Coulomb Dissociation of Beam Particles*

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The possibility of the dissociation of beam particles by the Coulomb field of the nucleus is discussed. The process is very similar in nature to the well-known electromagnetic processes of pair production and bremsstrahlung. Analogous processes might be (a) $\pi^+ + {}_zN^A \rightarrow \bar{p} + n + {}_zN^A$, and (b) $p + {}_zN^A \rightarrow p + \pi^0 + {}_zN^A$. These processes will probably have a sizeable cross section for occurrence at energies greater than 74 Bev for (a) and 14 Bev for (b) if Pb is used as the target material. The useful feature of this sort of reaction is that in essence one can do photoproduction experiments on unstable particle targets. (Piccioni has pointed out the possibility of disintegrating π mesons.) Cross-section estimates for dissociation can be made using the Weizsäcker-Williams approach.

It is possible to change the mass state of a particle only as the result of an interaction with another particle. As the momentum of a particle is raised, its energy will differ only very little from that of a more massive particle of the same momentum. Consider particles of masses M and M^*. Their energies at a momentum P are given by $(P^2+M^2)^{\frac{1}{2}}$ and $(P^2+M^{*2})^{\frac{1}{2}}$. If the momentum $P \gg M$, M^* then the difference between their energies is $(M^{*2}-M^2)/2P$. The theoretical consequence of this result is that a particle of mass M can make a virtual transition into a state of mass M^* and then can stay in that state a time of the order of $2P/(M^{*2}-M^2)$ (setting $\hbar = c = 1$). Obviously as P becomes larger and larger the time gets stretched out, and virtual states corresponding to more massive systems can live a relatively long time. Another way of considering this is in the rest system of the particle of mass M. The virtual state can exist a time of the order of $1/(M^*-M)$. In a Lorentz frame in which the particle is in motion this time is then stretched by the Lorentz time dilation.

One can hope to observe the intermediate state directly by "bumping" the object up onto the energy or mass shell by giving the particle a small longitudinal kick. The momentum which needs be transferred is just $(M^{*2}-M^2)/2P \ll (M^*-M)$ so that the struck particle, if it is massive, absorbs virtually no energy in the process. It is possible for the momentum transfer to be accomplished by a Coulomb field. This picture describes what happens for example in bremsstrahlung or pair production. In those cases the intermediate states are $e \rightarrow e + \gamma$ and $\gamma \rightarrow e^+ + e^-$. The consequences of the long lifetime of the intermediate state have been explored quite thoroughly in the case of the photon-electron system in a series of papers.[1,2] In these papers coherence effects extending over many atomic diameters are predicted; there has been considerable experimental verification of these results.[3]

The main point of this note is that the same sort of analysis can be done for other elementary particles. Consider, for example, the $\pi^- \rightarrow \bar{p} + n$. If the energy of the π is sufficiently high, then the intermediate state will propagate for distances the order of 10^{-12} centimeter and thus can be brought to life with a relatively small longitudinal kick (~ 20 Mev/c) in the Coulomb field. Then one can observe a reaction of the type $\pi^- + {}_zN^A \rightarrow \bar{p} + n + {}_zN^A$. In Table I is given a list of reactions that might conceivably be studied by means of this Coulomb scattering process.[4]

Table I is not intended to be a comprehensive list, but merely to show the possible richness of this mode of approach to high-energy physics.

Physically, what the process amounts to is photodissociation of beam particles, as may be seen by the Weizsäcker-Williams approach. The advantage is that

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[1] See the excellent summary by E. L. Feinberg and I. Ia. Pomerancuk, Suppl. Nuovo cimento **3**, 652 (1956). At least a partial list of papers having to do with the physical consequences of long-lived intermediate states in electrodynamic processes are as follows: (a) E. J. Williams, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **13**, 276 (1935). (b) B. Ferretti, Nuovo cimento **7**, 118 (1950). (c) L. D. Landau and I. Ia. Pomerancuk, Doklady Akad. Nauk S.S.S.R. **92**, 535 (1953); Doklady Akad. Nauk S.S.S.R. **92**, 735 (1953). (d) M. L. Ter-Mikaeljan, J. Exptl. Theoret. Phys. (U.S.S.R.) **25**, 289 (1954); J. Exptl. Theoret. Phys. (U.S.S.R.) **25**, 296 (1954). (e) A. B. Migdal, Doklady Akad. Nauk S.S.S.R. **96**, 49 (1954); Doklady Akad. Nauk S.S.S.R. **105**, 77 (1955); J. Exptl. Theoret. Phys. (U.S.S.R.) **32**, 633 (1957) [translation: Soviet Phys. JETP **5**, 527 (1957)]. (f) H. Überall, Phys. Rev. **103**, 1055 (1956); **107**, 223 (1957). (g) F. J. Dyson and H. Überall, Phys. Rev. **99**, 604 (1955). (h) A. B. Migdal and N. M. Polievktov-Nikoladze, Doklady Akad. Nauk S.S.S.R. **105**, 233 (1955).

[2] The possibility of photodisintegration of nuclei has been considered by: (a) S. M. Dancoff, Phys. Rev. **72**, 1017 (1947). (b) M. Ia. Kobiashvili, J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 1505 (1957) [translation: Soviet Phys-JETP **6**, 1162 (1958)].

[3] (a) T. G. Volkonskaia, I. P. Ivanenko and G. A. Timofeev, J. Exptl. Theoret. Phys. (U.S.S.R.) **35**, 293 (1958) [translation: Soviet Phys-JETP **8**, 202 (1959). (b) O. R. Frisch and D. H. Olson, Phys. Rev. Letters **3**, 141 (1959). (c) G. Bologna, G. Diambrini and G. P. Murtas, Phys. Rev. Letters **4**, 134 (1960). (d) A. N. Saxena, Phys. Rev. Letters **4**, 311 (1960).

