$\frac{2}{3}\lambda \log_{10}2 = 0.20\lambda$ in the direction of the ordinate axis, as compared to those for protons. The shift determined from the figure has a value of about 0.44, which thus confirms the expected $E2$ character of the excitation. The small difference from the theoretical value 0.40 may well be due to the experimental uncertainties.

Since the function $f_2\{\xi\}$ is known,[4] one can also compare the experimental ξ-dependence with the theory. The theoretical curves shown in Fig. 2 have been normalized at the experimental point corresponding to 1.75-Mev protons. The measurements are seen to confirm the theoretical calculations of the excitation function. The experimental accuracy is not quite sufficient to test to what extent the bombarding energy should be corrected for the energy loss in the excitation process. The comparison provides, nevertheless, still a relatively critical test on the evaluation of ξ, and can therefore be considered as a check on the value used for $Z_2\Delta E$. This can be an aid in cases where the assignment of a particular peak is not clear.

The kind of particle one should use in a given case in order to get the highest absolute yield is determined by the bombarding energy available. This is illustrated by Fig. 3, where the $E2$

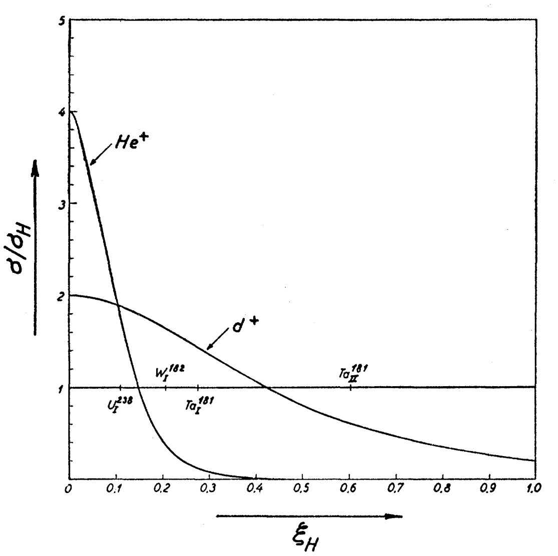

FIG. 3. Ratio of theoretical values for $E2$ excitation cross sections for deuterons and α particles, to those for protons accelerated with the same high voltage, plotted as a function of $\xi_H = Z_2\Delta E/(13U^{\frac{1}{2}})$, where ΔE is the excitation energy in Mev and U the voltage in Mv. $4(\sigma_d/\sigma_H)$ gives the curve for α particles accelerated as He^{++} ions. The marks give the ξ_H values for the first (I) and second (II) excited state corresponding to $U=2$ Mv.

excitation cross sections calculated by means of Eqs. (1) and (2) are compared for the various particles. The use of protons is evidently advantageous for the higher excitation energies. For lower excitation energies the heavier projectiles are the most suitable, and in particular so, because the background radiation found in this region is much smaller for slow particles. This is demonstrated by the appearance of the K lines shown in Fig. 1. In the spectrum obtained with protons[7] these lines were concealed by the background of stopping electrons, which was an order of magnitude larger than in the case of deuterons.

Similar considerations apply to the γ-ray experiments,[5,8] which are preferable when the conversion coefficients are small. In using Fig. 3, however, it should be remembered that thick-target measurements give relatively larger yields for protons because of their longer range.

The processes responsible for the background radiation from the target atoms are discussed in the following Letter.

[1] We are grateful to A. Bohr and B. Mottelson for bringing this point to our attention.

