PHYSICAL REVIEW VOLUME 73, NUMBER 1 JANUARY 1, 1948

The (H^3, p) Reaction in Rh and Co and Probable Evidence of the Di-Neutron

D. N. KUNDU AND M. L. POOL
Ohio State University, Columbus, Ohio

(Received September 24, 1947)

By H^3 bombardment, two neutrons have been introduced into Rh and Co nuclei according to reactions $Rh^{103}(H^3, p)Rh^{105}$ and $Co^{59}(H^3, p)Co^{61}$, with half-lives of 35 hours and 1.75 hours, respectively. The mechanism appears to be an Oppenheimer-Phillips process with H^3. The results are interpreted in the light of the di-neutron (${}_0n^2$). It is believed that ${}_0n^2$ may exist under the physical conditions of the experiments reported.

1. INTRODUCTION

IN previous works,[1,2] H^3 was used as the bombarding particle for producing nuclear reactions in Ag leading to Pd^{107}. A series of investigations was undertaken with a view to introduce two neutrons into a nucleus. Considering the ease with which (d, p) reactions proceed according to the Oppenheimer-Phillips[3-6] process, the H^3 particle was regarded as suitable for the above purpose.

Two similar nucleons are known to have forces of attraction between them. It has, therefore, been speculated[7] that the so-called "di-neutron" (${}_0n^2$) may exist. The di-neutron might be examined experimentally if by an Oppenheimer-Phillips process the proton could be separated from the H^3 nucleus and the remaining neutron pair could be observed to behave as a single group.

Bombardments with H^3, made with these aims in view, are mostly complicated by extraneous activities produced by deuterons, neutrons, etc., because the H^3 was produced, as in the previous works by bombarding Be with deuterons. These non-essential activities usually come in such great strength as to mask, in many cases, the H^3 activation, if there is any. However, in the case of Rh and Co the experimental results are sufficiently free from ambiguity and are therefore, reported in the present paper. The reactions observed are $Rh^{103}(H^3, p)Rh^{105}$ and $Co^{59}(H^3, p)Co^{61}$.

2. EXPERIMENTAL

Rhodium+H^3

A Be foil was bombarded with 10-Mev deuterons and the H^3 thus produced was made to bombard a number of Rh foils (each 1 or 2 mils thick), placed immediately behind the Be foil. Two thicknesses of Be (5 and 8 mils) were used in different experiments. After the bombardment* the foils were separately cut to very fine pieces, sealed into heavy-walled glass tubes with a mixture of HCl and $HClO_4$ (20:1) and heated to 300°C for 4 hours. The tubes were then cooled to liquid-air temperature and opened while cold. Ruthenium carrier and later sufficient $HClO_4$ was added to change the Ru to RuO_4. The mixture was distilled by bubbling air through it while heating with a microburner and the distillate was collected in very concentrated KOH kept in an ice bath as potassium perruthenate. The residue was evaporated nearly to dryness with concentrated H_2SO_4 till there was copious evolution of SO_3 fumes, distilled and the Rh precipitated by adding $TiCl_2$.

The decay curve of the Rh fraction of the first foil is shown in Fig. 1. The 35-hour Rh^{105} activity is seen above the long-period background which is mostly 210-day Rh^{102}. The strong 12.8-hour activity was suspected to be due to copper impurity in the Rh sample. This was confirmed by a spectro-chemical examination of the Rh sample. Repeated separations of

---

[1] D. N. Kundu and M. L. Pool, Phys. Rev. **71**, 467 (1947).
[2] D. N. Kundu and M. L. Pool, Phys. Rev. **72**, 101 (1947).
[3] J. R. Oppenheimer and M. Phillips, Phys. Rev. **48**, 500 (1935).
[4] H. A. Bethe, Rev. Mod. Phys. **9**, 201 (1937).
[5] H. A. Bethe, Phys. Rev. **53**, 39 (1938).
[6] H. A. Bethe, Phys. Rev. **53**, 205 (1938).
[7] M. Y. Colby and R. N. Little, Phys. Rev. **70**, 437 (1946).

* The Rh chemistry was kindly done by H. L. Finston and Ula M. Bigham of the Ohio State University.

