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By Leo Szilard

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July 31, 1946

CREATIVE INTELLIGENCE AND SOCIETY:

THE CASE OF ATOMIC RESEARCH

THE BACKGROUND IN FUNDAMENTAL SCIENCE

As you probably know, it all started one day around the turn of the century when Becquerel in Paris noticed that uranium minerals, placed in a drawer near some photographic plates, blackened those plates.

Uranium minerals affected photographic plates even if they were wrapped in black paper, yes, even if they were placed in a wooden or metal case.

This effect of uranium minerals was due to penetrating rays which they emitted and which were similar to x-rays.

Immediately the question arose, where does the energy for these x-rays come from. But it took a few years before the answer to this question was found.

Madame Curie was at that time a graduate student with Becquerel, and she had a suspicion that uranium minerals contained some element other than uranium which was more active than uranium.

And as you know, years later she isolated radium from such minerals.

Radium which was an element until then unknown, is chemically rather similar to barium.

It slowly changes over into another radioactive element which is chemically different from it.

This other element is not similar to barium but is similar to neon, and like neon, it is a gas.

It is called radon or radium emanation in order to indicate that it emanates from radium.

We refer to this by saying that radium undergoes a spontaneous transmutation. Its half lifetime is about 1500 years which means that out of one gram of radium during a period of 1500 years, 1/2 gram will transmute into radium emanation.

Transmuting one chemical element into another chemical element was, as you know, the unsolved problem of the alchemists.

But Madame Curie, who isolated radium could not pride herself to be a successful alchemist.

She did not produce radium.

She merely separated it chemically from a mineral in which it was previously contained and she was in no position either to accelerate or even to slow down the transmutation of radium into radium emanation.

So, in spite of this new discovery, God remained the first and only successful alchemist.

As uranium and radium were further investigated it gradually became apparent that we had to deal with a whole family of naturally occurring radioactive elements.

Any one member of this family either emits beta rays, that is, negatively charged electrons, or it emits alpha rays, that is, positively charged, fast moving helium atoms.

Up to the 30's, it was much easier to observe the single alpha particles of the alpha rays than it was to observe the single electrons of the beta rays.

In air such an alpha particle travels in a straight line over a length of a few centimeters and then it stops.

The range of alpha particles in air is a few centimeters.

Because the alpha particle carries a positive charge, it ionizes the air in its path and therefore it is possible to make visible the track of the alpha particle.

Its track in air can be made visible to the naked eye and can also easily be photographed.

When an atom of a radioactive element emits an alpha particle, it undergoes a spontaneous transmutation and goes over into a chemically different element.

A radium atom for instance, which is similar to barium, emits an alpha particle and becomes an atom of radium emanation which is similar to neon.

The alpha particle which is emitted carries away the energy liberated in this transformation from one chemical element into another chemical element and the energy liberated in such a process is of the order of several million e-volts.

You have to contrast this with the energy which is liberated when carbon is burned, that is, when a carbon atom combines chemically with two oxygen atoms.

The energy liberated when carbon is burned amounts to a few electron volts.

So you see that as far as energies are concerned, the two types of processes differ by a factor of a million.

Becquerel's original observation that uranium minerals emit rays that blacken the photographic plate was the very first manifestation of the enormous energies liberated in nuclear transformations.

Until that observation was made, physicists had no inkling that there are any sources of energy other than the chemical processes of which the burning of carbon is the most common example.

Much of the investigation of the properties of radioactive elements and the behavior of alpha particles was done by Rutherford.

Rutherford noticed that an alpha particle does not always travel in air in a straight line along the whole course of its path but that occasionally its track is sharply deflected.

As long as an alpha particle merely ionizes the air, its track remains straight but when it hits the nucleus of a nitrogen or oxygen atom, the alpha particle gets sharply deflected.

But sometimes the track of the alpha particle in air is neither a straight line nor a line with a break, but a line which shows a fork.

Pictures of this sort were first obtained by Blackett in Rutherford's laboratory and were interpreted on the basis of some early experiments of Rutherford, by assuming that an alpha particle smashed a nitrogen nucleus and knocked a proton out of it while the alpha particle itself was captured by the nucleus.

According to Rutherford the long track of the proton and the short track of the rest of the nucleus formed the fork which was observed.

It was evident that in an individual process of this type, energy could be liberated, but it was also easy to see that processes of this type could <u>not</u> lead to large scale liberation of nuclear energy.

Because for every track which showed a fork there were thousands of tracks which did <u>not</u> and this means that in most cases the alpha particle does not produce energy but loses its own energy by ionizing the air through which it travels.

Whenever a charge particle moves through matter, it will ionize and in the vast majority of the cases it will lose its energy and stop before it has had a chance to make a collision with a nucleus and to smash that nucleus.

Looking back at the steps which led us from the discovery of radium to the large scale liberation of atomic energy by means of a chain reaction, we can now see that the alpha particles were able to give us the answer to almost all of our questions.

In order to discover all the things which we had to know, we merely had to observe the tracks of these alpha particles in air and to look sharp and see what happened when alpha particles were allowed to bombard various elements.

Bothe in Germany bombarded, with alpha particles, some light elements such as boron and beryllium and he noticed a penetrating radiation emanating during the bombardment from these light elements.

He thought he had to deal with penetrating x-rays or gamma rays, and this was an interesting discovery, but nothing to get excited about.

But now Joliot performed a curious experiment with these penetrating rays.

For some reason or other he placed a sheet of paraffin into their path and looked to see if anything was happening to the paraffin.

You might say that this was a rather pointless experiment and there really was very little justification for it.

However, this experiment changed the course of history.

For Joliot found that hydrogen atoms were knocked out of the paraffin by the penetrating radiation to which it was exposed.

Joliot further found that these hydrogen atoms or, more correctly, protons, had curiously enough, energies of several million volts and inevitably the question arose, by what mechanism could x-rays passing through paraffin transmit several million volts of energy to the protons in the paraffin.

There was no such mechanism known and it was therefore pretty evident that Joliot had found a phenomenon which could not be explained on the assumption that the penetrating radiations with which he had to deal were x-rays.

Chadwick, in Cambridge, looked therefore at the tracks of these protons in air and saw that the radiation which was responsible for them must consist of particles which carry no charge since their track in air could not be made visible.

Chadwick found further to his great surprise that the mass of these particles must be pretty close to the mass of the proton itself.

This meant that he had to deal with some new particle which carried neither a positive nor a negative charge, and he decided therefore to call the particle, neutron.

Now this was a very interesting discovery but at first these neutrons proved to be rather elusive.

You could not make visible and see the track of the neutron.

You could produce neutrons but you could not collect them in any bottle because, having no charge, the neutrons would pass through the wall of the bottle.

In those early days experiments with neutrons were rather clumsy to perform, they required some instrument like a Wilson cloud chamber which is suitable for some experiments but not so suitable for others.

Progress of neutron physics would have probably remained slow if it had not been for another discovery made by Joliot and his wife, Irene Curie.

I am speaking of the discovery that it is possible to make elements artifically radioactive.

Now the thought that when we shoot alpha particles at some element and smash nuclei of that element that we might then produce unstable or radioactive elements did not escape earlier investigators.

If you look at the last edition of the classical textbook on radioactivity by Rutherford, Chadwick and Ellis, printed in the 1930's, you will find a paragraph devoted to this topic.

Rutherford and his school made some such experiments and they summed up their results in one short paragraph.

Their experiments showed that the disintegration of elements by alpha particles leads to stable and not to radioactive elements.

"This conclusion appears inescapable"—so they stated—"unless the elements produced should happen to be beta ray emitters."

But the joke is that the artificial radioactive elements which Joliot later produced from ordinary elements by bombarding them with alpha particles all happen to be beta ray emitters.

Beta rays cannot be easily observed in the same manner as alpha particles can, but they can be detected by means of a so-called Geiger-Muller counter tube.

It may be that the discovery of artificial radioactivity had to wait until the Geiger-Muller counter became available.

Each time an electron passes through a Geiger-Muller tube, it causes an electric discharge which can be made visible and can be registered.

Such a Geiger-Muller tube will not only register the electrons from the beta rays of radioactive elements but will also register the electrons of the cosmic rays which pass through it.

In the counter tube of the usual size, you obtain something like 20 discharges per minute from the cosmic ray particles passing through the counter and this count of about 20 per minute is called the background of the counter.

E. O. Lawrence of Berkeley California, relates that sometime in the 30's, he thought of using such a Geiger-Muller tube for various experiments in the laboratory where his cyclotron was installed.

He had no previous experience with these counter tubes and he put one of his students to work on it.

Of course, during the time when the cyclotron was in operation its radiations interfered with the counter, but whenever the cyclotron was switched off, they could turn on the counter tube and begin to experiment with it.

To his dismay, Lawrence found however that he could not get the background of his counter tube to be constant.

