complication which is almost prohibitive if we further take into account the interaction with other fields, because the general method of reducing the theory of nonlocal fields to that of the nonlocal interaction between local fields as discussed in the preceding letter can no longer be applied straightforwardly to our case. On the other hand, it may well be that one could arrive at the desired removal of the infinite degeneracy as a consequence of the interaction between nonlocal fields without assuming the coupling between external and internal degrees of freedom for each of the nonlocal fields. This is plausible, because the submatrix of the S matrix corresponding to one-particle states can always be represented by an equivalent coupling between the external and internal variables for the particle in question, so that one can hope that a reasonable mass spectrum which is free from the infinite degeneracy may come out even without assuming the coupling between external and internal degrees of freedom at the outset.

A detailed account of all these points, including the quantization of nonlocal fields, will be given in a forthcoming paper.

* Now at Kyoto University, Kyoto, Japan, on leave of absence from Columbia University (July, 1953).

[1] M. Born and H. S. Green, Proc. Roy. Soc. Edinburgh **62**, 470 (1949); M. Born, Revs. Modern Phys. **21**, 463 (1949).

[2] Equation (5) has no solution which is quadratically integral unless k is time-like, i.e., $k_\mu k_\mu < 0$.

Inverse Oppenheimer-Phillips Process in the $Cu^{65}(He^3,\alpha)$ Reaction

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An inverse Oppenheimer-Phillips process may be conceived where the bombarding particle picks up a nucleon from the target nucleus without actual penetration when the two are in close proximity of each other. A high binding energy of the nucleus composed of the projectile and the pickup nucleon would be a desirable condition.

A situation favorable to this inverse O−P process arises in connection with (He^3, α) reactions. Experimental evidence is now available to test this phenomenon.

Copper was bombarded with 13-Mev He^3 in the cyclotron and the 12.9-hour Cu^{64} was produced according to the reaction $Cu^{65}(He^3, \alpha)$. The excitation curve obtained for this reaction is shown in Fig. 1 which also shows, for comparison, a corresponding curve for the 9.4-hour Ga^{66} produced from the reaction $Cu^{65}(He^3, 2n)$.

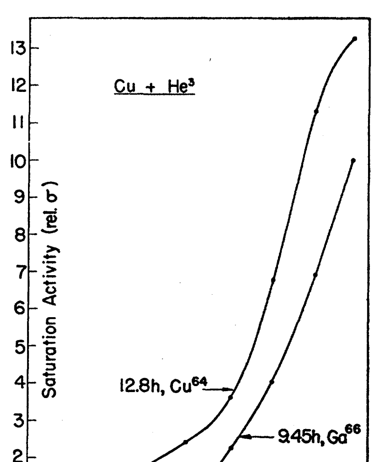

FIG. 1. The excitation curve for the 12.9-hour Cu^{64} and 9.4-hour Ga^{66} produced by He^3 bombardment of copper.

A study of the shapes of these curves indicates that the $Cu^{65}(He^3, 2n)$ curve fits smoothly a theoretical curve involving compound nucleus formation, as expected. The high-energy part of the experimental curve for the $Cu^{65}(He^3, \alpha)$ reaction can be similarly fitted to a theoretical curve down to about 9.0 Mev. For lower energies the shape of the curve changes in a marked way. The cross section is less energy-sensitive and the reaction can be traced to as low as 5.4 Mev where essentially no penetration of the potential barrier would be expected.

The experimental data appear to indicate that the inverse O−P phenomenon comes into evidence from very low energies up to an energy where compound nucleus formation mechanism takes over and, from there on, the latter plays the major role in the $Cu^{65}(He^3, \alpha)$ reaction.

It may be pointed out that the 5.10-minute Cu^{66} activity was not produced in measurable amount by the reaction $Cu^{65}(He^3, 2p)$. The similar reaction $Cu^{63}(He^3, 2p)$ has a Q value of only $+0.18$ Mev as compared with the Q value of $+10.7$ Mev for the reaction $Cu^{65}(He^3, \alpha)Cu^{64}$. Analogous to the latter is the reaction $Cu^{63}(He^3, \alpha)$ which gave a substantial yield of the 9.9-minute Cu^{62} activity.

Bremsstrahlung at High Energies

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Two of us[1] have published a formula for the cross section for bremsstrahlung which was derived without the use of the Born approximation. The matrix element was taken to be

$$M = \int \psi_f^* \alpha_\lambda \psi_i e^{-i\mathbf{k}\cdot\mathbf{r}} d\tau, \tag{1}$$

with α_λ the Dirac matrix in the direction of polarization of the emitted quantum, and ψ_i and ψ_f wave functions of the electron in the Coulomb field of a nucleus.

