Defense Threat Reduction Agency
And
United States Strategic Command
Center for Combating Weapons of Mass Destruction
8725 John J. Kingman Road, MSC 6201
Fort Belvoir, VA 22060-6201

Mr. John Greenwald
[redacted]

November 19, 2014

Dear Mr. Greenwald:

This is the final response to your Freedom of Information Act (FOIA) request dated October 26, 2013. This FOIA request was received from Defense Technical Information Center and was forwarded to Defense Threat Reduction Agency/USSTRACOM Center for Combating Weapons of Mass Destruction (DTRA/SCC/WMD) on December 13, 2013. Your request was assigned a Case Number 14-025. You requested AD356945, entitled, "Emissions from the Reactions in Nuclear Weapons".

Enclosed is a copy of the responsive document. Some information is exempt from disclosure under FOIA Exemptions 3 of Title 5 U.S.C. § 552. Exemption 3 applies to information specifically exempted by a statute establishing particular criteria for withholding. The underlying statute applied is: 42 USC 2162 – Classification and declassification of Restricted Data.

The Department of Energy has purview over some of the responsive document. Release determinations made by Department of Energy are marked accordingly. If you consider this to be an adverse determination, you may file a written appeal Department of Energy, see enclosure 2.

If you need further assistance regarding this request, please contact the FOIA action office, at (703) 767-1792 or efoia@dtra.mil.

Sincerely,

LaTonya L. Small, Ed.D

LaTonya L. Small Ed.D
Chief, Freedom of Information/
Privacy Act Office

Enclosures:
1. Responsive Documents
2. Information for Requesters

C00026415

Enclosure 2

20140007715-TP

Information for Requester

Pursuant to Title 10, Code of Federal Regulations, section 1004.6 (10 C.F.R. 1004.6), the Office of Classification, Office of Environment, Health, Safety and Security, in the Department of Energy (DOE) has completed its review(s) of the document(s) responsive to your request. This/These document(s), located in the files of the Defense Technical Information Center, contain(s) information properly classified Restricted Data (RD); therefore, it is/they are provided to you with deletions.

Title 5, United States Code, section 552(b)(3) (5 U.S.C. 552(b)(3)) (Exemption 3), exempts from disclosure information "specifically exempted from disclosure by statute (other than section 552(b) of this title), provided that such statute (A) requires that the matters be withheld from the public in such a manner as to leave no discretion on the issue, or (B) establishes particular criteria for withholding or refers to particular types of matters to be withheld . . . ." The Atomic Energy Act (AEA) of 1954, as amended, 42 U.S.C. 2011 et seq., is an Exemption 3 statute. Sections 141-146 of this Act (42 U.S.C. 2161-2166) prohibit the disclosure of information concerning atomic energy defense programs that is classified as either RD or Formerly Restricted Data pursuant to the AEA, as amended. The portions deleted from the subject document(s) pursuant to Exemption 3 contain information about weapon design that has been classified as RD. Disclosure of the exempt data could jeopardize the common defense and the security of the nation.

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Pursuant to 10 C.F.R. 1004.8, the denial of a FOIA request may be appealed, in writing, within 30 days after receipt of a letter denying any portion of the request, to the Director, Office of Hearings and Appeals, Department of Energy, 1000 Independence Avenue, SW., Washington, D.C. 20585. The written appeal, including envelope, must clearly indicate that a Freedom of Information appeal is being made, and the appeal must contain all other elements required by 10 C.F.R. 1004.8. Judicial review will thereafter be available to you in the District of Columbia or in the district where: (1) you reside, (2) you have your principal place of business, or (3) the Department's records are situated.

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DASA-1368-9

EMISSIONS FROM REACTIONS IN NUCLEAR WEAPONS

Report No. 55829

by

Harris L. Mayer
Frances Richey

29 June 1963

Prepared for: The Chief
Defense Atomic Support Agency
Department of Defense
Washington 25, D. C.

DASA 1368-9

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

INTRODUCTION AND CONCLUSIONS

This paper treats the emissions from the reactions occurring in nuclear weapons, specifically the neutrons, gamma-rays, X-rays, and electrons emitted during the course of a nuclear explosion. The basic physics of the processes leading to these emissions – fission, inelastic scattering, interactions with orbital electrons and others – is discussed qualitatively so that a good understanding of what occurs in nuclear weapons may be gained. In most instances semiquantitative estimates also are made of the number, energy, and energy distribution of the emissions.

Clearly in weapon performance research, and in nuclear weapon effects, it is these outputs of the nuclear weapon which are relevant. In past work emphasis has usually been placed on the emissions carrying the major fraction of the energy of the weapon such as the thermal X-rays, or on some particular emission useful for a special diagnostic purpose such as the prompt gamma-rays indicative of the neutron multiplication rate, or on an output important in a damage effect such as the fast neutrons for neutron heating of fissile material. In contrast, this paper attempts a systematic listing of all the emissions from the major reactions with the hope of stimulating ideas concerning their importance in various possible applications. As a consequence, even very minor processes have been recorded, often with no further point than to show that they are indeed negligible for all conceivable applications. As the method of approach, the events in each major type of reaction are ordered in a careful time sequence thereby reducing the probability of omitting any specific weapon output.

Section I of this paper discusses the γ-rays both from fission and from

other nuclear reactions in the weapon. Since the reactions leading to γ-rays often are accompanied by X-rays due to disturbances in the orbital electron shells, these specific types of X-rays are also treated in this section. Neutrons are the subject of Section 2, including neutrons from fission, from thermonuclear reactions, and from reaction scattering. Section 3 treats the electrons emitted during the reactions, not merely the β decay electrons but the electrons due to compton scattering of γ-rays, to internal conversion, and to a variety of other minor reactions. The major results are summarized in tabular form in the two tables at the end of the paper. In each section an outline is given of some of the weapon diagnostics, phenomena, and effects related to the specific weapon emission.

Since the purpose of the paper is largely didactic, the numbers quoted are typical, or of example, and are not intended to be the last word in accuracy. Particularly for the non-fission reactions which can take place with a large number of nuclear species, the numbers for energy and spectrum are not given for each species, but for a representative one, and large factors of difference may be expected in specific cases. The discussions in the body of the paper seek to point this out. Moreover, fission has been discussed in generic terms, obliterating the distinctions between U^{235}, Pu^{239} and U^{238} fission.