[4] The table includes cases in which apparently parity, angular momentum, and isotopic spin are not conserved. The reason for this is that the orbital angular momentum can change as a result of the longitudinal kick in the Coulomb field. The most probable impact parameter for a change of momentum q is given by $q=1/r$. Thus it may be seen that $|\mathbf{q}\times\mathbf{r}| \approx 1$ which means that the orbital angular momentum can change by 1 (or more) unit. This angular momentum goes into the products. This result is well known in the case of bremsstrahlung and pair production [F. J. Dyson and K. McVoy, Phys. Rev. **106**, 1360 (1957)]. In the case of photon reactions it is well known that isotopic spin can be changed.

TABLE I. Possible reactions.

Reaction	Threshold in carbon in Bev	Threshold in Pb in Bev
(1) $\pi \to 2\pi$	0.500	1.2
(2) $\pi \to 3\pi$	1.3	3.3
(3) $\pi \to K+\bar{K}$	8	21
(4) $\pi \to K+\bar{K}+\pi$	11	27
(5) $\pi \to \bar{p}+n$	29	74
(6) $\pi \to \Sigma+\bar{\Lambda}^0$	45	114
(7) $K \to K+\pi$	1.3	3.3
(8) $K \to K+2\pi$	3.0	8.0
(9) $K \to K+K+\bar{K}$	17	43
(10) $K^+ \to \bar{\Sigma}^-+n$	39	100
(11) $K^+ \to \bar{\Xi}^-+\Lambda^0$	54	138
(12) $\mu^+ \to B^+ + \nu$	8	22
(13) $\mu^+ \to \pi^+ + \nu$	0.18	0.32
(14) $p \begin{cases} \to n+\pi^+ \\ \to p+\pi^0 \end{cases}$	(in 3, 3 state) 5.4	14
(15) $p \to \Lambda^0 + K^+$	14	38

unstable particles can be used as the target, as Piccioni has pointed out.[5]

The thresholds in Table I were computed by figuring the most energetic photon to be found in the field of the nucleus (i.e., $q=1/r_0A^{\frac{1}{3}}\cong m_\pi/A^{\frac{1}{3}}$) and then using the formula $q=(M^{*2}-M^2)/2p$. The threshold energies also mean that the M^* is equal to the mass of the products. Thus to get reasonable yields from a given reaction, experiments should be done at the order of 1.5 to 2 times the threshold energies. By using photoproduction cross sections with the Weizsäcker-Williams method one can estimate yields. The formula is

$$\sigma=\frac{3}{2\pi}Z^2e^2\int_{K_{\rm th}}^{K_{\rm max}}\sigma_\gamma\frac{dK}{K}\ln\frac{\gamma m_\pi}{KA^{\frac{1}{3}}}, \tag{1}$$

where σ_γ = photoproduction cross section for the process considered, $K_{\rm th}$ = the photon threshold for whatever process is being discussed, and $K_{\rm max}$ = maximum photon energy available in the Coulomb field.

For an incoming proton we have calculated the cross section for single pion production (reaction 14) in the Coulomb field. If one added in addition the cross section for multiple and strange particle reactions the cross section will be increased by $\approx 20\%$. The results are shown in Table II.

TABLE II. Photodisintegration of protons on lead.

E in Bev	50	100	200	500	1000
σ in mb	6.9	10.0	13.0	18.0	21.0

This calculation is admittedly rough and only an exercise as one would probably not gain much new insight by studying photopion production in this fashion since σ_γ is already known for this process. The calculations are, however, important in obtaining a feeling for what energies are necessary before such experiments become feasible and useful. One can estimate the cross section of any of these strong reactions roughly by using $\sigma_\gamma=e^2/m^2$, where m is the mass of the lightest product. Substituting this in (1) gives

$$\sigma=\frac{3}{4\pi}\frac{Z^2e^4}{m^2}\left[\ln\frac{2(P/m_\pi)}{[(M_{\rm min}{}^*/m_\pi)^2-(M/m_\pi)^2]A^{\frac{1}{3}}}\right]^2, \tag{2}$$

where M^* = rest energy of the products, i.e., energy of products $=\gamma^*M^*$, $\gamma^*=1/(1-\beta^{*2})^{\frac{1}{2}}$; $M_{\rm min}{}^*$ = rest masses of the products.

Detailed calculations have also been done on reactions (5) and (12).[6] In the case of reaction (5) there is a question of the effect of strong final-state interactions. For this reason we do not publish the results. In the process $\pi^- \to \bar{p}+n$ [reaction (5)] if the nucleon-antinucleon pair had very small relative energy (i.e., $M^*=2\times$nucleon mass) then the nucleons would presumably usually annihilate. Thus it is possible that what would be found would be a bump in the measured M^* spectrum for the π meson.

In the case of transitions involving weak interactions (i.e., $\mu^+ \to B^+ + \nu$), we know of no such complicating effect. Since the vector boson B^+ (if it exists) would presumably not have strong interactions.

In conclusion reactions of the type discussed may provide a very useful tool for probing into the structure of fundamental particles.

[5] The possibility of reaction No. 1 was first suggested by O. Piccioni at the Ninth Annual International Conference on High-Energy Physics, Kiev, 1959 (to be published). The cross section for this reaction may be quite large if indeed there is a resonance in the $I=1$, $J=1$ system as suggested by W. R. Frazer and J. R. Fulco, Phys. Rev. Letters **2**, 365 (1959).

[6] M. Ebel and W. D. Walker (to be published).