Like most authors before us,[2] we took *both* electron wave functions to be plane waves plus outgoing spherical waves. This is of course correct for the initial state ψ_i, but it is wrong for the final state ψ_f; the latter must be taken as a plane wave plus *ingoing* spherical waves.

To show this, we note that in the process of determining a differential cross section, we *observe* (e.g., by means of a counter) an electron moving in direction $\mathbf{p}_2$ some time *after* the radiation process has taken place. This observation is described by a plane wave packet concentrated around the point $\mathbf{v}_2 t$; this wave packet is moving away from the nucleus and is not accompanied by any other waves at this late time. We now follow the development of this wave packet *backwards in time* by use of the Dirac equation. As long as the packet is outside the field of the nucleus, it remains a plane wave packet. When the time t approaches zero (from above), the Coulomb field will scatter the wave packet, and for $t<0$ the plane wave packet will be accompanied by scattered spherical waves. As t becomes more and more negative, both the plane wave and the spherical waves will move farther away from the nucleus. But in the usual language in which one describes the motion with increasing time, both waves will, for $t<0$, move *towards* the nucleus. This shows that we have indeed ingoing spherical waves associated with the plane wave, and this result can be carried over into the time-independent formalism.

In fact, the use of converging spherical waves in ψ_f is the natural counterpart of the use of outgoing spherical waves in ψ_i. Here the observation of an electron going in the direction $\mathbf{p}_1$ is made in the beginning; therefore the electron will be described by a pure plane wave until it hits the nucleus, and by a plane wave plus outgoing spherical waves thereafter.

The need for using ingoing spherical waves in ψ_f was realized by Mott and Massey,[3] using a more mathematical argument. The application of this argument to our problem will be discussed in a subsequent, more extensive paper. It was also realized by Sommerfeld in his book.[4]

If the matrix element (1) is calculated for high relativistic energies and with the same method as in reference 1, it is found that the Born approximation result is multiplied by the factor

$$R=(1-x)^2(1+a^2)[V(1)]^{-2}|F(2-ia,\ 1+ia,\ 2,\ x)|^2, \qquad (2)$$

where $a=Ze^2/\hbar c$; F is the hypergeometric function whose argument is

$$x=1-(k^2/\epsilon_1\epsilon_2 q^2)(\epsilon_1-p_1\cos\theta_1)(\epsilon_2-p_2\cos\theta_2); \qquad (3)$$

and

$$V(x)=F(ia,\ -ia,\ 1,\ x). \qquad (4)$$

The notation is the same as that of Bess[2] and our earlier letter.[1]

Using relations between hypergeometric functions, it can be shown that

$$R=[V^2(x)+a^2(1-x)^2W^2(x)]/V^2(1), \qquad (5)$$

with $W=a^{-2}dV/dx$. It can then be shown that this expression is always less than unity. Moreover, the argument of the hypergeometric function is very close to unity except when q is near its minimum value. Therefore, ordinarily, the correction to the Born approximation is very small. Only for small q is there a noticeable reduction in the cross section. For *very* high energy, when screening eliminates the contribution from small values of q, the total cross section will tend towards that of the Born approximation.

Obviously, this behavior is very different from that of the pair production cross section. Since we have not yet integrated the bremsstrahlung cross section over angle, we cannot make a comparison with the (somewhat scanty) experimental information. However, we can give a qualitative explanation of the remarkable result that, over most of the important range, the Born approximation is nearly correct. We know that, at high energies, only the small-angle scattering of the electrons by the nucleus matters in the electron wave functions ψ_i and ψ_f. Since ψ_i has outgoing scattered waves, they are almost entirely *behind* the nucleus (when looking in the direction of propagation of the plane electron wave) while the ingoing spherical waves of ψ_f are *in front of* the nucleus. The scattered waves in ψ_i and ψ_f therefore do not overlap appreciably, and M [Eq. (1)] comes almost entirely from the overlap of the *plane* wave in one of the ψ's with the scattered wave in the other. This leads essentially to the Born approximation.

Nothing is changed in our earlier argument[1] for pair production. In this case, *both* electrons are created in the process; therefore both must be represented by ψ^* functions, with ψ a plane wave plus convergent spherical waves. In this case, the result is the same as if both wave functions had outgoing spherical waves. The integral cross section then shows the reduction by about 10 percent previously reported,[5] which was found to be in agreement with experiment.