On some days the background count was down to 20 per minute, as it should be, but on other days it was 100-200 or even 1000 counts per minute.

Clearly, the background of the counter was as the physicist would put it, irreproducible.

Since he had no previous experience with it, Lawrence concluded that the Geiger-Muller counter was an unreliable instrument, not fit to be used in his laboratory.

Today, we can easily understand just what took place in these Berkeley experiments.

During the operation of the cyclotron the copper parts of the cyclotron became radioactive.

When the cyclotron was switched off, these copper parts continued to give off radiations which affected the Geiger-Muller counter and were registered by the counter in the form of 100 or on some days, 1000 counts per minute.

So what may be considered the greatest discovery of this century was passed by at Berkeley as a mere nuisance.

In physics it is really difficult to know how to behave.

Perhaps Lawrence did make the mistake of not trusting his eyes.

But in physics, while you may look like an idiot if you do not trust your eyes, you may also look like a fool if you do.

In physics, there are no recipes which you can follow, and all we can say is that in the present case, Joliot succeeded where Lawrence failed.

In 1933 Joliot was again bombarding some light elements such as boron with alpha particles and he noticed that, apart from the mysterious penetrating radiation which he now knew were neutrons, boron also emitted positive electrons under the effect of this boron bombardment.

Joliot registered these positive electrons by means of a Geiger-Muller counter and one day, towards the end of 1933, he noticed that when he cut off the alpha particles from the boron, the Geiger-Muller counter still continued to register electrons.

These electrons did not keep on coming however for very long.

Their number fell off fairly rapidly and they vanished after a few minutes.

At first Joliot thought he had to deal with some curious after effect in the Geiger-Muller counter.

He did not conclude, as Lawrence did, that the counter is an unreliable instrument.

He merely concluded that there was something wrong with his particular counter.

So he had his counter tested, and having convinced himself that there was nothing wrong with it, he saw at last that he had to deal with a new phenomenon.

Boron, if bombarded with alpha particles, undergoes a nuclear transmutation.

It turns into a radioactive nitrogen which emits positive electrons and in doing so, transmutes into stable carbon.

A number of other light elements can be made radioactive in the same way, that is, simply by bombarding them with alpha particles.

Now, the discovery of artificial radioactivity had been predicted as early as 1914.

It had been predicted not by any physicist, but by H. G. Wells. Wells put this discovery into the year of 1933, the year in which it actually happened.

His book, called "The World Set Free," was published before the first World War, and goes far beyond predicting Joliot's discovery.

It also predicts the large scale liberation and industrial use of atomic energy, the manufacture of atomic bombs, and a world war in 1956 in which Chicago, Paris, London, and other cities are destroyed at the very outbreak of the war.

According to Wells, these cities are transformed into rubble, or to be quite precise, into radioactive rubble.

Finally, the book describes how after this catastrophe, a world government is established and begins to operate.

For all we know, every single one of these predictions may yet come true.

I happened to read Well's book in 1932 and at that time I did not have the notion that it had much to do with reality.

I remember very clearly that the first thought that liberation of atomic energy might in fact be possible came to be in October 1933, as I waited for the change of a traffic light in Southampton Row in London.

The thought did not come entirely out of the clear sky.

A week or two earlier there had been the annual meeting of the British Association and Lord Rutherford was reported to have said at that meeting that whoever talks of the large scale liberation of atomic energy is talking moonshine.

I was wondering whether Rutherford was right when it occurred to me that neutrons, in contrast to alpha particles, do not ionize the substance through which they pass.

Consequently, neutrons need not stop until they hit a nucleus with which they may react.

If we could now find an element which captures neutrons, and in the process of doing so, emits further neutrons, we might have something like a chain reaction.

This looked like a rather attractive possibility, but the question was, is there such an element which captures a neutron and emits other neutrons in its place and if there is such an element, how would we recognize it.

I did not see how to go about looking for such elements, until a few months later, when I learned of Joliot's discovery that alpha particles can make elements radioactive.

If alpha particles can do this it was reasonable to think that neutrons could do it also and indeed this was demonstrated shortly afterwards by Fermi.

Fermi found that if you have a neutron radiation and if you expose for instance Iodine to this radiation, the neutrons will be captured by the Iodine atoms and you obtain a radioactive Iodine which will emit beta rays and which decays to half of its amount in about twenty-five minutes.

Many other elements behave quite similarly.

Now it became possible to devise new types of experiments with neutrons, in which the presence of the invisible neutrons could be detected by their ability to make iodine, and other elements, radioactive.

This new technique appeared to me to be so promising that I decided to start experimenting with neutrons even though prior to this time I had done no work whatsoever in the field of nuclear physics.

By 1935, I began to take very seriously the thought that some elements might emit more than one neutron for every neutron which they capture, and that they might therefore be capable of sustaining a chain reaction.

I particularly suspected the elements which showed a peculiar phenomenon called isomerism and among them were indium, bromium, and uranium. But there was no telling which of the elements would really perform this service.

So it appeared that rather than to try to be too clever, one ought to examine patiently all of the 92 elements in order to detect which of them might show such a phenomenon.

None of my colleagues among the physicists seemed to show much enthusiasm for such a project and I thought that I might perhaps have better luck with some of the chemists.

To the chemist, the word "chain reaction," had at least a familiar sound.

For chain reactions, of a sort, can be set up in some chemical mixtures, for instance, in a mixture of chlorine and hydrogen gas.

So, one day, I paid a visit to a distinguished chemist who had shown signs of vision and courage in the past and told him of these thoughts, suggesting that we organize a survey, going through the whole periodic system of the elements.

The cost of the survey estimated at $8,000.

This proposal was favorably received, but somehow the funds did not materialize and the survey did not get under way.

Though some preparations were made and some apparatus was actually built.

Of course, I had no conception of uranium breaking up into two about equally heavy fragments; that is, I had no conception of what is these days called, the fission process.

Later on, as my knowledge of nuclear physics increased, my faith in the possibility of a chain reaction gradually decreased, and just about reached the vanishing point at the time when fission was actually discovered in Europe.

Apparently between the years of 1935 and 1938 I went through the process of becoming an expert, that is, a man who knows what cannot be done.

I have no apology to offer and my only consolation is that I was in very good company.

For fission really ought to have been discovered as early as 1934.

Uranium was not overlooked by Fermi who was the first one to make elements radioactive by bombarding them with neutrons.

He bombarded uranium with neutrons and found that quite a number of radioactive elements are produced from it.

Since uranium was the heaviest element and since these radioactive elements could not be identified with any of the other known radioactive elements which are lighter than uranium, Fermi concluded that he produced transuranic elements.

For the discovery of these transuranic elements, he was awarded the Nobel Prize in 1938.

The Swedish Academy has always been very anxious to avoid awarding the Nobel Prize for advances which later on might turn out to have been in error and therefore in general it does not like to award the Nobel Prize for results which are derived by means of theory rather than by means of experiments.

This is probably the reason why the Swedish Academy preferred to give Fermi the Nobel Prize for the discovery of transuranic elements rather than for his beautiful theory of beta ray emission.

But unfortunately, truth in science is a rather elusive creature, and the principle of "safety first" is not a reliable guide for action in any field of human endeavour.

Fermi's transuranic elements were further investigated and were incorporated in a more and more elaborate pattern of new radioactive elements by Hahn and Meitner in Germany.

This went on until the end of 1938 when suddenly the soap bubble burst and Hahn himself discovered that he had been wrong all along.

Uranium splits into two approximately equally heavy fragments in a number of different ways and these fragments which are radioactive are responsible for the radioactivities which were previously thought to belong to transuranic elements.

It seems to me we ought to thank God that the fission of Uranium was not discovered, as it should have been, in 1934 or in 1935.

It is almost certain that if this discovery had been made at that time, with Germany planning for war and England and America being in the frame of mind in which they were, the Germans would have found a way to make a chain reaction and would have won the war within a few weeks after they started it.

Perhaps those of us who missed this discovery 12 years ago, ought to be considered as candidates for the next award of the Nobel Prize for Peace.

The news of fission reached us here in the United States in January 1939.

I personally heard about fission first through Mr. Wigner, whom I visited in Princeton and immediately I was convinced that neutrons would be emitted in the process.

So the question arose, how to demonstrate this fact by means of experiments? As it turned out, Fermi in New York and Joliot in Paris, had also thought of this possibility and were also devising experiments for the same purpose.

Three different experiments got thus under way and were completed practically at the same time, in the first week of March, 1939.

About two neutrons were found to be emitted from every uranium atom which undergoes fission and the big question was: does it mean that we can make a chain reaction in a large mass containing uranium.

The mere fact that two neutrons are emitted in fission is not sufficient for answering this question.

As Bohr immediately realized, uranium 238, which makes up 99 per cent of uranium, does not undergo fission if it absorbs a neutron.