The fission reaction occupies the major portion of the discussion in this paper, because so many phases are involved in its description, starting with the ingestion of a neutron to form a compound nucleus, through the formation of two daughter nuclei, to their separation and subsequent radioactive decay. A time table has been made for these phases which is summarized in Table I. In this table the origin of time is the ingestion of the incident neutron. However, because fissions occur over a long period

of time in the development of the nuclear explosion, later phases of one fission overlap with the early phases of another. The useful time resolution in discussing the outputs of the weapon due to the fission reaction therefore is related to the time scale of the weapon. In early stages this is the neutron multiplication time or thermonuclear burn time, of the order of 10^{-8} seconds, while in later stages this is the hydrodynamic expansion time, of the order of a few times 10^{-7} sec. Time intervals less that 10^{-9} sec. therefore are specified only roughly to give an ordering of the events and to estimate relative probabilities of competing reactions. It appears however that there is a significant quiescent period in the reactions following fission from the time that the prompt reactions cease, after, say 10^{-13} sec. until the time beta decay reaches an appreciable level, say 10^{-3} sec. This period spans the disassembly time of the bomb.

In the discussion of fission, we have tried to follow side reactions of low probability or of minor energy release in a systematic way, in case the products might prove important in some as yet undiscovered diagnostic or effects application. Particularly the possibilities of the appearance of most of the enormous energy of fission in channels other than the kinetic energy of the daughter nuclei were explored. No possibility for concentrating this energy into neutrons was found. However, two processes causing this energy to be given to a γ-ray or X-ray are discussed, the coherent oscillations of the daughter nuclei resulting in a giant resonance type of radiation, and the acceleration radiation from the daughter nuclei on separation. Albeit with small probability, these processes are capable of giving very much higher energy γ-rays than are usually considered in the treatment of fission. Experimental confirmation of these possibilities is lacking at present.

Painstaking attention has also been paid to the electrons accompanying the fission reaction. In addition to the beta decay electrons which only appear

at late times in the explosion history – indeed after complete disassembly of the weapon and widespread distribution of the bomb debris, there are a few prompt high energy internal conversion electrons and very many low energy electrons from a variety of atomic rather than nuclear processes which ionize the orbital electrons. While such electrons when created during the main fission reaction can scarcely ever be emitted into the outside world, the corresponding electrons from later fissions when the weapon has disassembled to some extent, can. This occurs during the otherwise quiescent period of the main fission reaction and even small numbers of electrons may therefore be of significance. These later electrons can, for example, play a role therefore in anomalous injection of electrons into the magnetic field in high altitude explosions.

Whereas no mechanism was found by which high energy neutrons could be produced from fission, several possibilities are discussed in connection with other bomb reactions. First there is the well known high energy end of the "14 Mev" DT neutrons due to center of mass motion of the reactants in a thermal distribution. Second is the neutrons from the DT reaction involving non-thermalized T giving even higher energy. Lastly there are neutrons which have been scattered from a fast proton, or even from another fast neutron, and have gained energy in the encounter. Neutrons are a well recognized diagnostic tool in the study of weapon kinetics, and the high energy tail of the spectrum will give the purest type of information. The small numbers of neutrons from these processes do not appear to be important in effects, since they are overwhelmed by the bulk of the neutrons at the peak of the energy distribution.

Copious numbers of X-rays are formed in many phases of the fission reaction and other reactions in weapons. In similar fashion to the low

energy electrons, the early X-rays usually will not get out of the bomb, but those emitted after partial disassembly will. No specific signature was found for these X-rays which would make them useful for diagnostics, and the bomb thermal X-rays emitted at the same time will no doubt overwhelm them in any effects.

Some of the material of this report is explained in more detail in separate papers on each of the emissions:

γ-rays
"Prompt Gamma Rays", by David Saxon, EHPA No. 55148, prepared for DASA, Unclassified

β-rays
"The Beta Spectrum From Nuclear Weapons", by Wendell Horning, Bob Hunter and Don Lynn, EHPA No. 55634, prepared for DASA, S-RD

Neutrons
"Theory of Fission and Fusion Neutron Spectra", by Igor Alexandrov, EHPA No. 55428, prepared for DASA, Unclassified

Weapon Outputs
"Prompt Emissions From Nuclear Weapons" by Olen Nance and Harris Mayer, EHPA No. 55650, prepared for DASA, S-RD

It is a pleasure to acknowledge the help given by the authors of these reports in stimulating this paper, and to Dr. John Wagner for his review of and helpful additions to the final manuscript. Furthermore, the analysis of the effects of changes in nuclear spin on the orbital electrons, given in Appendix A-3, is due to Dr. William Ramsay, whose cooperation in various discussions of the nuclear mechanisms is appreciated.

SECTION 1

GAMMA RAYS AND X-RAYS FROM REACTIONS IN NUCLEAR WEAPONS

The principle classes of nuclear reactions producing γ-rays in nuclear weapons are

1. Fission in fissionable nuclei, principally U^{235}, U^{238}, Pu^{239}.
2. Neutron capture in weapon materials, for example U^{238} (n, γ) U^{239}.
3. Reaction or inelastic neutron scattering in weapon materials, for example U^{238} (n, nγ) U^{238}, C^{14} (n, n) C^{14}.
4. Specific reactions in thermonuclear fuel, for example $H^1 + H^3 = He^4 + \gamma$.

These reactions as sources of the γ-rays and associated X-rays from the atomic electrons will be treated in successive sub-sections.

1.1 The γ-Rays Associated with the Fission Process

In this section the sequence of events that follows when a neutron hits a fissionable nucleus is outlined, with emphasis on the γ-ray production. We shall try to explain the times in the sequence at which γ-rays are emitted and the γ-ray energy. Our purpose is to trace very carefully the time variation in the γ-ray production, since the γ-ray rate is an important diagnostic tool for nuclear weapon performance, and is related to damage and interference weapon effects. The sequence of events is as follows:

1.1.1 Compound Nucleus Formation

A neutron hits a fissionable nucleus and with a certain probability is incorporated into a compound nucleus in an excited state.

