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.

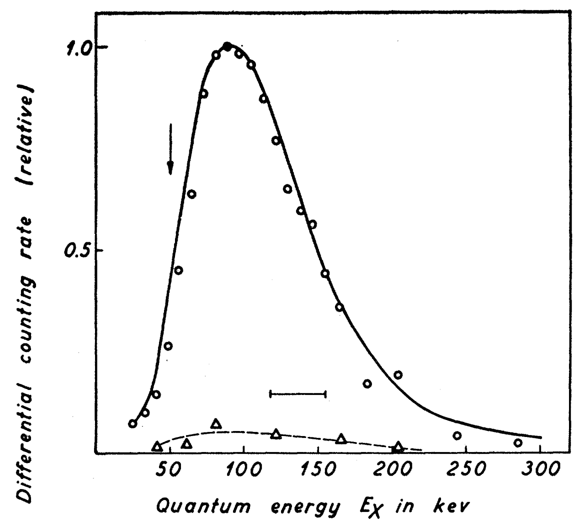

FIG. 1. The experimental points give the spectrum of x-rays from a thick Sn target bombarded with 1.75-Mev protons. Measurements were made at 90°. The theoretical spectrum (solid curve) is normalized at the highest experimental point. The dashed curve shows the background. The arrow indicates the energy 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:

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

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

$$\alpha_{i,f} = Z_1 Z_2 e^2/\hbar v_{i,f}. \tag{5}$$

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
(Received February 15, 1954)

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 been demonstrated by means of a $\gamma-\alpha$ coincidence experiment that a γ-ray transition from the 17.63-Mev (1+) state of Be^8 occurs to the level concerned. In 1952 Trumpy, Grotdal, and Graue[7] repeated the $Li^7(d,n)Be^8$ experiment, confirmed the presence of a state at 4.1 Mev, and suggested a new state at 2.2 Mev. More recently, the Bristol group,[8] using the same reaction, have clearly resolved a group corresponding to a level at 4.05 Mev and at the same time confirm the presence of a group corresponding to a state at 2.2 Mev. Later, photodisintegration experiments[9,10] on the reactions $B^{11}(\gamma,t)Be^8$ and $B^{10}(\gamma,d)Be^8$ confirm the results mentioned in the foregoing.

(b) *Evidence against a 4.9-Mev γ-Emitting State*. In our photographic plate experiments on $B^{10}(\gamma,d)Be^8$ and $C^{12}(\gamma,\alpha)Be^8$ with γ rays from the $Li^7(p,\gamma)$ 440-kev resonance, we have made a careful search for events which would correspond to formation of a γ-emitting state of Be^8 at 4.9 Mev. Such events would be characterized by an energy deficit of 4.9 Mev, the presence of two low-energy α particles from the ground state of Be^8 (provided the lifetime of the state is shorter than 10^{-12} sec) and, since the γ-ray momentum is negligible, the events should still satisfy momentum balance. Such events have not been observed in the boron experiments. However, "low-energy" events are observed in the $C^{12}(\gamma,\alpha)Be^8$ experiment but, in general, they are not characterized by the presence of the ground state of Be.[8] It has been shown[11,12,6] that they correspond to a weak γ-ray line in the $Li^7(p,\gamma)$ spectrum located at 12.3 Mev. These results, while not conclusive, indicate that, if a 4.9-Mev state of Be^8 exists at all, it is either long-lived or does not lead to γ-ray emission.

The original suggestion of the level came from the Rice group[13] who detected γ rays of 4.9-Mev energy in the $Li^7(d,n)Be^8$ reaction. If their interpretation is correct, the γ ray should be in coincidence with a neutron. Such coincidences have been searched for in an an experiment undertaken in the University of Melbourne,[14] the preliminary results of which are against the presence of coincidences.

The conclusions of these experiments are supported by recent work at the Rice Institute,[15] where it is now believed the original results can be explained as due to effects arising from the competing reaction $Li^7(d,p)Li^8(\beta^-)$.

(c) *The 5.3-Mev State of Be⁸*. The first evidence for a state in this general vicinity came from the photodisintegration reactions,[4,5] $B^{10}(\gamma,d)Be^8$ and $B^{11}(\gamma,t)Be^8$. Apart from this, several observers noticed the "low-energy" $C^{12}(\gamma,3\alpha)$ events induced by the $Li^7(p,\gamma)$ radiation which were mentioned above. Nabholz, Stoll, and Wäffler[11] suggested that they were caused by a γ ray of 12.7-Mev energy formed in a cascade transition via the reported 4.9-Mev state of Be^8. It was shown by Titterton[12] that this was unlikely and the alternative suggestion was made that the transition took place through the even state of Be^8 at 5.3 Mev observed in the photodisintegration experiments. To elucidate the point, a $(\gamma-\alpha)$ coincidence experiment was undertaken in this laboratory by Inall and Boyle,[6] the results of which confirm the presence of the 5.3-Mev state.

The new work at Bristol[8] on the neutron spectrum from $Li^7(d,n)Be^8$ gives further confirmation of these results—a clearly separated group is found corresponding to a state at 5.2 Mev.