Only uranium 235 which accounts for less than 1 per cent of the uranium, will split when it absorbs a neutron and will emit additional neutrons.

So the question arose, will the uranium 238 which forms the bulk of uranium, so strongly compete for neutrons with uranium 235 that it will make a chain reaction in natural uranium impossible?

Since uranium 235 likes to react with slow neutrons, conditions for a chain reaction could obviously be made more favorable by mixing uranium with something that will slow down the neutrons.

Now the classical agent for slowing down neutrons is hydrogen.

The neutrons will collide with hydrogen atoms and on the average, their velocity will drop down to half in each such collision.

As a practical matter, hydrogen is used not in the form of hydrogen gas, but in the form of water.

And so, in May of 1939, Fermi, Anderson, and I began to experiment at Columbia University with mixtures of uranium and water.

Joliot, Halban and Kowarski did the same in Paris.

As I said before, a neutron which is produced in such a system will not necessarily cause fission in U 235.

It may die, by being absorbed in U 238 which makes up 99 per cent of the natural uranium.

It may also die after it has been slowed down in such a system by being absorbed in the water rather than in uranium.

So, the question, whether a uranium-water mixture can maintain a self-sustaining chain reaction, had to be decided by rather elaborate measurement of the balance of all these different absorption processes.

The last experiment which was performed by us on such a system in the United States was completed in June of 1939 and was not wholly decisive.

But I personally rather lost faith in this system at the time.

I felt that even if a chain reaction could be maintained in a uranium-water mixture, we would have to deal with very disagreeable chemical processes in such a system, if we attempted to use it for the liberation of atomic energy on a large scale.

The radiations emitted from uranium would decompose water into hydrogen and oxygen and this explosive gas mixture would have to be removed.

So, from an engineering point of view, the water-uranium system appeared to be a rather messy one.

It was this consideration which first led me to contemplate the possibility of using graphite, rather than water, for slowing down the neutrons. Then gradually, from July 1939 until February 1940, I became more and more convinced that it should be possible to set up a chain reaction in a graphite-uranium system.

The first experiments with graphite were started at Columbia University in April of 1940, and would have very quickly led to the establishment of a chain reaction if it had not been for the slowness of securing the needed materials in the required degree of purity.

The fact is, however, that the chain reaction was not actually produced until the 2nd of December, 1942, when it was first in operation here at the Campus of the University of Chicago.

Perhaps this is a good time to pause and to ask ourselves what were the fundamental discoveries which led to the liberation of atomic energy?

In answer to this question I would list only three discoveries.

1) The discovery of Becquerel, that uranium minerals emit x-rays, which led to the study of radioactivity.

2) Joliot's discovery, that the penetrating radiation emitted from boron, under bombardment with alpha particles, is capable of knocking out protons from paraffin wax.

It was this discovery which led to the study of the neutron.

3) And finally, Joliot's discovery that boron, if bombarded by alpha-particles, emits positive electrons because this led to the discovery of artificial radioactivity.

It may very well be that if Becquerel had not lived, another hundred years might have had to pass before radium was discovered.

It may very well be, that if Joliot had not fooled around with paraffin wax, another fifty years might be needed before the neutron was discovered.

And, it may very well be, that if Joliot had not noticed the positive electrons coming from the boron, the discovery of artificial radioactivity might have been delayed for a further twenty-five years.

It is curious indeed that all these fundamental discoveries were made in France.

Naturally, there were many other important discoveries along the road, many of them fully deserving the Nobel Prize, but in a way, all these other discoveries were inevitable consequences of these three fundamental steps which I have listed.

Returning now to the state of our knowledge as it was in February 1940, even though it appeared almost certain that we can set up a chain reaction in a uranium-graphite system, there was still another step missing before we became aware of the full importance of this line of development.

This missing step was made by Turner in Princeton.

Turner, who knew of the work which Fermi and I were getting under way in the Spring of '40, sent us a manuscript in which he pointed out the importance of a secondary reaction which would accompany any such chain reaction.

As I mentioned repeatedly, a fraction of the neutrons in the chain reaction will be captured by Uraniun 238.

This leads to a radioactive element which after going through two beta transformations, goes over into a long-lived element nowadays called Plutonium.

Fermi and I considered this absorption of neutrons by U238 merely as a nuisance.

Turner pointed out that the resulting element, plutonium, will be capable of fission, just as U235 is capable of fission.

There are however significant differences between plutonium and U235.

U235 is chemically not different from uranium and it takes therefore a very laborious process to separate it from uranium.

Plutonium, being chemically different from uranium, can be separated by ordinary chemical methods.

Another significant difference is that the amount of U235 is strictly limited, its abundance being less than 1 per cent in natural uranium.

Plutonium, since it is produced from uranium 238, which forms more than 99 per cent of natural uranium, is at least in theory, not so severely limited in quantity.

With this remark of Turner, a whole landscape of the future of atomic energy arose before our eyes in the Spring of 1940 and from then on the struggle with ideas ceased and the struggle with the inertia of Man began.

Such further ideas as were necessary for the completion of this work concerned either technical details or concerned the detonation of the bomb.

The former class would not be of interest to you, and the latter one is in an area which is considered highly secret.

The first use of plutonium, as you know, was in the form of a bomb which destroyed a city.

The next use of plutonium might be the same again.

With the production of plutonium carried out on an industrial scale during the war, the dream of the alchemists came true and now we can change, at will, one element into another.

That is more than Mme. Curie could do.

But while the first successful alchemist was undoubtedly God, I sometimes wonder whether the second successful alchemist may not have been the Devil himself.

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Public Lecture ~~Seminar~~ given at Univ. of Chicago (orga by Milton Singer)

L. Szilard
July 31, 1946

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Any one member of this family either emits beta rays, that is, negatively charged electrons, or it emits alpha rays, that is, positively charged, fast moving helium atoms.

Up to the 30's, it was much easier to observe the single alpha particles of the alpha rays than it was to observe the single electrons of the beta rays.

In air such an alpha particle travels in a straight line over a length of a few centimeters and then it stops.

The range of alpha particles in air is a few centimeters.

Because the alpha particle carries a positive charge, it ionizes the air in its path and therefore it is possible to make visible the track of the alpha particle.

Its track in air can be made visible to the naked eye and can also easily be photographed.

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You have to contrast this with the energy which is liberated when carbon is burned, that is, when a carbon atom combines chemically with two oxygen atoms.

The energy liberated when carbon is burned amounts to a few electron volts.

So you see that as far as energies are concerned, the two types of processes differ by a factor of a million.

Becquerel's original observation that uranium minerals emit rays that blacken the photographic plate was the very first manifestation of the enormous energies liberated in nuclear transformations.

Until that observation was made, physicists had no inkling that there are any sources of energy other than the chemical processes of which the burning of carbon is the most common example.

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Rutherford noticed that an alpha particle does not always travel in air in a straight line along the whole course of its path but that occasionally its track is sharply deflected.

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But now Joliot performed a curious experiment with these penetrating curious experiment with these penetrating rays.

For some reason or other he placed a sheet of paraffin into their path and looked to see if anything was happening to the paraffin.

You might say that this was a rather pointless experiment and there really was very little justification for it.

However, this experiment changed the course of history.

For Joliot found that hydrogen atoms were knocked out of the paraffin by the penetrating radiation to which it was exposed.

Joliot further found that these hydrogen atoms or, more correctly, protons, had curiously enough, energies of several million volts and inevitably the question arose, by what mechanism could x-rays passing through paraffin transmit several million volts of energy to the protons in the paraffin.

There was no such mechanism known and it was therefore pretty evident that Joliot had found a phenomenon which could not be explained on the assumption that the penetrating radiations with which he had to deal were x-rays.

Chadwick, in Cambridge, looked therefore at the tracks of these protons in air and saw that the radiation which was responsible for them must consist of particles which carry no charge since their track in air could not be made visible.

Chadwick found further to his great surprise thatthe mass of these particles must be pretty close to the massof the proton itself.

This meant that he had to deal with some new particle which carried neither a positive nor a negative charge, and he decided therefore to call the particle, neutron.

Now this was a very interesting discovery but at first these neutrons proved to be rather elusive.

You could not make visible and see the track of the neutron.

You could produce neutrons but you could not collect them in any bottle because, having no charge, the neutrons would pass through the wall of the bottle.

In those early days experiments with neutrons were rather clumsy with neutrons were rather clumsy to perform, they required some instrument like a Wilson cloud chamber which is suitable for some experiments but not so suitable for others.

Progress of neutron physics would have probably remained slow if it had not been for another discovery made by Joliot and his wife, Irene Curie.

I am speaking of the discovery that it is possible to make elements artificially radioactive.

Now the thought that when we shoot alpha particles at some element and smash nuclei of that element that we might then produce unstable or radioactive elements did not escape earlier investigators.