[1] L. Maximon and H. A. Bethe, Phys. Rev. **87**, 156 (1952).
[2] A. Sommerfeld, Ann. Physik **11**, 257 (1931) (see, however, reference 4); L. Bess, Phys. Rev. **77**, 550 (1950), and others.
[3] N. F. Mott and H. S. W. Massey, *Atomic Collisions* (Oxford University Press, London, 1949), second edition, pp. 111–113; also first edition (1933), pp. 82–84. Their formulation differs somewhat from ours.
[4] A. Sommerfeld, *Atombau and Spektrallinien* (F. Vieweg and Son, Braunschweig, 1939), Vol. 2, pp. 457 and 502.
[5] H. Davies and H. A. Bethe, Phys. Rev. **87**, 156 (1952).

The Decay of Re^{188} and the Lifetimes of Os^{186m} and Os^{188m}

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THE radiations from radioactive Re^{188} have been studied by a number of investigators.[1–6] None of these studies has produced a complete decay scheme for this isotope.

An investigation of the gamma-ray spectrum has been carried out with a double-focusing beta-ray spectrometer[7] having an instrumental resolution of 0.7 percent. The gamma-rays were converted in a 19 mg cm^{-2} lead radiator, and the energy determinations were made by comparing the point of inflection on the sharp high energy edge of each peak with the external conversion peaks produced by the well known gamma rays of ThB, Cs^{137}, and Co^{60}. The relative intensities were calculated from the photoelectron peak heights and the known dependence of photoelectron cross section on energy. The gamma-ray energies and relative intensities are presented in Table I.

TABLE I. Energies and relative intensities of the gamma rays of Re^{188}.

Gamma energy (kev)	Relative intensity
155.3 ±0.5	~130 (from the *L* peak only)
478.2 ±0.6	10
633.1 ±0.7	15
673.6 ±1.0	1
827.8 ±1.0	5
931.0 ±1.1	6
1132.4 ±1.7	1
1607.8 ±1.9	2

The line width of the electron peaks varied from 1 percent for the 1.61-Mev radiation to 4 percent for the 0.155-Mev gamma ray.

The intensity of the 0.155-Mev radiation involves an approximation for the K/L conversion ratio in lead and is therefore somewhat less accurate than the other estimates. Previous work with a lens spectrometer (both in this laboratory and elsewhere) did not resolve the 0.828-Mev radiation from the Compton distribution produced by the 0.931-Mev gamma ray. The 1.43-Mev gamma ray, which has also been reported, was not observed in this investigation. If it exists, its intensity is less than one-half that of the 1.13-Mev radiation.

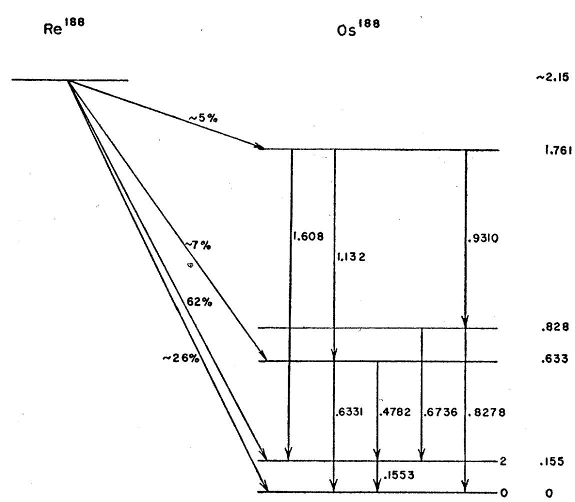

FIG. 1. The decay scheme for Re^{188}. All energies are in Mev.

A measurable lifetime for the 0.155-Mev excited state of Re^{188} was found by delayed coincidence techniques using a fast coincidence circuit[8] of resolving time 3.5×10^{-9} sec, 1*P*21 photomultipliers and stilbene crystals. The analysis of the resolution curves was carried out using the methods which have been described by Newton[9] and by Bell and Graham.[10] The half-life for the level was found to be $(1.7\times0.4)\times10^{-9}$ sec.

After the Re^{188} activity had decayed through 10 half-lives, a measurement was made on the lifetime of the 0.137-Mev excited state in Os^{186}. The value of $(1.8\times0.4)\times10^{-9}$ sec obtained is in poor agreement with that previously reported by McGowan[11] and tends to improve the agreement with the theoretical predictions