(d) *The 7.5-Mev State of Be⁸*. Evidence for this broad level was given by Richards[16] [$Li^7(d,n)Be^8$] and confirmed by Green and Gibson[3] in later experiments. The $(\gamma-\alpha)$ coincidence experiment[6] mentioned above gives direct confirmation of the assignment, and a recent $\alpha-\alpha$ scattering experiment by Steigert and Sampson[17] requires a state at 7.65 Mev, of spin zero, for its interpretation. This spin assignment is compatible with the γ-ray intensity observed in the $Li^7(p,\gamma)$ Canberra experiment[6] which implies a magnetic dipole or electric quadrupole transition.

The body of evidence outlined above strongly indicates the presence of even states of Be^8 at 4.05, 5.3, and 7.5 Mev, and a study of the $(\gamma-\alpha)$ angular correlations in the reaction $Li^7(p,\gamma)Be^8 \times(\alpha)He^4$ currently in progress in this laboratory should enable spin assignments to be made in due course.

In addition to these levels, others have been suggested in the energy region under consideration, namely: 2.2 Mev,[7,8,10] 3.4 Mev,[10] 4.62 Mev,[18] 4.9 Mev (even state; not γ emitter),[10] and 6.8 Mev.[10] As pointed out by Malm and Inglis in their Letter, more experimental evidence is required before these can be regarded as established.

1 R. Malm and D. R. Inglis, Phys. Rev. **92**, 1326 (1953).
2 P. B. Treacy, Phil. Mag. **44**, 325 (1953).
3 L. L. Green and W. M. Gibson, Proc. Phys. Soc. (London) **62**, 407 (1949).
4 M. E. Calcraft and E. W. Titterton, Phil. Mag. **42**, 666 (1951).
5 M. J. Brinkworth and E. W. Titterton, Phil. Mag. **42**, 952 (1951).
6 E. K. Inall and A. J. F. Boyle, Phil. Mag. **44**, 1081 (1953).
7 Trumpy, Grotdal, and Graue, Nature **170**, 1118 (1952).
8 W. M. Gibson, (private communication).
9 R. Müller and P. Stoll, Nuovo cimento (supp.) **9**, 1232 (1952).
10 Erdös, Scherrer, and Stoll, Helv. Phys. Acta. **26**, 207 (1953).
11 Nabholz, Stoll, and Wäffler, Phys. Rev. **82**, 963 (1951).
12 E. W. Titterton, Australian, J. Sci. **15**, 174 (1953).
13 Bennett, Bonner, Richards, and Watt, Phys. Rev. **59**, 904 (1941); Phys. Rev. **71**, 11 (1947).
14 L. H. Martin and J. Campbell (private communication).
15 T. Bonner (private communication).
16 H. T. Richards, Phys. Rev. **59**, 796 (1941).
17 F. E. Steigert and M. B. Sampson, Phys. Rev. **92**, 660 (1953).
18 K. Boyer, Massachusetts Institute of Technology, unpublished report as quoted in F. Ajzenberg, and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).

Kinematics of Λ^0 Production*

GEORGE T. REYNOLDS AND S. B. TREIMAN
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Received February 15, 1954)

CLOUD-CHAMBER observations by the Princeton Cosmic-Ray Group indicate that an appreciable fraction of Λ^0 particles produced in heavy elements (lead and copper) have low kinetic energies in the laboratory system.[1] At least 10 percent of the observed Λ^0 particles have energies below 70 Mev; whereas chamber bias against the observation of high-energy Λ^0 particles is not serious below a few Bev.

In order to investigate the implications of this result, we have considered the kinematics of several fundamental interactions which might lead to Λ^0 production, of the type

$$m_0+m_1\rightarrow m+m_2+\cdots, \qquad (1)$$

where m_0 is the incident particle (pion or nucleon), m_1 the target nucleon, m the Λ^0 particle, m_2 a secondary particle, and the possibility is allowed that additional particles may be produced in the interaction. The essential assumption is that the interaction occurs with a single nucleon in the nucleus. It is also assumed that the Λ^0 particle suffers no appreciable loss of energy in escaping from the nucleus.

We then find that it is difficult to explain the large fraction of low-energy Λ^0 particles if the production is isotropic in the center-of-mass system. There is of course no *a priori* reason why the production should be isotropic; but the departure from isotropy indicated by our results is so pronounced as to merit quantitative discussion.

Let $P(E_0,<E')$ be the probability that an incident particle of energy E_0 in the target-nucleon rest frame Σ gives rise to a Λ^0 particle of energy $<E'$ in the laboratory frame Σ', taking into account the internal motion of the nucleons in the nucleus. Let $P(E_0,E)dE$ be the probability that the incident particle produce a Λ^0 particle of energy between E and $E+dE$ in the Σ frame; and let $w(E,<E')$ be the probability that this Λ^0 particle have energy $<E'$ in the Σ' frame. Then,

$$P(E_0,<E')=\int P(E_0,E)w(E,<E')dE. \qquad (2)$$

To obtain the function $w(E,<E')$—which expresses the effect of the internal motion of the target nucleons—a Fermi gas model of the nucleus was adopted, with maximum nucleon kinetic energy of 20 Mev (our final numerical results are insensitive to this choice