If you look at the last edition of the classical textbook on radioactivity by Rutherford, Chadwick and Ellis, printed in the 1930's, you will find a paragraph devoted to this topic.

Rutherford and his school made some such experiments and they summed up their results in one short paragraph.

Their experiments showed that the disintegration of elements by alpha particles leads to stable and not to radioactive elements.

"This conclusion appears inescapable"--so they stated--"unless the elements produced should happen to be beta ray emitters."

But the joke is that the artificial radioactive elements which Joliot later produced from ordinary elements by bombarding them with alpha particles all happen to be beta ray emitters.

Beta rays cannot be easily observed in the same manner as alpha particles can, but they can be detected by means of a so-called Geiger-Muller counter tube.

It may be that the discovery of artificial radioactivity had to wait until the Geiger-Muller counter became available.

Each time an electron passes through a Geiger-Muller tube, it causes an electric discharge which can be made visible and can be registered.

Such a Geiger-Muller tube will not only register the electrons will not only register the electrons from the beta rays of radioactive elements but will also register the electrons of the cosmic rays which pass through it.

In the counter tube of the usual size, you obtain something like 20 discharges per minute from the cosmic ray particles passing through the counter and this count of about 20 per minute is called the background of the counter.

E. O. Lawrence of Berkeley California, relates that sometime in the 30's, he thought of using such a Geiger-Muller tube for various experiments in the laboratory where his cyclotron was installed.

He had no previous experience with these counter tubes and he put one of his students to work on it.

Of course, during the time when the cyclotron was in operation its radiations interfered with the counter, but whenever the cyclotron was switched off, they could turn on the counter tube and begin to experiment with it.

To his dismay, Lawrence found however that he could not get the background of his counter tube to be constant.

On some days the background count was down to 20 per minute, as it should be, but on other days it was 100-200 or even 1000 counts per minute.

Clearly, the background of the counter was as the physicist would put it, irreproducible.

Since he had no previous experience with it, Lawrence concluded that the Geiger-Muller counter was an unreliable instrument, not fit to be used in his laboratory.

Today, we can easily understand just what took place in these Berkeley experiments.

During the operation of the cyclotron the copper parts of the cyclotron became radioactive.

When the cyclotron was switched off, these copper parts continued to give off radiations which affected the Geiger-Muller counter and were registered by the counter in the form of 100 or on some days, 1000 counts per minute.

So what may be considered the greatest discovery of this century was passed by at Berkeley as a mere nuisance.

In physics it is really difficult to know how to behave.

to know how to behave.

Perhaps Lawrence did make the mistake of not trusting his eyes.

But in physics, while you may look like an idiot if you do not trust your eyes, you may also look like a fool if you do.

In physics, there are no recipes which you can follow, and all we can say is that in the present case, Joliot succeeded where Lawrence failed.

In 1933 Joliot was again bombarding some light elements such as boron with alpha particles and he noticed that, apart from the mysterious penetrating radiation which he now knew were neutrons, boron also emitted positive electrons under the effect of this boron bombardment.

Joliot registered these positive electrons by means of a Geiger-Muller counter and one day, towards the end of 1933, he noticed that when he cut off the alpha particles from the boron, the Geiger-Muller counter still continued to register electrons.

These electrons did not keep on coming however for very long.

Their number fell off fairly rapidly and they vanished after a few minutes.

At first Joliot thought he had to deal with some curious after effect in the Gieger-Muller counter.

He did not conclude, as Lawrence did, that the counter is an unreliable instrument.

He merely concluded that there was something wrong with his particular counter.

So he had his counter tested, and having convinced himself that there was nothing wrong with it, he saw at last that he had to deal with a new phenomenon.

Boron, if bombarded with alpha particles, undergoes a nuclear transmutation.

It turns into a radioactive nitrogen which emits positive electrons and in doing so, transmutes into stable carbon.

A number of other light elements can be made radioactive in the same way, that is, simply by bombarding them with alpha particles.

Now, the discovery of artificial radioactivity had been predicted artificial radioactivity had been predicted as early as 1914.

It had been predicted not by any physicist, but by H. G. Wells. Wells put this discovery into the year of 1933, the year in which it actually happened.

His book, called "The World Set Free", was published before the first World War, and goes far beyond predicting Joliot's discovery.

It also predicts the large scale liberation and industrial use of atomic energy, the manufacture of atomic bombs, and a world war in 1956 in which Chicago, Paris, London, and other cities are destroyed at the very outbreak of the war.

According to Wells, these cities are transformed into rubble, or to be quite precise, into radioactive rubble.

Finally, the book describes how after this catastrophe, a world government is established and begins to operate.

For all we know, every single one of these predictions may yet come true.

I happened to read Well's book in 1932 and at that time I did not have the notion that it had much to do with reality.

I remember very clearly that the first thought that liberation of atomic energy might in fact be possible came to me in October 1933, as I waited for the change of a traffic light in Southampton Row in London.

The thought did not come entirely out of the clear sky.

A week or two earlier there had been the annual meeting of the British Association and Lord Rutherford was reported to have said at that meeting that whoever talks of the large scale liberation of atomic energy is talking moonshine.

I was wondering whether Rutherford was right when it occurred to me that neutrons, in contrast to alpha particles, do not ionize the substance through which they pass.

Consequently, neutrons need not stop until they hit a nucleus with which they may react.

If we could now find an element which captures neutrons, an element which captures neutrons, and in the process of doing so, emits further neutrons, we might have something like a chain reaction.

This looked like a rather attractive possibility, but the question was, is there such an element which captures a neutron and emits other neutrons in its place and if there is such an element, how would we recognize it.

I did not see how to go about looking for such elements, until a few months later, when I learned of Juliot's discovery that alpha particles can ~~be~~ make elements radioactive.

If alpha particles can do this it was reasonable to think that neutrons could do it also and indeed this was demonstrated shortly afterwards by Fermi.

Fermi found that if you have a neutron radiation and if you expose for instance Iodine to this radiation, the neutrons will be captured by the Iodine atoms and you obtain a radioactive Iodine which will emit beta rays and which decays to half of its amount in about twenty-five minutes.

Many other elements behave quite similarly.

Now it became possible to devise new types of experiments with neutrons, in which the presence of the invisible neutrons could be detected by their ability to make iodine, and other elements, radioactive.

This new technique appeared to me to be so promising that I decided to start experimenting with neutrons even though prior to this time I had done no work whatsoever in the field of nuclear physics.

By 1935, I began to take very seriously the thought that some elements might emit more than one neutron for every neutron which they capture, and that they might therefore "be capable" of sustaining a chain reaction.

I particularly suspected the elements which showed a peculiar phenomenon called isomerism and among them were indium, bromium, and uranium. But there was no telling which of the elements would really perform this service.

So it appeared that rather than to try to be too clever, one to try to be too clever, one ought to examine patiently all of the 92 elements in order to detect which of them might show such a phenomenon.

None of my colleagues among the physicists seemed to show much enthusiasm for such a project and I thought that I might perhaps have better luck with some of the chemists.

To the chemist, the word "chain reaction", had at least a familiar sound.

For chain reactions, of a sort, can be set up in some chemical mixtures, for instance, in a mixture of chlorine and hydrogen gas.

So, one day, I paid a visit to a distinguished chemist who had shown signs of vision and courage in the past and told him of these thoughts, suggesting that we organize a survey, going through the whole preiodic system of the elements.

The cost of the survey estimated at $8,000.

This proposal was favorably received, but somehow the funds did not materialize and the survey did not get under way.

Though some preparations were made and some apparatus was actually built.

Of course, I had no conception of uranium breaking up into two about equally heavy fragments; that is, I had no conception of what is these days called, the fission process.

Later on, as my knowledge of nuclear physics increased, my faith in the possibility of a chain reaction gradually decreased, and just about reached the vanishing point at the time when fission was actually discovered in Europe.

Apparently between the years of 1935 and 1938 I went through the process of becoming an expert, that is, a man who knows what cannot be done.

I have no apology to offer and my only consolation is that I was in very good company.

For fission really ought to have been discovered as early as 1934.

Uranium was not overlooked by Fermi who was the first one to make elements radioactive by bombarding them with neutrons.

He bombarded uranium with neutrons and found that quite a number of and found that quite a number of radioactive elements are produced from it.

Since uranium was the heaviest element and since these radioactive elements could not be identified with any of the other known radioactive elements which are lighter than uranium, Fermi concluded that he produced transuranic elements.

For the discovery of these transuranic elements, he was awarded the Nobel Prize in 1938.

The Swedish Academy has always been very anxious to avoid awarding the Nobel Prize for advances which later on might turn out to have been in error and therefore in general it does not like to award the Nobel Prize for results which are derived by means of theory rather than by means of experiments.

This is probably the reason why the Swedish Academy preferred to give Fermi the Nobel Prize for the discovery of transuranic elements rather than for his beautiful theory of beta ray emission.