1.1.2 Alternative Modes of Decay of the Compound Nucleus

The excited state may emit a neutron, returning to its ground state — a process termed capture elastic scattering; it may emit a neutron in a transition to a lower excited state — termed inelastic scattering; it may retain the neutron and emit the excitation energy of the compound nucleus in γ-rays, singly or in cascade, — termed radiative capture; or it may decay by fission. Each process has its characteristic probability, depending upon the fissionable nucleus and the neutron energy.

1.1.3 Daughter Nuclei Formed before γ-Ray Emission

It is known experimentally that γ-rays accompany fission. However it is extremely improbable that a γ-ray will be emitted by the compound nucleus before fission. If there is sufficient excitation energy for fission to occur with reasonable probability, the fission mode of decay will prevail over the γ-ray mode, because of the relatively poor coupling of the nuclear energy with the electromagnetic field. Because of the small coupling, typical times even for strong γ-ray dipole transitions in nuclei are about 10^{-15} sec, while typical times for neutron induced fission in U^{235} and Pu^{239} are about 10^{-20} sec. In contrast, if there is sufficient excitation energy for fission to overwhelm γ-ray emission, so that a γ-ray is actually emitted first, the residual state of the compound nucleus will have even less excitation and so small a probability of fission that it may be neglected in weapons discussions. The conclusion is, therefore, that fission occurs before γ-ray emission, or not at all.

1.1.4 Electrostatic Repulsive Energy of Daughters not Available for γ-Ray Emission

We will treat the theory of fission according to the liquid drop model, which, at least in its general features, is still regarded as applicable. During fission, a configuration is reached in which two distorted daughter nuclei are formed but have not yet moved apart, somewhat as illustrated in the sketch Figure 1. The question is, whether the γ-rays are emitted at this stage, or are produced even later. At this time the full energy of fission, about 200 Mev, is released, but is not available because most of it is already in the form of electrostatic energy of repulsion of the two daughter fragments. Immediately after fission the centers of the daughters are separated by about 10^{-12} cm. By the time this separation increases tenfold to about 10^{-11} cm, 90 percent of the electrostatic energy has been converted into kinetic energy of the fragments, and little will be available for conversion into other forms. The additional separation takes only 10^{-20} seconds, insufficient for noticeable γ-ray emission from the usual one particle states.

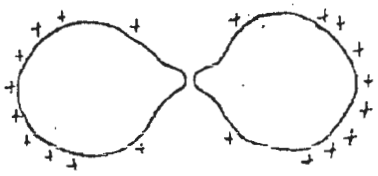

Figure 1

1.1.5 Coherent Oscillation for γ-Ray Emission Before Separation of Daughters

It is possible, however, to have enhanced γ-ray emission due to a coherent motion of the charges. At the moment of fission, there is a preponderance of protons at opposite ends of the distorted nuclear drop, as indicated in Figure 1. After separation, there can be a coordinated oscillation of the displaced protons from end to end of a daughter nucleus. If Z^* is the number of excess protons initially at one end, then the one

particle γ-ray emission probability will be increased by the order of Z^{*2}. The limiting value of Z^* is about 60, the full number of protons in the more massive daughter. A more reasonable estimate is a Z^* of about 10 or less. As a result, γ-ray emission times will probably be decreased from the one particle value of 10^{-15} sec to 10^{-17} and certainly to no less than 3×10^{-19} seconds. Therefore, by comparison with the effective separation time of 10^{-20} sec of paragraph 4, it appears that some contribution to γ-ray emission by this mechanism is possible, but likely to be small. This coherent oscillation is of the same nature as that responsible for the so-called giant resonances in ordinary nuclei.

This mechanism might be important because a great deal of the total fission energy is available at this time for conversion into γ-radiation, and indeed a many particle transition of the type discussed could release much of this energy in a single hard γ-ray. Since, however, fission occurs in many modes, as seen by the broad mass distribution of daughter fragments, one does not expect the γ-rays to have a single energy or even a small group of energies but rather a broad distribution. It is not known by the authors whether or not this mechanism is consistent with the experimentally observed spectrum of γ-rays from fission. If these γ-rays are indeed present in the estimated quantity, their observation would be borderline in the usual experimental arrangements.

1.1.6 Radiation Due to Acceleration of Fission Daughters

The acceleration of the daughter fragments on separation may also give rise to γ-ray emission by the purely classical effect. This process is quite analogous to Bremsstrahlung, but massive nuclei are invoved in acceleration, rather than light electrons in deceleration. To a large extent the radiation from one daughter fragment is cancelled by that of

the other, since the motion of the two fragments is coherent. In symmetrical fission, for example, there would be no dipole radiation at all caused by this mechanism. Unsymmetrical fission being the rule, rather than the exception, however, one would expect to find acceleration radiation due to the net charge difference of the daughters. The energy radiated is estimated by classical formulas in Appendix A-1. There it is found to be $E = .78 \times 10^{-2} mc^2$ or only 4 kev, which is quite negligible. A refined treatment of this process is thus unnecessary.

1.1.7 Prompt γ-Ray Emitted After Neutron Boil-off

Although the major fraction of the fission energy is converted into the kinetic energy of the fragments in a time of the order of 10^{-20} seconds, an important minor fraction remains as nuclear excitation of the daughters. Most of this excitation energy is used in boiling-off prompt neutrons from the daughters, since, when energetically possible, the emission of a neutron is favored over γ-ray emission. On the average each daughter emits 1.25 neutrons in U^{235} fission, and 1.5 in Pu^{239} fission, each neutron taking away about 6 Mev binding energy and 2 Mev kinetic energy. After the final neutron is emitted, the excitation of the remaining nucleus should be below threshold for further neutron emission, that is, less than about 6 Mev. Indeed all values of residual excitation up to this maximum are possible and about equally likely, so that the average excitation is about 3 Mev. This excitation energy is then emitted in the form of γ-rays, by isomeric transitions, usually in cascade, to the ground state of the nucleus. Emission times range from 10^{-15} seconds at the shortest, to the more likely values of 10^{-14} or 10^{-13} seconds. The total γ-ray energy emitted this promptly is about 3 Mev per daughter, or 6 Mev per fission. Furthermore, it is very unlikely that any single γ-ray will have energy above 6 Mev, for with that much energy available, neutron emission is possible. A few photons are observed experimentally above this energy; the theoretical explanation of these is not clear. Because of the cascading,

the mean energy of the γ's will be only 1 Mev. Furthermore, because of the statistical nature of the emission, which comes from a distribution of daughter fragments, with each single daughter containing a distribution of nuclear energy levels from which the γ's can originate, the energy spectrum of the γ's should be very dense in lines forming a Poisson distribution but with an energy cut off at about 6 Mev. Experimentally the Poisson distribution is indeed reproduced up to about 6 Mev, and the number of γ's above this energy is much less that a simple continuation of the Poisson distribution would give.