[2] K. A. Ter-Martirosyan, J. Exptl. Theoret. Phys. U.S.S.R. **22**, 284 (1952).
[3] See A. Bohr and B. Mottelson [Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **27**, No. 16 (1953)], whose notation we follow.
[4] K. Alder and A. Winther, Phys. Rev. **91**, 1578 (1953). The function $g_2\{\xi\}$ given by these authors is equal to $25f_2\{\xi\}/2\pi^2$.
[5] G. M. Temmer and N. P. Heydenburg [Phys. Rev. **93**, 351 (1954)] have produced Coulomb excitation by α particles as well as by protons, and their results are consistent with the $E2$ character of the process, in the cases studied.
[6] A small contribution to the peak should come from the first excited state in W^{183}, the energy of which, however, is only slightly larger than for W^{182}. [C. L. McClelland and C. Goodman, Phys. Rev. **93**, 904 (1954)]. The most precise value for the first excited state of W^{182} seems to be that obtained from the work of Muller, Hoyt, Klein, and DuMond [Phys. Rev. **88**, 775 (1952)].
[7] T. Huus and J. H. Bjerregaard, Phys. Rev. **92**, 1579 (1953).
[8] D. Hill, Phys. Rev. **93**, 923 (1954).

Emission of δ- and X-Rays from Targets Bombarded by Accelerated Ions

ČRTOMIR ZUPANČIČ* AND TORBEN HUUS
Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark
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WHEN one bombards elements with protons or heavier ions of such a low energy that they cannot penetrate into the nucleus, then nuclear reactions are confined to Coulomb excitation. In addition one observes other inelastic events, which are due to the ejection of atomic electrons and to bremsstrahlung in the Coulomb field of the nucleus. In the present note we discuss some measurements on these latter radiations, which provide the most important background in Coulomb excitation experiments.

The cross section for the ejection of K electrons from atoms bombarded with heavy charged particles has been calculated by Henneberg.[1] He used plane waves to represent the bombarding particles and nonrelativistic wave functions for the electrons. In this approximation the differential cross section per atom (i.e., per two K electrons) for ejection of a K electron with an energy E_δ, is given by

$$d\sigma_K \simeq 1.4\times 10^{-8} Z_1^2 e^4 (E_1/A_1)^4 E_K^3 (E_K+E_\delta)^{-10} dE_\delta, \qquad E_K \gg E_0 \quad \text{or} \quad E_\delta \gg E_0, \tag{1}$$

where Z_1e is the charge, A_1 the mass number, and E_1 the energy of the bombarding particle. The expression is valid if the binding energy E_K is large compared to the maximum energy E_0 which an electron can obtain in a free collision with the bombarding particle. By integrating (1) over E_δ, one can in this case easily obtain the total cross section for ionization of the K shell. However, regardless of the magnitude of E_K, Eq. (1) should hold for the higher energies in the spectra, i.e., for $E_\delta > E_0$.

In this region the yields of electrons found experimentally by bombardment with protons, deuterons, and α particles[2] correspond to cross sections of the order[3]

$$d\sigma \simeq 10^{-16} Z_1^2 e^4 (E_1/A_1)^4 Z_2^4 E_\delta^{-7} dE_\delta, \tag{2}$$

for $E_1 \simeq 1$ to 2 Mev, $E_\delta \simeq 40$ to 100 kev, and $Z_2 \simeq 50$ to 80. Z_2 is the atomic number of the target material. The electrons were measured in a broad angular region around 90°, and anisotropy has been disregarded in the evaluation of the total 4π cross section (2). Thick target yields can be estimated from (2) by assuming that the electrons are produced in an effective layer of thickness t, where $t \simeq 2\times 10^{-3} E_\delta^2$ mg/cm² for E_δ in kev.

The form of (2) is similar to (1), but the magnitude is much larger. For the heavier elements already the number of electrons in the investigated part of the spectrum is larger than the total number of the ejected K electrons as deduced from x-ray measurements.[4,5] The observed electrons are therefore probably mainly L electrons. For this high-energy region of the spectrum, relativistic effects are important; theoretical estimates indicate that a relativistic treatment may yield cross sections in closer agreement with (2).