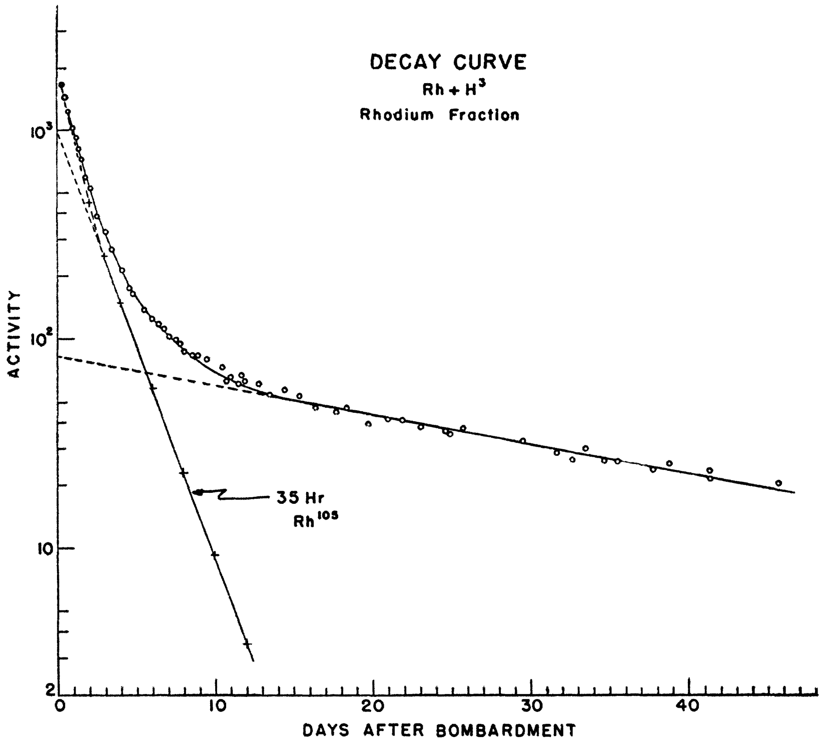

FIG. 1. Decay curve of the rhodium fraction after bombardment of rhodium with H^3 showing the 35-hour Rh^{105}. The crosses denote the points obtained by subtracting the base line from the earlier part of the decay curve

Cu from the Rh fraction removed a large fraction of this 12.8-hour activity. Beta-energy measurements of Rh final fraction by absorption in aluminum, gave 0.6 Mev which checks with accepted Rh^{105} value. No 35-hour activity was observed in the Rh fraction of the foils behind the first one. The Pd fraction of the first foil showed the 17-day Pd^{103} due to the reaction $Rh^{103}(d, 2n)Pd^{103}$, but no 13-hour activity was found.

Cobalt+H^3

Hilger Co metal was used in the form of a 40-mil thick block. After bombardment** with H^3, a few mils of the material from the front surface, which was hit by the H^3, were etched out with concentrated HNO_3. The sample on manufacturer's analysis contained less than 0.1, 0.01 percent of Ni and Cu, respectively, and spectroscopically just observable traces of Cr, Fe, and Ag. Carriers of Cu, Ni, and Mn were added and the Mn separated as MnO_2 with $KBrO_3$ from the 1–N solution in HNO_3. The Cu was then repeatedly precipitated with H_2S from the 3N HCl solution. The supernate was made basic with NH_4OH and NH_4Cl and, the Ni precipitated with alcoholic solution of dimethyl glyoxime. The Co was later precipitated from 1–N HCl medium with α-nitroso-β-naphthol solution. Initial tests with separation of Fe and Cr showed that these introduce no complications and were, therefore, eliminated from the general procedure.

Figure 2 shows the decay curve of the Co fraction. The 1.75-hour Co^{61} activity recently reported[8] is seen above the very long-period activity. The short length of the curve is due to the long time needed for the chemistry and the comparatively short half-life under study. The identification was substantiated by β-energy measurements which gave 1.1 Mev for the maximum value by absorption in aluminum. The 1.75-hour Co^{61} emits no γ-radiation as seen from the γ-decay curve.

** The Co chemistry was kindly done by J. M. Hollander of the Ohio State University.

[8] T. J. Parmley and B. J. Moyer, Phys. Rev. **72**, 82 (1947).