1.1.8 Angular Distribution of Gamma Rays

The line of centers of the two daughter nuclei forms a preferred direction in space, and it is therefore possible that the angular distribution of the γ-rays from a fission is not spherically symmetric. The theoretical arguments are too vague to be conclusive. On the one hand, as mentioned in the paragraph on coherent motion of the protons during the early stage of daughter separation, the protons initially will tend to oscillate along the line of centers, if not in a collective state, at least in one particle states. The dipole radiation from these protons will have the typical angular distribution concentrated at right angles to the proton motion. On the other hand, γ-rays are emitted after a neutron is evaporated from a fission daughter. The neutron transition causes the nucleus in some measure to "forget" its mode of formation, and subsequent γ-rays emission should be spherically symmetrical. An experimental resolution of this question is required.

1.1.9 Doppler Effect

Being emitted by the fission daughters after the daughters have gained their full velocity, $\sim 10^9$ cm/sec, the γ-rays should be doppler shifted. Observations along the line of centers, then, would show a slightly greater

energy spread to the γ's, about 5 percent greater, than observation at right angles to the line of centers.

1.1.10 Quiescent Interval Until β Decay

After emission of the prompt neutrons and immediately following the γ-rays, the fission daughters drop to their ground state with insufficient energy for further heavy particle emission. Nevertheless, they are very far from the stability curve of the stable nucleids, since they are still neutron rich for their mass number. This defect is rectified by β decay, which effectively converts a neutron into a proton in the nucleus. But, because of the very poor coupling of the nuclear particles with the electron-neutrino field governing beta decay, the transitions are slow. Mean life times of the nuclei against beta decay are no shorter than 10^{-3} seconds even for the most energetic betas likely, and the actual decay times are probably considerably longer. Therefore there is a quiescent interval in the history of the nuclear reactions of the fission fragment, from about 10^{-13} seconds when (except for some forbidden transitions) the γ-ray emission is complete until at least 10^{-3} seconds when beta decay occurs and further nuclear reactions may follow.

1.1.11 Prompt X-Ray Emission Following Fission

Although nuclear γ-rays are very improbable from about 10^{-13} seconds after fission until the onset of β decay in the fragments, in the interim electromagnetic energy can be emitted by the rearrangement of the orbital electrons of the fissioning atom, a process which eventually fills up the orbitals of the daughters. The source of this energy, which will be emitted as soft X-rays, is the kinetic energy of the daughters; therefore a very large amount of energy is available. The coupling acts through the Coulomb field between orbital electrons and the nuclear charge, a strong coupling. However, as will be discussed, only a very small

fraction of the kinetic energy is converted into X-rays, essentially because of the difficulty of transfer of energy from the massive nucleus to the light electrons. Therefore this source of X-radiation does not appear to be significant in weapon discussions.

a. Effect of Nuclear Deformation

It is known from the isotope shift in the heaviest elements that the electron energy levels of the s electrons in particular depend slightly upon the nuclear structure. In the first stages of fission when the nucleus is deformed, but not yet separated into daughters, the change in the nuclear configuration from the original must be large compared to that between two isotopes. Furthermore the change occurs suddenly compared to the period of the orbital electrons. In such a sudden perturbation, transitions of the electrons may be induced, leading to a vacancy in the K shell to be filled later with accompanying X-ray emission. The probability of such transitions, however, is necessarily small, since the orbital wave functions before and after the deformation are so similar. Indeed, except for normalization, the wave functions outside the nucleus are essentially the same, and that region of space contributes all but a fraction $\alpha^2(\alpha Z)^4$ of the overlap integral which determines the transition. The transition probability is of the order of the fractional change in effective nuclear volume multiplied by the above fraction, a negligibly small quantity.

b. Ejection of Outer Electrons as Daughters Separate: Sudden Approximation

When the daughter nuclei begin to separate, the orbital electrons find themselves in a changing electrostatic field, varying from the initial Coulomb field of the combined nuclei to the final two-center field of the separated nuclei. For the outer electrons of the fission atom, this change in field is sudden compared to the period of the electrons, and

the sudden approximation for treating the process may be used. The fission fragments have velocities of the order of 10^9 cm/sec. Any orbital electron with mean velocity less than 10^9 cm/sec, corresponding to a kinetic energy which is numerically equal to a binding energy of about 300 ev, is unable to change its orbital motion quickly enough to adjust to the changing nuclear field. According to the sudden approximation such an electron will, with probability close to one, make a quantum transition to an excited state which is most probably an ionized state of the fission daughter. Each daughter will therefore be ionized down to the level of about 300 ev binding energy so that about 15 electrons are missing, and X-rays will be emitted as these outer shells are subsequently filled. The X-rays then have less than 300 ev energy each, while the total photon energy per fission from this source is about 5,000 volts.

c. Behavior of Inner Electrons: Adiabatic Approximation

Electrons with binding energies greater than about 300 ev, in contrast to the case just discussed, can be expected to resist fission-caused transitions to new states. One can visualize that the inner uranium electrons move so fast that they can, by a slight change in orbit in each period, adjust to the new orbits required around the daughter. Mathematically, they obey the adiabatic approximation; the daughter electron shells to first approximation are filled by electrons from the uranium orbitals of proper symmetry without any quantum transitions.