The yield of the characteristic K, L, and M x-rays, which are emitted in the de-excitation process, have been studied by a number of investigators. Recent measurements[4,5] of the K x-rays gave cross sections in rough agreement with Henneberg's theory. Deviations were found especially in heavy elements and for high bombarding energies and were attributed to relativistic effects.[4]

Another contribution to the radiation from the targets comes from the bremsstrahlung produced by the bombarding particles.

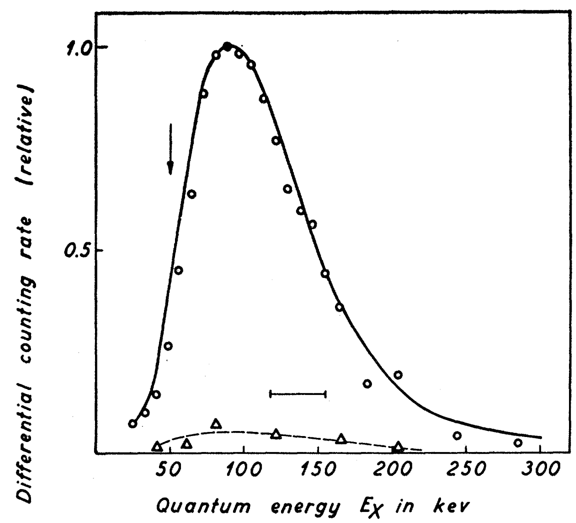

FIG. 1. The experimental points give the spectrum of x-rays from a thick Sn target bombarded with 1.75-Mev protons. Measurements were made at 90°. The theoretical spectrum (solid curve) is normalized at the highest experimental point. The dashed curve shows the background. The arrow indicates the energy at which the absorber (about 2 mm Cu) reduced the intensity by a factor 100. For comparison the experimental half-width of the 137-kev line (see reference 5) in Ta is indicated by the horizontal bar. Under the present conditions this line would have a relative height of about 5.

Sommerfeld and his collaborators[6] have calculated the rate of emission of dipole quanta for the cases in which nonrelativistic particles are deflected in the Coulomb field of the target nuclei. They find for the differential cross section, after integrating over all angles:

$$d\sigma_X=(16\pi/3^{\frac{3}{2}})137r_0^2\alpha_i^2FGdE_X/E_X \quad \text{for } \alpha_i\gg 1, \tag{3}$$

with

$$F=1 \quad \text{for } \alpha_f-\alpha_i\gg 1, \tag{4a}$$

$$F=(\sqrt{3}/\pi)(\alpha_f/\alpha_i)\log_e\{(\alpha_f+\alpha_i)/(\alpha_f-\alpha_i)\} \quad \text{for } \alpha_f-\alpha_i\ll 1, \tag{4b}$$

where

$$\alpha_{i,f}=Z_1Z_2e^2/\hbar v_{i,f}. \tag{5}$$

Here $r_0=e^2/mc^2$ is the classical radius of the electron, while v_i and v_f are the relative velocities of the bombarding particle before and after the collision, respectively. E_X is the energy of the bremsstrahlung quantum.

In the case of electrons the factor G equals 1, while for positive particles impinging on nuclei with mass number A_2, this factor is given by

$$G=(1836)^{-2}(Z_1/A_1-Z_2/A_2)^2\exp\{-2\pi(\alpha_f-\alpha_i)\}. \tag{6}$$

By bombarding heavy elements with protons,[5] we have found continuous x-radiation in approximate agreement with the aforementioned cross sections. It was found for all the elements investigated (e.g., Ag, Sn, Sb, W, Au, Pb), whenever it was not hidden by other phenomena. In most cases the amount of higher-energy γ rays was small, so that no explanation in terms of backscattering or Compton peaks was possible.