But unfortunately, truth in science is a rather elusive creature, and the principle of "safety first" is not a reliable guide for action in any field of human endeavour.

Fermi's transuranic elements were further investigated and were incorporated in a more and more elaborate pattern of new radioactive elements by Hahn and Meitner in Germany.

This went on until the end of 1938 when suddenly the soap bubble burst and Hahn himself discovered that he had been wrong all along.

Uranium splits into two approximately equally heavy fragments in a number of different ways and these fragments which are radioactive are responsible for the radioactivities which were previously thought to belong to transuranic elements.

It seems to me we ought to thank God that the fission of Uranium was not discovered, as it should have been, in 1934 or in 1935.

It is almost certain that if this discovery had been made at that time, with Germany planning for war and England and America being in the frame of mind in which they were, the Germans would have found a way to make a chain reaction and would have won the war within a few weeks after they started it.

weeks after they started it.

Perhaps those of us who missed this discovery 12 years ago, ought to be considered as candidates for the next award of the Nobel Prize for Peace.

The news of fission reached us here in the United States in January 1939.

I personally heard about fission first through Mr. Wigner, whom I visited in Princeton and immediately I was convinced that neutrons would be emitted in the process.

So the question arose, how to demonstrate this fact by means of experiments? As it turned out, Fermi in New York and Joliot in Paris, had also thought of this possibility and were also devising experiments for the same purpose.

Three different experiments got thus under way and were completed practically at the same time, in the first week of March, 1939.

About two neutrons were found to be emitted from every uranium atom which undergoes fission and the big question was: does it mean that we can make a chain reaction in a large mass containing uranium.

The mere fact that two neutrons are emitted in fission is not sufficient for answering this question.

As Bohr immediately realized, uranium 238, which makes up 99 percent of uranium, does not undergo fission if it absorbs a neutron.

Only uranium 235 which accounts for less than 1 percent of the uranium, will split when it absorbs a neutron and will emit additional neutrons.

So the question arose, will the uranium 238 which forms the bulk of uranium, so strongly compete for neutrons with uranium 235 that it will make a chain reaction in natural uranium impossible?

Since uranium 235 likes to react with slow neutrons, conditions for a chain reaction could obviously be made more favorable by mixing xxxx uranium with something that will slow down the neutrons.

that will slow down the neutrons.

Now the classical agent for slowing down neutrons is hydrogen.

The neutrons will collide with hydrogen atoms and on the average, their velocity will drop down to half in each such collision.

As a practical matter, hydrogen is used not in the form of hydrogen gas, but in the form of water.

And so, in May of 1939, Fermi, Anderson, and I began to experiment at Columbia University with mixtures of uranium and water.

Joliot, Halban and Kowarski did the same in Paris.

As I said before, a neutron which is produced in such a system will not necessarily cause fission in U 235.

It may die, by being absorbed in U238 which makes up 99 percent of the natural uranium.

It may also die after it has been slowed down in such a system by being absorbed in the water rather than in uranium.

So, the question, whether a uranium-water mixture can maintain a self-sustaining chain reaction, had to be decided by rather elaborate measurement of the balance of all these different absorption processes.

The last experiment which was performed by us on such a system in the United States was completed in June of 1939 and was not wholly decisive.

But I personally rather lost faith in this system at the time.

I felt that even if a chain reaction could be maintained in a uranium-water mixture, we would have to deal with very disagreeable chemical processes in such a system, if we attempted to use it for the liberation of atomic energy on a large scale.

The radiations emitted from uranium would decompose water into hydrogen and oxygen and this explosive gas mixture would have to be removed.

So, from an engineering point of view, the water-uranium system appeared to be a rather messy one.

It was this consideration which first led me to contemplate the possibility of using graphite, rather than water, for slowing down the neutrons. Then gradually, from July 1939 until February 1940, I became more and more convinced that it should be possible to set up a chain reaction in a graphite-uranium system.

a chain reaction in a graphite-uranium system.

The first experiments with graphite were started at Columbia University in April of 1940, and would have very quickly led to the establishment of a chain reaction if it had not been for the slowness of securing the needed materials in the required degree of purity.

The fact is, however, that the chain reaction was not actually produced until the 2nd of December, 1942, when it was first in operation here at the Campus of the University of Chicago.

Perhaps this is a good time to pause and to ask ourselves what were the fundamental discoveries which led to the liberation of atomic energy?

In answer to this question I would list only three discoveries.

1) The discovery of Becquerel, that uranium minerals emit x-rays, which led to the study of radioactivity,

2) Joliot's discovery, that the penetrating radiation emitted from boron, under bombardment with alpha particles, is capable of knocking out protons from paraffin wax.

It was this discovery which led to the study of the neutron.

3) And finally, Joliot's discovery that boron, if bombarded by alpha-particles, emits positive electrons because this led to the discovery of artificial radioactivity.

It may very well be that if Becquerel had not lived, another hundred years might have had to pass before radium was discovered.

It may very well be, that if Joliot had not fooled around with paraffin wax, another fifty years might be needed before the neutron was discovered.

And, it may very well be, that if Joliot had not noticed the positive electrons coming from the boron, the discovery of artificial radioactivity might have been delayed for a further twenty-five years.

It is curious indeed that all these fundamental discoveries were made in France.

Naturally, there were many other important discoveries along the road, many of them fully deserving the Nobel Prize, but in a way, all these other discoveries were inevitable consequences of these three fundamental steps which I have listed.

Returning now to the state of our knowledge as it was in February 1940, as it was in February 1940, even though it appeared almost certain that we can set up a chain reaction in a uranium-graphite system, there was still another step missing before we became aware of the full importance of this line of development.

This missing step was made by Turner in Princeton.

Turner, who knew of the work which Fermi and I were getting under way in the Spring of '40, sent us a manuscript in which he pointed out the importance of a secondary reaction which would accompany any such chain reaction.

As I mentioned repeatedly, a fraction of the neutrons in the chain reaction will be captured by Uranium 238.

This leads to a radioactive element which after going through two beta transformations, goes over into a long-lived element nowadays called Plutonium.

Fermi and I considered this absorption of neutrons by U238 merely as a nuisance.

Turner pointed out that the resulting element, plutonium, willbe capable of fission, just as U235 is capable of fission.

There are however significant differences between plutonium and U235.

U235 is chemically not different from uranium and it takes therefore a very laborious process to separate it from uranium.

Plutonium, being chemically different from uranium, can be separated by ordinary chemical methods.

Another significant difference is that the amount of U235 is strictly limited, its abundance being less than 1 percent in natural uranium.

Plutonium, since it is produced from uranijm 238, which forms more than 99 percent of natural uranium, is at least in theory, not so severely limited in quantity.

With this remark of Turner, a whole landscape of the future of atomic energy arose before our eyes in the Spring of 1940 and from then on the struggle with ideas ceased and the struggle with the inertia of Man began.

Such further ideas as were necessary for the completion of this work concerned either technical details or concerned the detonation of the bomb.

The former class would not be of interest to you, and the latter one is in an area which is considered highly secret.

The first use of plutonium, as you know, was in the form of a bomb was in the form of a bomb which destroyed a city.

The next use of plutonium ight be the same again.

With the production of plutonium carried out on an industrial scale during the war, the dream of the alchemists came true and now we can change, at will, one element into another.

That is more than Mme. Curie dould do.

But while the first successful alchemist was undoubtedly God, I sometimes wonder whether the second successful alchemist may not have been the Devil himself.

* * * * *

L. Szilard
July 31, 1946

CREATIVE INTELLIGENCE AND SOCIETY

THE CASE OF ATOMIC RESEARCH ([illegible])

THE BACKGROUND IN FUNDAMENTAL SCIENCE

As you probably know, it all started one day around the turn of the century when Becquerel in Paris noticed that uranium minerals placed in a drawer near some photographic plates ~~in a drawer~~ blackened those ~~photographic~~ plates.

Uranium minerals affected photographic plates even if they were wrapped in black paper, yes, even if they were placed in a wooden or metal case.

This effect of uranium minerals was due to penetrating rays which they emitted and which were similar to x-rays.

Immediately the question arose, where does the energy for these x-rays come from? But it took a few yearsbefore the answer to this question was found.

Madame Curie ~~who~~ was at that time ~~was~~ a graduate student with Becquerel, and she had a suspicion that uranium minerals contained some element other than uranium which was more active than uranium. And as you know, years later she isolated radium from such minerals.

Radium which was an element until then unknown, is chemically rather similar to barium.

It slowly changes over into another radioactive element which is chemically ~~is~~ different from it.

This other element is not similar to barium but is similar to neon and like neon it is a gas.

It is called radon or radium emanation in order to indicate that it emanates from radium.

