*INVERSE β PROCESS**

B.M.Pontecorvo

Chalk River Laboratories, Chalk River, Ontario

INTRODUCTION

The Fermi theory of the β disintegration is not yet in a final stage; not only detailed problems are to be solved, but also the fundamental assumption — the neutrino hypothesis — has not yet been definitely proven. I will recall briefly the main experimental facts which have led Pauli to propose the neutrino hypothesis.

1. In a β disintegration, the atomic nucleus Z changes by one unit, while the mass number does not change.

2. The β spectrum is continuous, while the parent and the daughter states correspond to well defined energy values of the nuclei Z and $Z \pm 1$.

3. The difference in energy between the initial and final states involved in a β transition is equal to the *upper* limit of the continuous spectrum.

We see that the fundamental facts can be reconciled only with one of the following alternative assumptions:

i. The law of the conservation of the energy does not hold in a single β process.

ii. The law of the conservation of the energy is valid, but a new hypothetical particle, undetectable in any calorimetric measurement — the neutrino — is emitted together with a β particle in a β transition, in such a way that the energy available in such transition is shared between the electron and the neutrino. This suggestion was made by Pauli and on this basis Fermi has built a consistent quantitative theory of the β disintegration. In addition to the difficulties already mentioned, the assumption ii removes some difficulties connected with the conservation of the spin and of the type of statistics of which we cannot speak here. The main neutrino properties follow «by definition» and are: zero charge, spin 1/2 and Fermi's statistics. The problem of the β disintegration has been attacked experimentally in many ways:

*National Reserach Council of Canada, Division of Atomic Energy. Chalk River, 1946, Report PD-205. This version was kindly provided by Prof. W.F.Davidson.

(a) β spectroscopy, i.e., study of the form of the β spectrum, the relationship between the energy release and the probability of disintegration, the ratio of positron to electron emission in cases where both electrons and positrons can be emitted, the ratio of the number of the K capture transitions to positron transitions.

(b) Neutron Decay. This fundamental β transition, the transformation of a free neutron into a proton, has not yet been detected. Plans for its detection, as well as for the study of the angular distribution of the proton and electron emitted, have been made in several laboratories in the U.S.A. and in the Chalk River Laboratory.

(c) Experiments on the recoils of nuclei in a β-ray disintegration. Several authors have attempted experiments of this type. The common feature of all these experiments is that the magnitude of the recoil energy of the nucleus having undergone a decay process is examined in the light of the laws of the conservation of energy and momentum. The most significant results were obtained by Allen, who studied the recoil of a nucleus having undergone a K electron capture, and by Jacobsen and Kofoed-Hansen, who deduced from their experiments that neutrinos and electrons are emitted prevalently in the same direction. It should be noticed that experiments of this type, while of fundamental significance in the understanding of the β process, cannot bring decisive *direct* evidence on the basic assumption of the existence of the neutrino. This statement can be understood if we keep in mind that recoil experiments are interpreted on the basis of the laws of the conservation of the energy and momentum in individual processes, i.e., on the basis of the alternative ii, which, in effect, corresponds essentially to the assumption of the existence of the neutrino.

Direct proof of the existence of the neutrino, consequently, must be based on experiments, the interpretation of which does not require the law of conservation of energy, i.e., on experiments in which some characteristic process produced by *free neutrinos* (a process produced by neutrinos after they have been emitted in a disintegration) is observed.

INVERSE β *PROCESS*

It is clear that inverse β transformations produced by neutrinos are processes of this type and certainly can be produced by neutrinos, if neutrinos exist at all. They consist of the concomitant absorption of a neutrino and emission of a β-particle (positron or negatron) by a nucleus. It is obvious, on thermodynamical grounds, that such process must have an extreme low yield since their inverse, the β process, is so unlikely. It has been currently stated in the literature that an inverse process produced by neutrinos cannot be observed, due to the low yield. As it will be shown below, this statement seems to be too drastic. The object of this note is to show that the experimental observation of an inverse β process produced by neutrinos is not out of the question with the modern experimental facilities, and to suggest a method which might make an experimental observation feasible.