3. DISCUSSION OF RESULTS

The elements Rh and Co were chosen as the target material because they have a single stable isotope (Fig. 3). This gives greater freedom in the interpretation of results. The 35-hour Rh^{105} activity can be produced only by the introduction of two neutrons into a Rh^{103} nucleus. This is not possible by activation with deuterons which have been used as the primary particles for producing H^3. Neither is it likely, on grounds of probability, that two neutrons which are available from the $Be+d$ source, will enter the same Rh nucleus one after another. Experimentally, also, this possibility is excluded for the back foils of Rh, which were bombarded by neutrons only, showed no 35-hour activity under similar conditions of chemistry. All efforts to impute the 35-hour activity to impurities were unsuccessful. For example, a small amount of Pd as impurity in the Rh metal might produce the 35-hour activity by (n, p) or $(d, 2p)$ reaction. This is, however, contrary to observtions, for it is experimentally well known that the 13-hour Pd^{109} activity is produced in very high strength by deuteron and neutron activation of Pd. The absence of the 13-hour activity in the Pd fraction of the first foil is strong evidence that no observable Pd is present in the Rh sample. The absence of the 35-hour activity in the back foils also indicates that the same activity, as measured in the first foil, is not due to (n, p) reaction from Pd impurity. The reaction must, therefore, be $Rh^{103}(H^3, p)Rh^{105}$.

Essentially similar arguments hold in the case

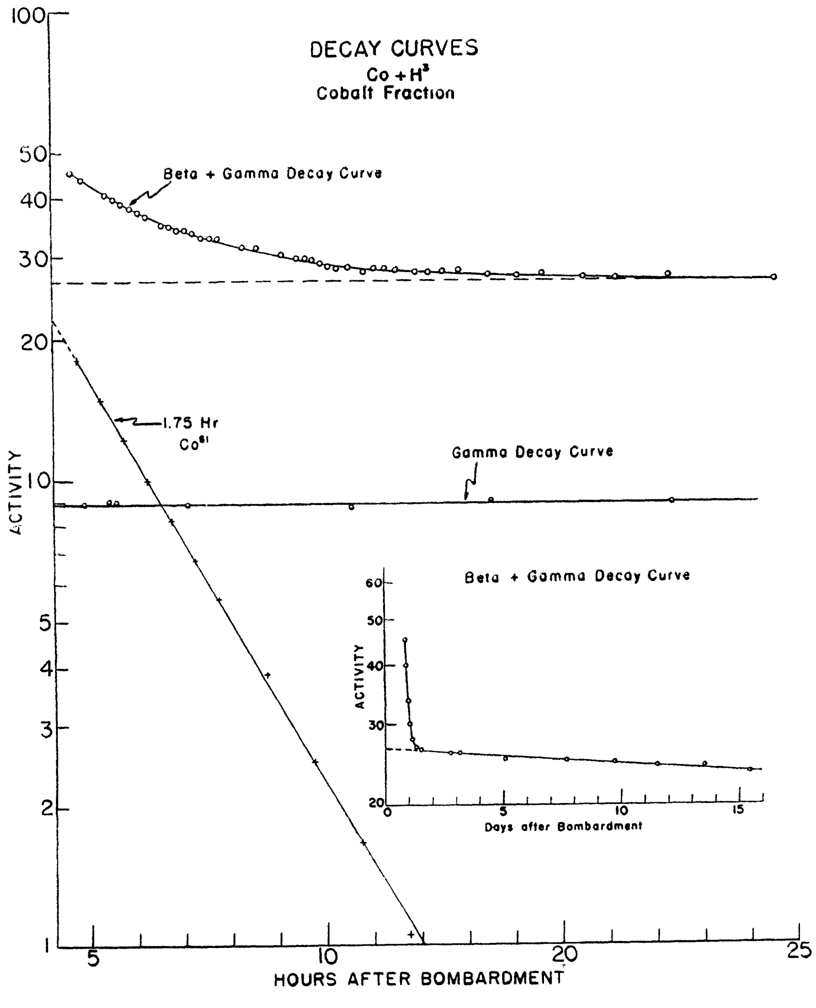

FIG. 2. Decay curve of the cobalt fraction after H^3 bombardment of cobalt showing the 1.75-hour Co^{61}. The crosses denote the points obtained by subtracting the base line from the earlier part of the beta- and gamma-decay curve.