Of course, there are not enough electrons in the fissile atom of the proper symmetry to fill up all the orbitals of both daughters; the lower shells are filled, but above a certain point there will be vacancies, even in the strict adiabatic limit. These vacancies will probably begin to appear in the 4s daughter shell, just about at the limit of applicability of the adiabatic approximation. The photons from later filling of these

vacancies will then be of relatively low energy.

This adiabatic approximation will, in fact, not be exactly valid, so there will be some transitions induced by the changing field of the separating daughters. In analogy with the Landau-Teller theory, the transition probability for an electron of orbital velocity V_e caused by a velocity of the daughter nucleus V_N will be

$$P \simeq 1 - \exp -\left(\frac{V_N}{V_E}\right) \simeq \frac{V_N}{V_E}$$

Therefore about 4 percent of the K electrons will be displaced, leaving vacancies which later produce hard X-rays of energy about 30 kev. The total energy from the average number of spaces left in the 4K electron positions of the two daughters is ~5 kev. The X-rays from L shell vacancies will be softer, but there are more positions to vacate and a higher probability of quantum transitions so that the total X-ray energy for the shell will be even greater than for the K shell. For a shell of principal quantum number n, the electron velocity $V_E \propto 1/n$ so that the probability of ionization $P \propto n$. There are $2n^2$ electrons in the shell each with binding energy proportional to $1/n^2$ so that the energy in X-rays per shell will be $E_n \propto \frac{1}{n^2} \times 2n^2 P \propto n$. The L shell therefore contributes about 10 kev, and in all there will be about 30 kev of X-rays per fission from this source.

The adjustment of electron orbitals, and their quantum transitions, take place essentially in the transit times of the daughter nuclei through the dimensions of the atom, about 10^{-17} sec. The subsequent emission of X-rays occurs slowly compared to this, about 10^{-13} sec or longer, and may therefore be considered as an independent process. The rate of X-ray emission is then given by the ordinary exponential decay law with the

mean life of the excited atom against radiation.

1.1.12 Delayed Gamma Rays Following Beta Decay

At this point, all the electromagnetic energy which accompanies the fission of an atom up to the time that beta decay occurs in the daughters has been categorized. There is a significant time gap between these radiations and those emitted following the beta decay, significant because of the nuclear weapon dynamics. The energy discussed thus far is all emitted during the period of the main nuclear reaction in the weapon (except for a small amount due to delayed fissions) when the weapon has not disassembled appreciably. As a result, only a few percent of the gammas and essentially none of the X-rays get out of the weapon. In contrast, radiation emitted after the beta decay occurs at a time when disassembly is complete, and all such radiation gets to the outside world. The later radiation is therefore relatively more important for external effects.

In the beta decay of a fission daughter it is equally likely that the nuclide formed in decay will or will not be in an excited state. De-excitation then follows, usually by gamma ray emission, and again usually in cascade. These gamma rays will have energies in the range from a tenth to a few Mev, with a mean of about .5 Mev obtained from a statistical treatment of the level schemes of the daughters. The total energy in gammas is also of the order of the total energy in the betas, a result which is reasonable considering the wide variety of daughter nuclides formed in fission. These considerations are indicated by the following decay scheme diagram, (Figure 2).

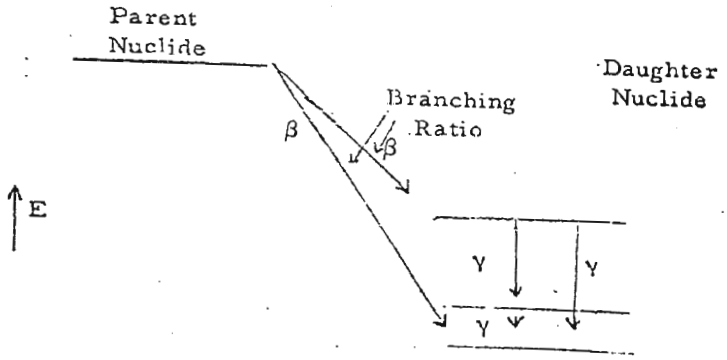

Figure 2

1. 1. 13 X-Rays Following Beta Decay

During process of beta decay, a side effect on the atom, the ejection of an orbital electron, sometimes occurs. The vacancy will then be filled by transitions of outer electrons, a process resulting in X-ray emission.

Since the beta particles almost always have higher velocity than even the K electrons of the daughter atoms, the transit of the beta through the atomic system may be considered in the sudden approximation. The atomic electrons will not be able to adjust their orbits adiabatically to the changing electrostatic field of the nucleus plus the beta, but occasionally will undergo quantum transitions. Actually there are two related sudden effects causing these transitions. In the first, the beta particle moving rapidly through the atom generates an electromagnetic pulse which can cause excitation or ionization similar to that occurring in the photoelectric effect. Although this process has been treated in the literature, we have not made an estimate of its magnitude. The second effect is due to the sudden increase by one unit of nuclear charge of the nucleus, and this change may excite the orbital electrons.

The probability that a K electron will be excited is calculated in Appendix A-2. There it is found that $P_{K \longrightarrow ex} = 3/(4Z^2)$ per K electron, which is about 0. 1% for one K electrons of one fission daughter. The energy of the X-ray emitted by a transition filling the K shell vacancy is about Z^2 Rh c, so that the total energy per β is just 2(3/4)Rh c or about 20 electron volts. Higher shells will contribute comparable amounts of energy to the X-rays, since, although the energy of the transition decreases as $1/n^2$, the number of electrons per shell increases as $2n^2$, and the probability of excitation is independent of n. Altogether, therefore, one may expect about 100 volts of X-rays per beta having an nergy distribution up to about 15 kev.