We ~~describe~~ refer to this by saying that radium undergoes a spontaneous transmutation. Its half lifetime is about 1500 years which means that out of one gram of radium during a period of 1500 years, ½ gram will ~~have~~ transmute~~d~~ into radium emanation.

Transmuting one chemical element into another chemical element

element into another chemical element was, as you know, the unsolved problem of the alchemists.

But Madame Curie, who isolated radium could not pride herself to be a successful alchemist.

She did not produce radium.

She merely separated it chemically from a mineral in which it was previously contained and she was in no position either to accelerate or even to slow down the transmutation of radium into radium emanation.

So, in spite of this new discovery, God remained the first and only successful alchemist.

As uranium and radium were further investigated it gradually became apparent that we had to deal with a whole family of naturally occurring radioactive elements.

Any one member of this family either emits beta rays, that is, negatively charged electrons, or it emits alpha rays, that is, positively charged, fast moving helium atoms.

Up to the 30's, it was much easier to observe the single alpha particles of the alpha rays than it was to observe the single electrons of the beta rays.

In air such an alpha particle travels in a straight line over a length of a few centimeters and then it stops.

~~We express this by saying that~~ the range of alpha particles in air is a few centimeters.

Because the alpha particle carries a positive charge~~, and thereby~~ it ionizes the air in its path, and therefore it is possible to make visible the track of the alpha particle. ~~[illegible]~~.

Its track in air can be made visible to the naked eye and can also easily be photographed.

When an atom of a radioactive element emits an alpha particle it undergoes a spontaneous transmutation and goes over into a chemically different element.

A Radium atom for instance which is similar to barium emits an alpha particle which is similar to barium emits an alpha particle and becomes ~~a gas~~ an atom of Radium emanation which is similar to neon. ~~similar to neon.~~

The alpha particle which is emitted carries away the energy liberated in this ~~spontaneous~~ transformation ~~of~~ from one chemical element into another chemical element and the energy liberated in such a process is of the order of several million e-volts.

You have to contrast this with the energy which is liberated when carbon is burned, that is, when a carbon atom combines chemically with two oxygen atoms.

The energy liberated when carbon is burned amounts to a few electron volts.

So you see that as far as energies are concerned, the two types of processes differ by a factor of a million.

Becquerel's original observation that uranium minerals emit~~ted~~ rays that blacken~~ed~~ the photographic plate ~~were~~ was the very first manifestation of the enormous energies liberated in nuclear transformations. Until that observation was made, physicists had no inkling that there are any sources of energy other than the chemical process as of which the burning of carbon is the most common example.

Much of the investigation of the properties of radioactive elements and the behavior of alpha particles was done by Rutherford.

Rutherford noticed that an alpha particle does not always travel in air in a straight line along the whole course of its ~~track~~ path but that occasionally ~~the~~ its track is sharply deflected.

As long as an alpha particle merely ionizes the air, its track remains straight but when it hits the nucleus of a nitrogen or oxygen atom, the alpha particle gets sharply deflected.

Insert Here.

~~Observations of this sort led Rutherford to the conclusion that the oxygen and nitrogen atoms which compose the air must have a positively charged nucleus which is surrounded by electrons that neutralize its charge.~~

~~So what has been later called the Rutherford-Bohr atom model, which today is the foundation of modern chemistry, was derived from experiments which used as a tool the emission of alpha particles which is a nuclear phenomenon.~~

~~So you see science had to borrow tools from the nucleus in order to understand chemistry, while these same nuclear tools were at first~~

INSERT to page 3

But sometimes the track of the alpha particle in air is neither a straight line nor a line with a break, but a line which shows a fork.

Pictures of this sort were first obtained by Blackett in Rutherford's laboratory and were interpreted on the basis of some early experiments of Rutherford, by assuming that an alpha particle........

~~nuclear tools were at first of not much help to the understanding of the nucleus itself.~~

Ins

~~Somewhat later it was observed that the track of the alpha particle in air sometimes showed a fork.~~

~~This was interpreted by Rutherford by assuming that an~~ alpha particle smashed a nitrogen nucleus and knocked a proton out of it while the alpha particle itself was captured by the nucleus.

According to Rutherford the long track of the proton and the short track of the rest of the nucleus formed the fork which was observed.

It was evident that in an individual process of this type, energy could be liberated but it was also easy to see that processes of this type could not lead to large scale liberation of nuclear energy.

Because for every track which showed a fork there were thousands of tracks which did not and this means that in most cases the alpha particle does not produce energy but loses its own energy by ionizing the air through which it travels.

Whenever a charged particle moves through matter, it will ionize and in the mast majority of the cases it will lose its energy and stop before it has had a chance to make a collision with a nucleus and to smash that nucleus.

Looking back at the steps which led us from the discovery of radium to the large scale liberation of atomic energy by means of a chain reaction, we can now see that the alpha particles were able to give us the answer to almost all of our questions.

In order to discover all the things which we had to know, we merely had to observe the tracks of these alpha particles in air and to look sharp and see what happened when alpha particles were allowed to bombard various elements.

Bothe in Germany bombarded with alpha particles ~~bombarded~~ some light elements such as boron and beryllium and he ~~observed~~ noticed a penetrating radiation emanating during the bombardment ~~of~~ from these light elements.

He thought he had to deal with penetrating x-rays or gamma rays.

Insert to Page 4.

He thought he had to deal with penetrating x-rays or gamma rays.

And this was an interesting discovery but nothing to get excited about.

But now Joliot performed a curious experiment with this penetrating ~~radiation.~~ rays.

For some reason or other he placed a sheet of paraffin into ~~its~~ their path and looked to see if anything was happening to the paraffin.

You might say that this was a rather pointless experiment and there really was very little justification for it.

However, this experiment changed the course of history.

For Joliot found that hydrogen atoms were knocked out of the paraffin by the penetrating radiation to which it was exposed.

~~with penetrating x-rays or gamma rays.~~

~~This was nothing to get excited about but Joliot who interposed layers of paraffin in the paths of these rays--incidentally a rather pointless thing to do--noticed that hydrogen atoms were knocked out of the paraffin by this penetrating radiation.~~

Joliot further found that these hydrogen atoms or more correctly, protons, had curiously enough energies of sereral million volts and inevitably the question arose, by what mechanism could x-rays passing through paraffin transmit several million votls of energy to the protons in the paraffin.

There was no such mechanism known and it was therefore pretty evident that Joliot had found a phenomenon which could not be explained on the assumption ~~of~~ that the penetrating radiations with which he had to deal were x-rays.

Chadwick in ~~Rutherford's Laboratory~~ Cambridge looked therefore at the tracks of these protons in air and saw that the radiation which was responsible for them must consist of particles which ~~have~~ carry no charge since their track in air could not be made visible.

Chadwick found further to his great surprise that the mass of these particles must be pretty close to the mass of the proton itself.

This meant that he had to deal with some new particle which carried neither a positive nor a negative charge. ~~and~~ He decided therefore to call the particle, neutron.

Now this was a very interesting discovery but at first these neutrons proved to be rather elusive.

You could not make visible and see the track of the neutron.

You could produce neutrons but you could not ~~keep~~ collect them in any bottle because, having no charge, the neutrons would pass through the wall of the bottle.

In those early days experiments with neutrons were rather clumsy with neutrons were rather clumsy to perform, they required some instrument like ~~the~~ a Wilson cloud chamber which is suitable for some experiments but not so ~~un~~suitable for others.

Progress of neutron physics would have probably remained slow if it had not been for another discovery made ~~at the end of 1935~~ by Joliot and his wife, Irene Curie.

I am speaking of the discovery that it is possible to make elements artificially radioactive.

Now the thought that when we shoot alpha particles ~~of~~ at some element and smash nuclei of that element that we might then produce unstable or radioactive elements ~~had~~ did not escape~~d~~ earlier investigators.

If you look at the last edition of the classical textbook on radioactivity by Rutherford, Chadwick and Ellis, printed in the 1930's, you will find a paragraph devoted to this topic.

Rutherford and his school made some such experiments and they summed up their results in one short paragraph.

Their experiments showed that the disintegration of elements by alpha particles ~~led~~ leads to stable and not to radioactive elements.

"This conclusion appears inescapable"--so they stated--"unless the elements produced should happen to be beta ray emitters."

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In the counter tube of the usual size, you obtain something like 20 discharges per minute from the cosmic ray particles passing through the counter and this count of about 20 per minute is called the background of the counter.

E. O. Lawrence of Berkeley California, relates that sometime in the 30's, he thought of using such a Geiger-Muller tube for various experiments in the laboratory where his cyclotron was installed.

He had no previous experience with these counter tubes and he put one of his students to work on it.

Of course, during the time when the cyclotron was in operation its radiations interfered with the ~~Geiger-Muller~~ counter, but whenever the cyclotron was switched off, they could turn on the counter tube and begin to experiment with it.

To his dismay, Lawrence found however that he could not get the background of his counter tube to be constant.

