates in order to obtain more quantitative information concerning the spectral energy distribution, at least over that part of the spectrum involving no overlap of the various orders of the instrument.

It is a pleasure to acknowledge the generous assistance of many members of the staff of the Nuclear Laboratory. We also wish to thank the director, Dr. R. R. Wilson, for his continued interest in the problem.

* This work was supported by the Office of Ordnance Research, U. S. Army.

[1] Elder, Langmuir, and Pollock, Phys. Rev. **74**, 52 (1948).
[2] P. Hartman and D. Tomboulian, Phys. Rev. **87**, 233 (1952).
[3] D. Corson, Phys. Rev. **90**, 748 (1953).
[4] J. Schwinger, Phys. Rev. **75**, 1912 (1949).

The Theory of Coulomb Excitation of Nuclei

K. ALDER* AND A. WINTHER
Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark
(Received July 28, 1953)

THE possibility of exciting nuclear states by the electric field of impinging charged particles has been discussed by several authors. We shall here follow the formulation of the theory of the Coulomb excitation process as given by Ter-Martirosyan.[1,2]

The feasibility of performing experiments of this type has recently been demonstrated,[3] and we here report numerical results of use in the application of the theory to the interpretation of the experiments.

The basis for the theory is that the trajectory of the impinging particle can be described by classical mechanics. This is possible if

$$\kappa = 2Z_1Z_2e^2/\hbar v \gg 1 \tag{1}$$

and if the particle loses only a small fraction of its energy in the collision. In the expression (1), Z_1 and Z_2 refer to the charge numbers of the projectile and the target nucleus respectively, and v means the relative velocity.

Usually one will bombard with energies below the Coulomb barrier to ensure that no nuclear interaction takes place, and thus $\kappa \gg 1$ is fulfilled. As the excitation probability is small, one may use quantum-mechanical perturbation theory to find the cross section. The perturbation energy is

$$V(t) = \sum_{p=1}^{A} \frac{Z_1 e_p^2}{|\mathbf{r}_p - \mathbf{r}(t)|}, \tag{2}$$

where $\mathbf{r}_p$ are the coordinates and e_p the charges of the nucleons in the target nucleus, and $\mathbf{r}(t)$ is the coordinate of the projectile in the classical hyperbolic orbit. It is now convenient to expand (2) in multipole components. One gets in this way an expression for the excitation probability as a sum over multipole components. Each term will be proportional to the square of the usual nuclear matrix element for emission of electric 2^n-pole radiation and a definite function $S^{(n)}$ of the orbit of the projectile.

Particularly well suited for Coulomb excitation are the rotational states in rather heavy nuclei for which the quadrupole component of the nuclear matrix elements are especially big.[4] Also the conditions for the semi-classical treatment are well satisfied here.

By taking n equal to 2 and performing an integration over the different orbits, one gets

$$\sigma_{\text{incl}} = \frac{4\pi^2}{25} \cdot \frac{m}{Z_2^2 e^2 \hbar} E B_e(2) g_2(\xi) \tag{3}$$

for the total inelastic cross section for excitation by the electric quadrupole field. The reduced mass is denoted by m, and E is the kinetic energy in the center-of-mass system. The energy-independent quantity

$$B_e(2) = \sum_{\mu, M_f} |\langle i | \sum_{p=1}^{A} e_p r_p^2 Y_{2,\mu}(\theta_p, \varphi_p) | f \rangle|^2 \tag{4}$$

is the reduced transition probability for the electric quadrupole excitation from the initial state i to the final state f with the magnetic quantum number M_f. Further, the $Y_{2,\mu}$ are the normalized spherical harmonics depending on the polar angles θ_p, φ_p of the nucleons in the target nucleus. The function $g_2(\xi)$ depends on the energy through the variable

$$\xi = \frac{\Delta E}{2E} \frac{Z_1 Z_2 e^2}{\hbar v}, \tag{5}$$

which measures the ratio of the collision time to the nuclear period, ΔE being the nuclear excitation.

The function $g_2(\xi)$ is given by

$$g_2(\xi) = \sum_{\mu} \int_1^{\infty} |S_\mu^{(2)}|^2 \epsilon d\epsilon, \tag{6}$$

where ϵ is the eccentricity of the orbit, and where the non-vanishing components of $S^{(2)}$ are

$$\begin{aligned} S_0^{(2)} &= \int_{-\infty}^{\infty} \exp[i\xi(\epsilon \sinh\omega + \omega)] \frac{1}{(\epsilon \cosh\omega + 1)^2} d\omega, \\ S_{\pm 2}^{(2)} &= -\sqrt{\tfrac{3}{2}} \int_{-\infty}^{\infty} \exp[i\xi(\epsilon \sinh\omega + \omega)] \\ &\qquad \times \frac{[\cosh\omega + \epsilon \mp i(\epsilon^2 - 1)^{\frac{1}{2}} \sinh\omega]^2}{(\epsilon \cosh\omega + 1)^4} d\omega. \end{aligned} \tag{7}$$

These integrals have been evaluated numerically, and the resultant function g_2 is given in Fig. 1.

The yield of γ quanta following the Coulomb excitation provides a measure of the cross section for the excitation. The direction of these quanta is, however, correlated with the direction of the incident particles and the angle in which the exciting projectile is scattered. If one measures only the angle of emission of the γ rays