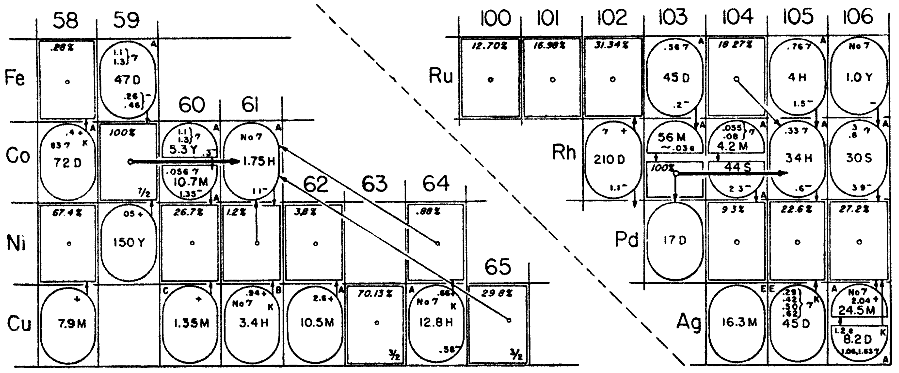

FIG. 3. Rhodium and cobalt regions in the chart of atomic nuclei. The heavy arrow indicates the formation of Rh^{105} and Co^{61} from Rh^{103} and Co^{59} respectively by the (H^3, p) reaction.

of the 1.75-hour Co^{61} activity which has been produced from the single stable Co^{59} isotope. In this case, the activity of the main block, after the etching out of the thin layer bombarded with H^3, was followed to check neutron activation. As seen from Fig. 3, Ni stands in the same relation to Co as Pd did to Rh. Though a minute trace of Ni is present in the Co Metal used, it is only less than 0.1 percent, and the percentage abundance of Ni^{61} from which Co^{61} might be produced by (n, p) or (d, $2p$) reaction is only 1.2. It would thus be impossible to detect any 1.75-hour activity produced from the Ni impurity. Moreover, the main block which was many times more active than the Co fraction showed no 1.75-hour period. The β-energy measurement was also an important help. Every test showed that the reaction is $Co^{50}(H^3, p)Co^{61}$.

H^3 has thus been instrumental for the simultaneous introduction of two neutrons into the nucleus of Rh^{103} and Co^{59}.

4. INTERPRETATION AND THE DI-NEUTRON HYPOTHESIS

Since H^3 is responsible for the introduction of the two neutrons into the Rh and Co nucleus, it is plausible, as indicated in the introduction, to assume that the mechanism involved is, in large part at least, the Oppenheimer-Phillips process with H^3 instead of with d as the bombarding particle. As the H^3 approaches the high potential barrier of the target nucleus, it is "polarized." The charged proton part of the polarized H^3 is strongly repelled. The two neutrons find no barrier in front and enter the target nucleus. As in the case of the deuteron, the formation of the compound nucleus, by Gamow-Condon-Gurney process, and then the ejection of the proton, would be less probable even for moderately heavy nuclei like Rh and Co. It was also experimentally noted by changing the thickness of the Be foil, that the yield of the 35-hour activity was not greatly sensitive to the energy of the H^3 particles as it should have been if the mechanism had been one in which a G–C–G compound nucleus was formed. The yield according to the O–P process, on the other hand, will not be strongly affected by small changes in the energy of the bombarding particle. Moreover, in the ordinary G–C–G scheme, the (H^3, p) reaction will probably have to compete with (H^3, n), (H^3, $2n$), and (H^3, $3n$) reactions whereas there will be no such competition in the O–P scheme. This is of special significance[5] because of the fact that the products of (H^3, n) and (H^3, $2n$) are each stable for Rh and Co while the product of (H^3, p) is β-active.