Figure 1 shows the x-ray spectrum measured when Sn was bombarded with 1.75-Mev protons. The theoretical curve (solid line) was obtained by computing the thick-target yields by means of Eqs. (3)–(6) and correcting for absorption, crystal sensitivity, and counter resolution. Since $\alpha_f-\alpha_i\lesssim 1$, we computed F from (4b), which gives a value of about 2 in the present region of interest, where it is not sensitive to the energy of either the protons or the x-rays. Anisotropy was disregarded. The curve was normalized at one of the experimental points, but within the experimental uncertainty of 50 percent the absolute theoretical yield also agreed with the measured one. Furthermore, spectra of Sn were taken at different bombarding energies and with various absorbers, and the results were found to be in agreement with theory.

The expressions (3) to (6) are valid for a bare nucleus. Some x-radiation should also be produced by the atomic electrons, partly during the collision with the incident particle, and partly during the subsequent stopping of ejected electrons. However, in the example of Sn considered above, this contribution to the x-radiation can presumably be neglected, since, in the region considered, the cross section given by Eqs. (3) to (6) for emission of proton bremsstrahlung is larger than the experimental cross section (2) for ejection of electrons of corresponding energy. This might not be true for lower quantum energies or heavier elements. In the case of α particles (and deuterons), the factor G appearing in the dipole cross section may be so small [see (6)] that higher-order terms become important.

* On leave from the "J. Stefan" Institute of Physics, Ljubljana, Yugoslavia.

1 W. Henneberg, Z. Physik **86**, 592 (1933); see also D. R. Bates and G. Griffing, Proc. Phys. Soc. (London) **A66**, 961 (1953).

2 T. Huus and J. H. Bjerregaard, Phys. Rev. **92**, 1579 (1953) and preceding letter [Phys. Rev. **94**, 204 (1954)].

3 The powers given are only approximately correct. In particular, the actual electron yields were decreased less than 16 times, when deuterons were used instead of protons.

4 Lewis, Simmons, and Merzbacher, Phys. Rev. **91**, 943 (1953). This paper includes references to previous work.

5 T. Huus and Č. Zupančič, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **28**, No. 1 (1953). (N.B. In Sec. 8, line 8, read "larger" instead of "smaller.")

6 A. Sommerfeld, Ann. Physik (5) **11**, 257 (1931); O. Scherzer, Ann. Physik (5) **13**, 137 (1932); G. Elwert, Ann. Physik (5) **34**, 178 (1939); see also: A. Sommerfeld, *Atombau und Spektrallinien* (F. Vieweg und Sohn, Braunschweig, 1939), Vol. 2, pp. 495–567.

Low-Lying States of Be^8

E. W. TITTERTON
Research School of Physical Sciences, Australian National University, Canberra, Australia
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In a recent letter Malm and Inglis[1] reviewed some of the evidence relating to the low-lying levels of Be^8 and gave new results for the reaction $B^{11}(p,\alpha)Be^8$ leading only to the well-established ground and first excited states. This reaction, like $B^{10}(d,\alpha)Be^8$ recently investigated by Treacy[2] in this laboratory, suffers from the difficulty that the continuum of α particles from the breakup of Be^8 itself tends to obscure α-particle groups corresponding to states which may be weakly excited.

Although, in principle, information on other states can be derived from the shape of the spectrum, the analysis is difficult and, for this reason, these two reactions do not readily give information about levels other than the ground and first excited states.

It is the purpose of this note to outline evidence from other reactions, especially ones studied in this laboratory, which suggest even states of Be^8 at 4.05, 5.3, and 7.5 Mev and provide evidence against a state at 4.9 Mev de-exciting by γ-ray emission.

(a) *The 4.05-Mev Level.* The first evidence for this state came from the work of Gibson and Green[3] in the neutron spectrum from $Li^7(d,n)Be^8$. That it has even properties was indicated by the observation of breakup into α particles by Calcraft and Titterton[4] in the reaction $B^{11}(\gamma,t)Be^8$ and by Brinkworth and Titterton[5] in the reaction $B^{10}(\gamma,d)Be^8$. Recently, in this laboratory,[6] it has