1.2 Gamma Rays and X-Rays from Neutron Capture

1.2.1 Compound Nucleus Formation and Gamma Ray Emission

At energies below about 6 Mev, neutrons captured by a nucleus share their energy with many other nucleons, forming a true compound nucleus with relatively sharply defined energy levels. De-excitation proceeds either by γ-ray emission or by neutron emission.

a. γ-Ray Emission — Preferred at Thermal Energies

For incident neutrons of low energy, from room temperature thermal up to a few kilovolts, the decay of the compound nucleus proceeds by way of γ-ray emission predominantly, there being so little energy available to a neutron when emitted that only a small volume in phase space is accessible. Capture cross-sections often vary as $1/v$ in this energy region. The total energy available for γ-rays is the binding plus kinetic energy of the incident neutron, about 7 Mev. Therefore no γ-rays of energy above 7 Mev are to be expected. In fact the γ-rays are emitted in cascade, the most probable energy being the mean spacing of levels of the proper symmetry in the compound nucleus. Light elements have widely spaced energy levels, so that energetic γ-rays may be expected. A smiliar effect is noted for closed shell heavy nuclei, such as Pb^{208}. For the medium and heavy elements in general, however, the level density is high, and the mean energy of the γ-rays is about 1 Mev.

b. Neutron Emission — Preferred at Higher Energies

Above a few kev, the phase space available for the re-emitted neutron is large enough so that this process competes with and wins out over γ-ray emission. The radiative capture cross-sections for fission energy neutrons range from a few hundredths to a few tenths of a barn, increasing

with increasing mass number through the table of isotopes. Total energy and spectrum of the γ-rays are determined by the same considerations as in thermal capture, and the resulting γ-ray spectrum is therefore insensitive to incident neutron energy.

1.2.2 Direct Radiative Capture

At energies above a few Mev, and in particular at the 14 Mev energy range characteristic of the thermonuclear neutrons from the DT reaction, the incident neutron does not share energy with many nucleons of the capture nucleus. Instead, it forms a single particle state which then makes a direct transition to a lower state. The single particle levels are spaced quite far apart, and even in cascade a typical γ-ray has much higher energy than is the case with compound nucleus formation. Even though they may be few, then, direct transitions are presumably the source of all the high energy γ-rays observed from capture.

1.2.3 X-Rays Due to Neutron Capture

A neutron added to the original nucleus on capture changes the spin and the size of the nucleus. This change occurs suddenly on the time scale of the orbital electrons. As a result there is a small probability that the electrons will be excited or ionized. On de-excitation X-rays are emitted.

X-rays are produced by yet another effect. In neutron capture, the nucleus recoils with velocity $1/(A + 1)$ times the velocity of the incoming neutron. For high energy neutrons and light nuclei the recoil velocity is comparable to orbital electron velocities, and the electrons usually are excited as a result. De-excitation results in X-rays whose energies are usually low, corresponding to outer shell transitions of the order of 100 to 1000 volts.

A different source of X-rays due to neutron capture is the following indirect process. The excited nucleus may on occasion decay via internal conversion rather than via γ-ray emission. The hole left in the orbital shell is then filled by an X-ray transition. Whereas the mechanisms described in the above two paragraphs favor vacancies in the higher shells, and therefore very low energy X-rays, internal conversion favors vacancies in the K shell and gives rise preferentially to X-rays of the order of Z^2 Ry, or about 30 kev for the average element.

1.3 Gamma and X-Rays Following the Reaction Scattering of Neutrons

At incident neutron energies above a few kev, reaction scattering becomes more important than capture. Often the nucleus after scattering is left in its ground state, so that no γ-ray is emitted. If the nucleus is left in an excited state, but below the threshold for neutron emission, γ-ray de-excitation is the rule. This process is a typical example of inelastic scattering. For high energy bombarding neutrons, after a single neutron is scattered a second neutron may be emitted, and usually leaves some residual excitation. This is a case of an (n, 2n) reaction. Final de-excitation comes about by γ-ray emission here also.

The de-excitation following reaction scattering is similar in nature to that following capture, and is determined by the balance of transition probabilities and nuclear level densities. One important quantitative difference, however, is that in capture, the entire binding energy of the neutron is available for γ-ray emission, whereas in reaction scattering the binding energy is returned to the emitted neutron leaving only a fraction, but usually the major fraction, of the incident kinetic energy of the neutron available for γ-ray emission. As a result, the γ-ray spectrum due to reaction scattering processes is weighted more heavily in the 0 to 1 Mev range than the radiative capture spectrum.

The sources, amounts, and energy spectrum of the X-rays resulting from reaction scattering are similar to those from radiative capture of neutrons.

1.4 γ-Rays from Reactions in Thermonuclear Fuel

γ-rays are not produced by the main line thermonuclear reactions in typical thermonuclear fuels. These reactions proceed with little kinetic energy of the incident particles and involve light elements with widely spaced energy levels, so that usually not enough energy is available in the reaction to lead to an excited state which may then decay by γ-ray emission. There are, however, some reactions which, though they have small probability, do give rise to characteristic γ-rays. Particularly, a reaction giving an alpha particle as one product will release a large amount of energy because of the relatively high binding energy of the α compared to the other light elements; a capture type reaction will then produce an energetic γ-ray. Two reactions in particular are known:

(1) $p + T^{\circ} \longrightarrow \alpha + h\nu, \quad Q = 19.8$ Mev

and

(2) $L_i^7 + p \longrightarrow Be^8 \longrightarrow 2\alpha + h\nu, \quad Q = 17.5$ Mev.

Measured values give the average cross-section for these reactions over the 0 - 1 Mev range of proton energy as 2×10^{-28} cm^2 and 2.4×10^{-28} cm^2, relatively small compared to the usual reaction cross-sections. The important low energy portion of the cross-section from 0 - 50 kev has not been measured directly. It is not easy to extrapolate into this region, since there are two opposing factors. On one hand, the cross-section should become smaller because in going from an energy of 1 Mev down to this lower region, one changes from a reaction with enough energy to go over the Coulomb barrier to one which

must tunnel through the barrier. On the other hand the full Coulomb factor should not be applied to the high energy cross-section, because there is a competing particle reaction, $p + T \longrightarrow D + D$, which is suppressed relative to capture. The latter reaction requires barrier penetration both on formation and on breakup of the combined nucleus, whereas the $p + T \longrightarrow \alpha + \gamma$ and $p + T \longrightarrow He^3 + n$ reactions need only penetrate the barrier on formation of the combined nucleus. The low energy values of the cross-sections of reactions (1) and (2) are therefore in doubt at present.

1.5 Effects of Prompt Gamma Rays

1. Diagnostic of Weapon Design and Performance

The rate of prompt γ-ray emission is indicative of the neutron population within the weapon and therefore may be used as a diagnostic tool of weapon design and performance. Effects which may be studies to gain more or less accurate information are:

1. the neutron multiplication rate,
2. the occurrence of thermonuclear boosting,
3. [redacted] DOE b(3)
4. the relative yield of similar weapons.