For completeness, we will mention also some inverse β processes produced by other particles than a neutrino; an inverse β process, more generally, can be defined as the transformation of a neutron into a proton, or vice versa, produced artificially by bombardment with neutrinos, electrons, or γ-rays. These processes are:

(a) Absorption of negative β particle (β) with emission of a neutrino

$$(\nu)\ \beta^- + Z \rightarrow \nu + (Z-1).$$

(b) Absorption of a neutrino with emission of a β particle

$$\nu + Z \rightarrow \beta^- + (Z+1) \qquad \nu + Z \rightarrow \beta^+ + (Z-1).$$

(c) Absorption of a neutrino accompanied by a K electron capture

$$\nu + Z + \beta^{-}(K) \rightarrow Z - 1.$$

(d) Processes involved by γ radiation

$$\gamma + Z \rightarrow \gamma + \beta^{-} + (Z + 1)$$

$$\gamma + Z \rightarrow \gamma + \beta^{+} + (Z - 1).$$

PROPOSED METHOD

It is true that the actual β transition involved, i.e., the *actual emission* of a β particle in processes (b) and (d), and the emission of X radiation in process (c) is certainly not detectable in practice. However, the nucleus of charge $Z \pm 1$, which is produced in any of the reactions indicated above, may be (and generally will be) radioactive, with a decay period well known (see, for example, Seaborg's Table of Radioelements). *Consequently, the radioactivity of the produced nucleus may be looked for as a proof of the inverse process.*

The essential point, in this method, is that radioactive atoms produced by an inverse β-ray process have different chemical properties from the irradiated atoms. Consequently, it may be possible to concentrate the radioactive atoms of known period from a very large irradiated volume. In the case of electron irradiation,the effective volume irradiated may be of the order of cubic centimeters; in the case of γ-ray irradiation, the volume may be of the order of a liter, and for neutrino irradiation, the volume is limited only by practical consideration and may be as high as 1 cubic meter. Elements to be considered for irradiation must be selected according to a compromise between their desirable properties, which are:

1. The material to be irradiated must not be too expensive, since large volumes are involved.

2. The nucleus produced in inverse β transformation must be radioactive with a period of at least one day, because of the long time involved in the separation.

3. The separation of the radioactive atoms from the irradiated material must be relatively simple. If a chemical separation is involved, it is necessary that the addition of only a few grams of a non-isotopic carrier, per hundred liters of material treated, gives an efficient separation. Isotopic carriers must be used only in the last phase of the separation. An electrochemical separation is another possibility, presenting some advantage because of the absence of carriers. If the nucleus formed in the inverse β process is a rare gas, the separation can be obtained by physical methods, again without carrier, for example, by boiling the material irradiated. This is the most promising method according to Dr. Frisch and the writer.

4. The maximum energy of the β-rays emitted by the radioelemeat produced must be very small, i.e., the difference in mass of the element Z and $Z \pm 1$ must be small. This is so because the probability of an inverse β process increases rapidly with the energy of the particle emitted, as will be explained. Of course, the requirement that the mass of Z is close to the mass of $Z \pm 1$ is not important if the bombarding particles have an energy much higher than the difference in the masses of Z and $Z \pm 1$. While γ-rays or electrons produced by betatrons or synchrotrons may easily satisfy this condition, strong sources of high energy neutrinos are not available, so that the requirement is of importance in a neutrino experiment.

5. The background (i.e., the production of element $Z \pm 1$ by other causes than the inverse β process) must be as small as possible.

AN EXAMPLE

There are several elements which can be used for neutrino radiation in the suggested investigation. Chlorine and Bromine, for example, fulfil reasonably well the desired conditions. The reactions of interest would be:

$\nu + {}^{37}Cl \rightarrow \beta^- + {}^{37}Ar$	$\nu + {}^{79,81}Br \rightarrow \beta^- + {}^{79,81}Kr$
${}^{37}Ar \rightarrow {}^{37}Cl$	${}^{79,81}Kr \rightarrow {}^{79,81}Br$
(34 days; *K* capture)	(34 h; emission of positrons of 0.4 MeV).

The experiment with Chlorine, for example, would consist in irradiating with neutrinos a large volume of Chlorine or Carbon Tetra-Chloride, for a time of the order of one month, and extracting the radioactive ${}^{37}Ar$ from such volume by boiling. The radioactive argon would be introduced inside a small counter; the counting efficiency is close to 100%, because of the high Auger electron yield. Conditions 1, 2, 3, 4, are reasonably fulfilled in this example. It can be shown also that condition 5, implying a relatively low background, is fulfilled.

Causes other than inverse processes capable of producing the radioelement looked for are:

(a) (n, p) Processes and Nuclear Explosions. The production of background by (n, p) process against the nucleus bombarded is zero if the particular inverse β process selected involves the emission of a negatron rather than the emission of a positron. This is the case in the inverse β process which would produce ${}^{37}Ar$ from ${}^{37}Cl$. Similar arguments show that «cosmic ray stars» cannot produce a direct background of ${}^{37}Ar$ from ${}^{37}Cl$. As for (n, p) processes in impurities, the fact that ${}^{37}K$ does not exist in nature rules out this possibility.