On some days the background count was down to 20 per minute, as it should be, but on other days it was 100-200 or even 1000 counts per minute.

Clearly, the background of the counter was as the physicist would put it, irreproducible.

Since he had no previous experience with it, Lawrence concluded that the Geiger-Muller counter was an unreliable instrument, not fit to be used in his laboratory.

Today we can easily understand just what took place in these Berkeley experiments.

During the operation of the cyclotron the copper parts of the cyclotron became artificially radioactive.

When the cyclotron was switched off, these copper parts continued to give off radiations which affected the Geiger-Muller counter and were registered by the counter in the form of 100 or on some days, 1000 counts per minute.

So what may be considered the greatest discovery of this century was passed by at Berkeley as a mere nuisance.

In physics it is really difficult to know how to behave.

to know how to behave.

Perhaps Lawrence did made the mistake of not trusting his eyes.

But in physics while you may look like an idiot if you do not trust your eyes, you may also look like a fool if you do.

In physics there are no recipes which you can follow , and all we can say is that in the present case, Joliot succeeded where Lawrence failed.

In 1933 Joliot was again bombarding some light elements such as boron with alpha particles and he noticed that apart from the mysterious penetrating radiation which he now knew were neutrons, boron ~~at the same time~~ also emitted positive electrons, under the effect of this boron bombardment.

Joliot registered these positive electrons by means of a Geiger-Muller counter and one day towards the end of 1933 he noticed that when he cut off the alpha particles from the boron, the Geiger-Muller counter still continued to register electrons.

These electrons did not keep on coming however for very long.

Their number fell off fairly rapidly and they vanished after a few minutes.

At first ~~he~~ Joliot thought he had to deal with some curious after effects in the Geiger-Muller counter.

~~Joliot~~ He did not conclude, as Lawrence did, that the Geiger Counter is an unreliable instrument.

He merely concluded that there was ~~nothing~~ something wrong with his particular counter.

So he had ~~the~~ his counter tested, and having convinced himself that there was nothing wrong with it, he saw at last that he had to deal with a new phenomenon.

Boron, if bombarded with alpha particles undergoes a nuclear transmutation.

It turns into a radioactive nitrogen which emits positive electrons and in doing so transmutes into stable carbon.

A number of other light elements can be made radioactive in the same way, that is, simply by bombarding them with alpha particles.

Now the discovery of artificial radioactivity had been predicted artificial radioactivity had been predicted as early as 1914.

It had been predicted not by any physicist~~s~~, but by H. G. Wells, ~~who~~ Wells put this discovery into the year of 1933, the year in which it actually happened.

His book called "The World Set Free", was published before the first World War, and goes far beyond predicting Joliot's discovery.

It also predicts the large scale liberation and industrial use of atomic energy, the manufacture of atomic bombs, and a world war in 1956 in which Chicago, Paris, London, and other cities are destroyed at the very outbreak of the war.

According to Wells, ~~the~~ these cities are transformed into rubble, or to be quite precise, into radioactive rubble.

Finally the book describes how after this catastrophe, a world government is established and begins to operate.

For all we know, every single one of these predictions may yet come true.

~~XX~~ I happened to read Wells' book in 1932 and at that time I did not have the notion that it had much to do with reality.

I remember very clearly that the first thought that liberation of atomic energy might in fact be possible came to me in October 1933 as I waited for ~~a~~ the change of a traffic light in Southampton Row in London.

The thought did not come entirely out of the clear sky.

A week or two earlier there had been the annual meeting of the British Association and Lord Rutherford was reported to have said at that meeting that whoever talks of the large scale liberation of atomic energy is talking moonshine.

I was wondering whether Rutherford was right when it occurred to me that neutrons, in contrast to alpha particles, do not ionize the substance through which they pass.

Consequently neutrons ~~are~~ need not stop~~ped~~ until they hit a nucleus with which they may react.

If we could now find an element which captures neutrons, an element which captures neutrons, and in the process of doing so, emits further neutrons, we might have something like a chain reaction.

This looked like a rather attractive possibility, but the question was, is there such an element which captures a neutron and emits other neutrons in its place and if there is such an element, how would we recognize it.

I did not see how to go about looking for such elements, until a few months later when I learned of Joliot's discovery that alpha particles can make elements radioactive.

If alpha particles can do this it was reasonable to think that neutrons could do it also and indeed this was demonstrated shortly afterwards by Fermi.

Fermi found that if you have a neutron radiation and if you expose for instance Iodine to this radiation, the neutrons will be captured by the Iodine atoms and ~~we~~ you obtain a radioactive Iodine which will emit beta ray, ~~emission~~ and which decays to half of its amount in about twenty-five minutes.

Many other elements behave quite similarly.

You can make use of the ability of the neutrons to induce radioactivity for the purpose of detecting the presence of neutrons, and from then on I began to think about experiments in which the presence of neutrons could be detected by allowing them to fall on Iodine and by observing the radioactivity induced in the iodine.

Prior to this, I had never worked in the field of nuclear physics but the possibilities of this new technic appeared to me so attractive that I decided to do some neutron experiments.

After having used this technique in various experiments carried out in 1934, in 1935 I began to take seriously the thought that some elements might emit more than one neutron for every neutron which they captured and might therefore be capable of sustaining a chain reaction.

I particularly suspected the elements which showed a peculiar phenomenon called isomerism and among them were indium, bromium, and uranium. But there was no telling which of the elements would really perform ~~the miracle~~ this service.

So it appeared that rather than to try to be too clever, one to try to be too clever, one ~~might~~ ought to examine patiently all of the 92 elements in order to detect which of them might show such a phenomenon.

None of my colleagues among the physicists seemed to show much ~~any~~ enthusiasm for such a project and I thought that I might perhaps have better luck with some of the chemists.

To the chemist, the word "chain reaction", had at least a familiar sound.

For chain reactions of a sort can be set up in some chemical mixtures, for instance, in a mixture of chlorine and hydrogen gas.

So, one day, I paid a visit to a distinguished chemist who had shown signs of vision and courage in the past and told him of these thoughts, suggesting that we organize a survey, going through the whole periodic system of the elements.

The cost of the survey ~~were~~ was estimated at $8,000.

This ~~My~~ proposal was favorably received, but somehow the funds did not materialize and the survey did not get under way.

Though some preparations were made and some apparatus was actually built.

Of course, I had no conception of uranium breaking up into ~~about~~ two about equally heavy fragments; that is, I had no conception of what is these days called, the fission process.

Later on, as my knowledge of nuclear physics increased, my faith in the possibility of a chain reaction gradually decreased, and just about reached the vanishing point at the time when fission was actually discovered in Europe.

Apparently between the years of 1935 and 1938 I went through the process of becoming an expert, that is, a man who knows what cannot be done.

I have no apology to offer and my only consolation is that I was in very good company.

For fission really ought to have been discovered as early as 1934.

Uranium was not overlooked by Fermi who was the first ~~man~~ one to make elements radioactive by bombarding them with neutrons.

He bombarded uranium with neutrons and found that quite a number of and found that quite a number of radioactive elements ~~that~~ are produced from it.

Since uranium was the heaviest element and since these radioactive elements could not be identified with any of the other known radioactive elements ~~that~~ which are lighter than uranium, Fermi concluded that he had produced transuranic elements.

For the discovery of these transuranic elements, he was awarded the Nobel Prize in 1938.

The Swedish Academy has always been very anxious to avoid awarding the Nobel Prize for advances which later on might turn out to have been in error and therefore in general it does not like to award the Nobel Prize for results which are derived by means of theory rather than by means of experiments.

This is probably the reason why the Swedish Academy preferred to give Fermi the Nobel Prize for the discovery of transuranic elements rather than for his beautiful theory of beta ray~~s~~ emission, ~~which after all [illegible] might turn out to be wrong.~~

But unfortunately truth in science is a rather elusive creature and the principle of "safety first" is not a reliable guide for action in any field of human endeavour.

Fermi's transuranic elements were further investigated and were incorporated in a more and more elaborate pattern of new radioactive elements by Hahn and Meitner in Germany.

This went on until the end of 1938 when suddenly the ~~whole~~ soap bubble burst and Hahn himself discovered that he had been wrong all along.

Uranium splits into two approximately equally heavy fragments in a number of different ways and these fragments which are radioactive are responsible for the ~~phenomenon previously attributed~~ radioactivities which were previously thought to belong to transuranic elements.

~~The news of this fission process reached us here in the United States in January, 1939.~~

It seems to me we ought to thank God that the fission of uranium was not discovered, as it should have been, in 1934 or in 1935.

It is almost certain that if this discovery had been made at that time, with Germany planning for war and England and America being in the frame of mind in which they were, the Germans would have found a way to make a chain reaction and would have won the war within a few weeks after they started it.

weeks after they started it.