By collimation type experiments which isolate a segment of the weapon, more detailed information may be gained, specifically,

5. [redacted] DOE b(3)
6. [redacted]
7. the geometric configuration during nuclear or thermo-

nuclear reactions.

2. Atmospheric Fluorescence

The γ-rays excite the air to radiate in the visible, producing the so-called Teller light. This light consists mainly of the first positive band of N_2 and the first negative band of N_2^+ both in the blue and the second positive band of N_2 in the red. Different experimental measurements give values of between 1 and 10 percent of the absorbed γ-ray energy emitted in the visible. It has been agreed to use a mean value of 5%.

The atmospheric fluorescence is important in diagnostic experimentation, and is useful as the earliest external signal of the explosion which may be employed as a trigger for experimental apparatus or damage prevention devices such as eyeburn shutters. Also there is sufficient intensity to be a possible danger to sensitive optical devices operating near an explosion.

3. Direct Damage Effects

1. Total radiation dose to sensitive components.
2. "Rate" effect, that is the effect of γ-ray energy delivered during the proper integration time of the irradiated component.
3. Transient response induced in electronic systems.
4. Sudden heating effect due to energy deposition. (Neutrons and X-rays are usually more effective.)

4. Interference Effects

1. Formation of ionization layers in the atmosphere causing

radar and communications interference. (Later γ's and β's are more important in most cases.)

SECTION 2

NEUTRONS FROM REACTIONS IN NUCLEAR WEAPONS

The major reactions giving rise to neutrons in nuclear weapons are fission, (n, 2n) reactions, and the thermonuclear reactions such as $D + T = \alpha + n$. In addition both elastic and inelastic scattering and absorption alter the energy or number of neutrons in the assembly.

2.1 Neutrons from the Fission Reaction

The steps in fission have been outlined in Section 1 on γ-rays, and they need be only briefly recapitulated here.

2.1.1 Compound Nucleus Formation

An incident neutron of low energy may be incorporated into the target nucleus and share its energy with many nucleons. At energies above about 7 Mev, the incident neutron may be scattered inelastically, a process usually involving only a few degrees of freedom of the target nucleus. Often, however, even after scattering sufficient energy is left in the target to excite it to fission. This excitation, shared by many nucleons, forms a compound nucleus in a manner similar to the case of low incident neutron energy.

2.1.2 Fission before Neutron Emission

If fission of the compound nucleus is going to occur, it must precede neutron emission, because the departing neutron would deprive it of the energy necessary for fission.

2.1.3 Fragment Daughters Gain Kinetic Energy before Neutron Emission

The fission daughters are repelled by strong Coulomb forces, and attain

their full separation velocity in a little over 10^{-21} seconds. This time is too short to allow the concentration of enough energy on a single neutron to insure its emission from a daughter during the acceleration.

2.1.4 Neutron Emission from Moving Daughters

The neutron widths of the daughter nuclei are such that the neutrons are emitted from the daughter nuclei only after the final velocity of $\sim 10^9$ cm/sec has been attained. Emission from the many level excited daughter may be considered in a statistical fashion analogous to the evaporation of a water molecule from a droplet by introducing a nuclear temperature T. The energy distribution of the evaporated neutron in the center of mass system is proportional to $\sqrt{E}$ exp - E/kT, and neutron emission is spherically symmetric. Usually there is only sufficient excitation per daughter for the emission of one neutron, although occasionally there may be two or three. Therefore, it is possible to have 0, 1, 2, 3, 4 and sometimes 5 or 6 neutrons per fission with the most probable number being 2 or 3, and the average number as determined by experiment being about 2.5 for U^{235} thermal fission and 3 for Pu^{239} thermal fission.

2.1.5 The Neutron Spectrum in the Laboratory System

By transforming to the laboratory system and averaging over emission directions, one may find the energy distribution in the laboratory system of coordinates. The analytical result is called the Watt spectrum. For U^{235} the data can be fitted by the Watt spectrum form by assuming a nuclear temperature of kT = 1 Mev and a fragment velocity of about 10^9 cm/sec (corresponding to a neutron energy of 0.5 Mev). An equally good fit to the data may be obtained by the simple evaporation spectrum $\sqrt{E}$ exp (-E/T). Of course such a formula must be regarded as empirical; certainly it is not indicative of emission from stationary fragments.

2.1.6 The Angular Distribution of the Neutrons

Since the average energy of the emitted neutrons is 3/2kT = 1.5 Mev in the center of mass system, corresponding to a velocity of about 2×10^9 cm/sec, and the fragments are moving at about 1×10^9 cm/sec at the time of neutron omission, the angular distribution will peak in a 60° semi-angle cone along the line of separation of the daughter nuclei. The energy distribution will also vary with angle, and will have higher mean energy in the preferred cones.

2.1.7 Delayed Neutrons

The prompt neutron emission just discussed takes place about 10^{-17} sec after fission. Then, for a time no additional neutron emission occurs until after a special class of beta decay transitions, which happen to leave the residual nucleus in a state with enough excitation for additional neutron emission. The periods of these delayed neutrons, therefore, are really the periods of these special beta decays. Theoretically they should be expected to be rather long since the beta itself must not take too much energy away from the nucleus. In practice a number of periods, of range from about 0.2 seconds to one minute have been observed, giving about .016 neutrons per fission for U^{235} or .006 for Pu^{239}. It is doubtful that shorter periods than 0.2 sec occur.

The delayed neutrons occur so late in time that the original velocity of the fission daughters has long since been lost in interactions with either the materials of the weapon, atmosphere, or magnetic field of the earth. Hence the angular distribution will be isotropic in the small, as well as the large. The energy distribution of the neutrons should be different in detail, and more weighted towards lower energy than that of the prompt neutrons from fission.

Contrary to their essential place in the control of reactors, the delayed

neutrons play no role in weapon neutronics — they appear only after the main reaction is over. They do, however, contribute to certain weapon phenomena and effects, just because they come at late times when the prompt neutrons have completely disappeared. For example, they contribute to the formation of an ionized layer at about 30 km altitude in a high altitude explosion, along with the delayed γ-rays.