(b) (n, γ) Process. This effect can produce background only through impurities. In principle at least, it can be reduced by addition of neutron absorbing material. In the case considered, ${}^{37}Ar$ could be produced by absorption of neutrons in ${}^{36}Ar$ present to an extent of 0.3% in natural argon still present as contamination. It is estimated that $(n, 2n)$ effects, again through impurities, would not produce high background.

(c) (p, n) Effects. These effects are estimated to be very small. They would arise from cosmic rays, and are consequently independent of the neutrino strength used. They could be investigated in a blank experiment.

CROSS SECTIONS

If W is the mass difference between the two atoms involved in the inverse transition, E_p is the energy of the impinging particle, E is the energy of the emitted particle, we have $E = E_p - W$. We will see that the cross section σ_{inv} for the inverse β process increases rapidly with E, so that there is advantage in having a small W, at least for an energy of the primary particle smaller than 10 MeV.

Fierz and Bethe first gave a theoretical value for the cross sections of an inverse β process. A general dimensional argument given by Bethe and Peierls will be given here. This argument permits the estimate of the order of magnitude of σ_{inv} by using only the empirical knowledge of the β-ray lifetimes.

On thermodynamical grounds, the cross section σ_{inv} of an inverse β process produced by neutrino must be given by a formula of the type $\sigma = K/\tau$ cm^2, where $1/\tau$ is the probability per unit time of a β disintegration involving energy E and K is a constant of proportionality having the dimensions of cm$^2\cdot$ sec. The largest possible length involved is the wave length of the impinging neutrino and the longest time involved is that length divided by c. We can write then, the above formula in the form

$$\sigma_{inv} \leq \lambda^2 \cdot \frac{\lambda}{c} \cdot \frac{1}{\tau}$$

which has a quite clear physical meaning. From the above formula, we can recognize immediately that the cross section will increase with the energy of the impinging particle, if $1/\tau$ increases with a power of E bigger than E^3. Now $1/\tau$, according to our knowledge of the β disintegration, increases about as E^5 for energy of the order of 1 MeV. For very high energies, the dependence of $1/\tau$ on the energy is not known. It might be considerably higher. The Konopinski and Uhlenbeck modification of Fermi theory would give a dependence αE^7. We can conclude that the cross section for an inverse β process produced by neutrinos with emission of a β particle, increases with a high power of the energy of the bombarding neutrino.

For $E = 5$ MeV, τ might be as small as 0.1 sec, λ^2 and λ/c are respectively of the order of 10^{-21} cm^2 and 10^{-22} sec, so that σ_{inv}, for neutrinos of 5 MeV may be of the order of 10^{-42} cm^2. The evaluation is more complicated when many levels participate in the process, because of the uncertain dependence of the matrix elements on the excitation energy. Assuming, for example, that 1 cu meter of CCl_4 is used for the experiment, the number of nuclei of ^{37}Cl is about 10^{28}, and the number of disintegrations N per second of ^{37}Ar produced at saturation in such volume is $N =$ neutrino flux $\times \sigma_{inv} \times 10^{28} \sim$ neutrino flux $\times 10^{-14}$. The effect might be detected if N is of the order of 1, requiring a neutrino flux of the order of 10^{14} neutrinos per cm^2/sec. Such a value of the neutrino flux, though extremely high, is not too far from what could be obtained with present day facilities.

SOURCES

The neutrino flux from the sun is of the order of 10^{16} neutrinos/cm$^2\cdot$ sec. The neutrinos emitted by the sun, however, are not very energetic. The use of high intensity piles permits two possible strong neutrino sources:

1. The neutrino source is the pile itself, *during operation*. In this case, neutrinos must be utilized beyond the usual pile shield. The advantage of such an arrangement is the possibility of using high energy neutrinos emitted by all the very short period fission fragments. Probably this is the most convenient neutrino source.

2. The neutrino source is the «hot» uranium metal extracted from a pile, or the fission fragment concentrate from «hot» uranium metal. In this case, neutrinos can be utilized near to the surface of the source, but the high energy neutrinos emitted by the short period fragments are not present.

In the case of the investigation of inverse β processes produced by electrons of γ-rays of high energy, the best source is a betatron or a synchrotron.

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