Perhaps those of us who ~~passed by~~ missed this ~~xxxxxxxxxxxx~~ discovery ~~over ten~~ 12 years ago, ought to be considered as candidates for the next award of the Nobel Prize for Peace.

The news of fission reached us here in the United States in January 1939. ~~As it happened~~ I personally heard about fission first through Mr. Wigner whom I visited in Princeton and ~~I was~~ immediately I was convinced that neutrons would be emitted in the process.

So the question arose, how to demonstrate this fact by means of experiments? As it turned out, Fermi in New York and Joliot in Paris had also thought of this possibility and were also devising experiments for the same purpose.

Three different experiments got thus under way and were completed practically at the same time, in the first week of March, 1939.

About two neutrons were found to be emitted from every uranium atom which undergoes fission and the big question was does it mean that we can make a chain reaction in a large mass containing uranium.

The mere fact that two neutrons are emitted in fission is not sufficient for answering this question.

First of all, as Bohr immediately realized, the bulk of uranium which consists of U238 does not undergo fission with slow neutrons.

It is only in U235 which is contained in natural uranium in the amount of less than one percent, which will capture a slow neutron, undergo fission, and emit neutrons.

If a U238 atom captures a neutron, that neutron is lost for the chain reaction.

Since U235 likes to react with slow neutrons we must slow down the neutrons if we want a large fraction of them to react with U235, rather than U238.

But during that process of slowing down, a fraction of neutrons is also lost by being captured by U238 and another fraction

As Bohr immediately realized uranium 238 which makes up 99 percent of uranium, does not undergo fission if it absorbs a neutron.

Only uranium 235 which accounts for less than 1 percent of the uranium will split when it absorbs a neutron and will emit additional neutrons.

So the question xxixxxx arose, will the uranium 238 which forms the bulk of uranium, so strongly compete for neutrons with uranium 235 that it will make a chain reaction in natural uranium impossible.

Since uranium[illegible] 235 likes to react with slow neutrons conditions for a chain reaction could obviously be made more xxx favorable by mixing uranium with something that will slow down the neutrons.

~~by U238 and another fraction is lost after the neutrons are slowed down by being captured by the slowing agent which is present.~~

~~From the point of view of being able to maintain a chain reaction everything turns on the balance of neutron absorption in U235 that is useful because it leads to neutron emission, and neutron absorption elsewhere, which is harmful, because it does not lead to neutron emission.~~

Now the classical agent for slowing down neutrons id hydrogen.

The neutrons will collide with hydrogen atoms and on the average their velocity will drop down to half in each such collision.

As a practical matter, hydrogen is used not in the form of hydrogen gas but in the form of water.

And so, in May of 1939, Fermi, Anderson, and I began to experiment at Columbia University with mixtures of uranium and water.

Joliot, Halban and Kowarski did the same in Paris.

As I said before, a neutron which is produced in such a system will not necessarily cause fission in U235.

It may die, by being absorbed in U238 which makes up 99 percent of the natural uranium.

It may also die after it has been slowed down in such a system by being absorbed in the water rather than in uranium.

So the question whether a uranium-water mixture can maintain a self-sustaining chain reaction had to be decided by rather elaborate measurement of the balance of all these different absorption processes.

The last ~~interesting~~ experiment which was performed by us on such a system in the United States was completed ~~[illegible]~~ in June of 1939 and was not wholly decisive.

But I personally rather lost faith in this system at the time.

I felt that even if a chain reaction could be maintained in a uranium-water mixture, we would have to deal with very disagreeable chemical processes in such a system if we attempted to use it for the liberation of atomic energy on a large scale.

The radiations emitted from uranium would decompose water into hydrogen and oxygen and this explosive gas mixture would have to be removed.

~~Those of my brain cells which absorbed some engineering~~

Now it became possible to devise new types of experiments with neutrons, in which the presence of the invisible neutrons could be detected by their ability to make iodine, and other elements, radioactive.

This new technique appeared to me to be so promising that I decided to start experimenting with neutrons even though prior to this time I had done no work whatsoever in the field of nuclear physics.

By 1935 I began to take very seriously the thought that some elements might emit more than one neutron for every neutron which they capture, and that they might therefore be capable of sustaining a chain reaction.

~~which absorbed some engineering knowledge in the course of my early studies apparently became rebellious at this thought and pushed me to look for some other, less messy, system.~~

~~Thus in July 1939, I began to play with the idea of using graphite for slowing down the neutrons.~~

Now graphite is not at all as efficient for slowing down as hydrogen, but the first simple calculations showed that the situation was not as bad as I had originally assumed and from that day on I personally put my faith in graphite.

In this I was greatly encouraged by a later experiment which Joliot and his group performed on the water-uranium system.

They showed that the water-uranium system even though it may not be able to maintain a self-sustaining chain reaction, came very close to it.

If this were true, so I reasoned, a graphite uranium system ~~which was appreciably better than the water-uranium system, could certainly be expected to be capable of sustaining a chain reaction.~~

~~This was the state of our thought by February 1940.~~

The first experiments with graphite were started at Columbia University in April of 1940, and would have very quickly led to the establishment of a chain reaction if it had not been for the slowness of securing the needed materials in the required degree of purity.

The fact is, however, that the chain reaction was not actually produced until the 2nd of December, 1942, when it was first in operation here at the campus of the University of Chicago.

So, from an engineering point of view, the water-uranium system appeared to be a very messy system.

It was this consideration which first led me to contemplate the possibility of using graphite, rather than water, for slowing down the neutrons, and gradually, from July 1939 until February 1940, I became more and more convinced that it should be possible to set up a chain reaction in a graphite-uranium system.

Insert to page 15.

Perhaps this is a good time to pause and to ~~It is~~ ask ourselves what were the essential fundamental discoveries which led to the liberation of atomic energy. In answer to this question I would ~~only~~ list only three discoveries.

1) The discovery of Becquerel that uranium minerals emitted x-rays, which led to the study of radioactivity,.

2) Joliot's discovery that the penetrating radiation emitted from boron, under bombardment with alpha particles, ~~was~~ is capable of knocking out protons from paraffin wax.

~~For this~~ It was this discovery which led to the study of the neutrons.

And finally, Joliot's discovery that boron, if bombarded by alpha-particles, ~~emitted~~ emits positive electrons ~~which~~ because this led to the discovery of artificial radioactivity.

It may very well be, that if Becquerel had not lived another hundred years might have had to pass~~ed~~ before radium was discovered.

It may very well be, that if Joliot had not fooled around with paraffin wax, another fifty years ~~might have been~~ might be needed before the neutron was discovered.

And, it may very well be, that if Joliot had not noticed the positive electrons coming from boron, the discovery of aritifical radioactivity might have been delayed for a further twenty-five years.

It is curious indeed that all these fundamental discoveries were made in France.

Naturally, there were many other important discoveries along the road , many of them fully deserving the Nobel Prize, but in a way all these other discoveries were inevitable consequences of these three fundamental steps which ~~were made in France.~~ I have listed.

Returning now to the state of our knowledge as it was in February 1940, which Fermi and I were getting under way in the Spring of '40 sent us a manuscript in which he pointed out the importance of a secondary reaction which would accompany any such chain reaction.

As I mentioned ~~earlier~~ repeatedly, a fraction of the neutrons in the chain reaction will be captured by Uranium 238.

This leads to a radioactive element which after going through two beta transformations, goes over into a long-lived element nowadays called plutonium.

Fermi and I considered this absorption of neutrons by U238 merely as a nuisance.

Turner pointed out that the resulting element, plutonium, will be capable of fission just as U235 is capable of fission.

There are however significant differences between plutonium and U235.

U235 is chemically not different from uranium and it takes therefore a very laborious process to separate it from uranium.

Plutonium, being chemically different from uranium, can be separated by ordinary chemical methods.

Another significant difference is ~~xx~~ that the amount of U235 is strictly limited, its abundance being less than 1 percent in natural uranium.

Plutonium, since it is produced from uranium 238 which forms more than 99 percent of natural uranium is at least in theory not so severely limited in quantity.

With this remark of Turner, the whole landscape of the future of atomic energy arose before our eyes in the Spring of 1940 and from then on the struggle with ideas ceased and the struggle with the ~~xxkxx~~ inertia of Man began.

Such further ideas as were necessary for the completion of ~~the atomic bomb~~ this work concerned either ~~minor~~ technical details or concerned the detonation of the bomb.

The former class would not be of interest to you, and the latter one is in an area which is ~~at present~~ considered highly secret.

The first use of plutonium, as you know, was in the form of a bomb which destroyed a city.

The next use of plutonium might be the same again.

might be the same again.

With the production of plutonium carried out on an industrial scale during the war the dream of the alchemists came true and now we can change at will one element into another.

That is more than Mme. Curie could do.

But while the first successful alchemist was undoubtedly God, I sometimes wonder whether the second successful alchemist may not have been the Devil himself.