If, therefore, the phenomenon is mostly an Oppenheimer-Phillips process with H^3, as it is very likely to be, the next question that arises is whether the two neutrons are captured separately one after another or whether they are captured simultaneously as a group. Inside the H^3 nucleus, the two neutrons had been within the range of nuclear forces and there was a force of attraction between them. When the H^3 comes in the immediate vicinity of the target nucleus, though the proton momentarily stays at some distance away from it, the two neutrons which are practically on its surface may still be held to each other by mutual forces of attraction. In other words, in the absence of specific causes which would take the two neutrons apart, they would hold together as a group and would be captured as such. This group would then be the di-neutron $({}_0n^2)$, but a di-neutron only under very peculiar physical conditions. It is being found in course of these (H^3, p) reactions only for a very short time, *viz.* the interval between the instant the H^3 begins to be polarized and the instant the capture takes place.

The di-neutron may be an extremely unstable particle and hence, the circumstances of the present investigations may be just the extreme physical conditions under which it may be observed.

The authors are grateful for the support received from the Ohio State University Development Fund. Thanks are also due the Watumull Foundation, Los Angeles, and the Ghosh Travelling Fellowship Board of the Calcutta University for their support to one of the authors.

PHYSICAL REVIEW VOLUME 73, NUMBER 1 JANUARY 1, 1948

On Infinities in Generalized Meson-Field Theory

ALEX E. S. GREEN
Department of Physics, University of Cincinnati, Cincinnati, Ohio

(Received September 24, 1947)

The results of an extension of Podolsky's generalized electrodynamics, corresponding to Proca's extension of Maxwellian electrodynamics, are presented. In this extension the Lagrangian is permitted to depend upon the field coordinates themselves, which is a major step in going from electrodynamics to meson-field theory.

The static interaction and static self-energy, derived by exact classical and quantum methods, as well as the dynamic interaction and dynamic self-energy, obtained by a quantum-mechanical perturbation method, are given. The complete interaction and self-energy are free from singularities and infinities. This is in contrast with the results of ordinary relativistic meson-field theory. It thus appears that these defects may be removed from meson theory, just as in electrodynamics, by going to a generalized field theory in which the Lagrangian contains the second derivatives of the field coordinates.

1. INTRODUCTION

IT is well known that the outstanding difficulty in the quantum theory of fields is the problem of infinite self-energies or inertia effects which arise in those theories which meet the requirement of relativistic invariance. In fact, most of the current research in field theory is directed at solving this problem.[1,2]

In a recent series of papers Podolsky,[3] Podolsky and Kikuchi,[4,5] Montgomery,[6] and Green[7] have developed a completely relativistic electrodynamics which appears to be free from the defect of infinite self-energies and which reduces to the Maxwell-Lorentz formulation for low energy phenomenon. In the present paper we extend this generalized field theory by allowing the Lagrangian to contain the field coordinates themselves. The corresponding extension of Maxwellian electrodynamics has been investigated by Proca[8] and others[9,10,11] and is considered to be among the more promising of meson-field theories.

In order to show the essential consequences of this generalization we shall consider only its simplest aspects. It is probable that modification of this theory by the inclusion of such concepts

---

[1] See G. Wentzel, Rev. Mod. Phys. **19**, 1 (1947).

[2] Also W. Pauli *Meson Theory of Nuclear Forces* (Interscience Publishers, Inc., New York, 1946).

[3] B. Podolsky, Phys. Rev. **62**, 68 (1942), to be referred to as GE I.

[4] B. Podolsky and C. Kikuchi, Phys. Rev. **65**, 228 (1944), to be referred to as GE II.

[5] B. Podolsky and C. Kikuchi, Phys. Rev. **67**, 184 (1945), to be referred to as GE III.

[6] D. J. Montgomery, Phys. Rev. **69**, 117 (1946), to be referred to as GE IV.

[7] A. E. S. Green, Phys. Rev. **72**, (1947), to be referred to as GE V.

This series of five papers will be called the GE S.

[8] A. Proca, J. Phys. Rad. (vii) **7**, 347 (1936).

[9] N. Kemmer, Proc. Roy. Soc. **A166**, 127 (1938).

[10] H. Frohlich, W. Heitler, and N. Kemmer, Proc. Roy. Soc. **A166**, 154 (1938).

[11] H. J. Bhabha, Proc. Roy. Soc. **A166**, 501 (1938).