2.2 Neutrons from (n, 2n) Reactions

When the energy of an incident neutron exceeds the binding energy of the neutrons in the target nucleus, usually about 7 Mev, an (n, 2n) reaction is energetically possible, and is in fact quite probable. The reaction usually proceeds by a direct route, the incident neutron colliding with one neutron of the target, and knocking it out of the nucleus, without the incident neutron ever being incorporated into the target. Sometimes, however, the reaction proceeds via the compound nucleus, the incident neutron being incorporated in the target, which then has sufficient energy to boil off two neutrons. Actually, there is no sharp division between one route and the other, because intermediary cases can occur for which the incident neutron reacts with a moderate number of nucleons, or more precisely a moderate number of degrees of freedom of the target, as well as the extremes of few for the direct reaction and many for the compound nucleus reaction.

The spectrum of the neutrons from the (n, 2n) reactions depends in principle upon the mode of interaction. For the direct interaction, the energy of the incident neutron, less the binding energy of the target neutron, will be shared almost randomly between them with a slight preference for equal sharing due to the larger volume of phase space available for that case. For example, with 14 Mev incident neutrons and a binding energy of 7 Mev, the average and also the most probable energy will be 3.5 Mev

per neutron. In the compound nucleus case energies lower than this should be more common, depending on the level spacing. There will moreover be considerable probability of a residual nucleus being left with up to 7 Mev energy after emission of the second neutron, this excitation energy coming off as γ-rays. As a result this neutron spectrum in actuality is quite broadly distributed in energy and not very different from the fission neutron spectrum.

2.3 Neutrons from Thermonuclear Reactions

2.3.1 Principal Reactions

The principal neutron producing reactions in thermonuclear devices are

		Neutron energy
(2-1)	$D + D \longrightarrow He^3 + n, \quad Q = 3.25$ Mev	2.4 Mev
(2-2)	$D + T \longrightarrow He^4 + n, \quad Q = 17.6$ Mev	14.1 Mev

The D + D reaction thus gives neutrons of energy comparable to fission neutrons, whereas the D + T reaction gives a new class of neutrons of much higher energy.

2.3.2 Energy Spread of Neutrons

The fission neutrons have a broad continuous spectrum. The thermonuclear neutrons are concentrated at the energies of 2.4 Mev and 14.1 Mev, but do not have a sharp line spectrum. The velocity of the center of mass V_M must be added to the neutron velocity V in the center of mass system to obtain the velocity of the neutron in the weapon system, V_L. Because these vectors may be oriented at random, there will be a velocity spread and an energy spread to the thermonuclear neutrons.

The velocity can have values between the limits $V_{L\pm} = V \pm V_M$, and the energy between limits $E_{L\pm} = \frac{1}{2} M(V \pm V_M)^2 \simeq E(1 \pm 2\frac{V_M}{V})$, where M is the neutron mass and E the neutron energy in the C.G. system. Now the velocity of the center of mass is of the order $\sqrt{kT/M}$ while the velocity of the neutron in $\sqrt{2E/M}$, so that the fractional spread in neutron energy is of the order of $\sqrt{kT/E}$. When the computation is done accurately the spread is actually found to be $2\sqrt{3kT/E}$. This is a considerable energy spread. For reaction temperatures of 10 kev, for example, the energy spread in the DT neutrons is about 10 percent, covering the range from 13.4 to 14.8 Mev.

2.3.3 Source of Faster Neutrons

In a thermonuclear mixture, some reactions occur with fast reaction products rather than with thermalized particles. Particularly, the DD reaction has with about equal probability, another branch in addition to equation (2-1), namely

(2-3) $\quad D + D \longrightarrow T + p, \quad Q = 4$ Mev.

The triton, which has 1 Mev energy, may react according to Equation (2-2) even before it is thermalized. The spread in neutron energy from the reaction (2-2) will now be very large, from about 10 to 19 Mev. These high energy neutrons are the so called kigme neutrons.

2.4 Scattering of Neutrons

2.4.1 Elastic Scattering

Elastic scattering modifies the energy of a neutron. The usual collisions

involve a loss of energy of the fast neutron to the slow moving target nucleus. The maximum fractional loss in energy of the neutron is 1/A where A is the mass number of the struck nucleus. Collisions with heavy nuclei like U present in nuclear weapons therefore do not seriously change the neutron spectrum, while collisions with hydrogen, also present in most weapons, do.

During a nuclear explosion, in contrast to the case of the ordinary nuclear reactors, it is possible for a neutron to gain energy by elastic collisions. In thermonuclear fuel, for example, the thermal energies of particles are of the order of 10 kilovolts, and in a small number of collisions, those close to head on, the neutron will gain energy. The gain itself will be small, comparable to the spread in energy of the thermonuclear neutrons discussed in Section 2.3.2. There are, however, particles with higher velocity present in the thermonuclear mixture, from which considerably more energy may be gained, for example, the products of reactions 1, 2, and 3 before they have been slowed down. Most notably among these are the 3 Mev protons of reaction (3-3). Finally there are the fast neutrons themselves, which, though present in low density due to their long mean free paths, have the possibility of highest energy gain during the occasional collision of one with another. Neutrons of energy up to 28 Mev may be formed in these collisions.

2.4.2 Inelastic Scattering

In the process of inelastic scattering a compound nucleus is first formed by capture of the incident neutron. The excitation energy is the incident kinetic energy plus the binding energy of the last neutron. The compound nucleus then decays by evaporation of a neutron, and the energy spectrum is therefore an evaporation type spectrum similar in form to that of the neutrons from the fission daughters. Since typical nuclear temperatures

in this process are of the order of 1 Mev, the evaporated neutron will have an energy of this order, usually considerably less than the incident neutron energy. For example, the 14 Mev thermonuclear neutrons usually give only 2 Mev inelastically scattered neutrons as a result of a collision with U^{235}.

2.5 Effects of Prompt Neutrons

2.5.1 Direct Damage Effects

1. Neutron heating of fissile material causing vaporization, melting, or phase change.
2. Neutron heating of fissile material to cause thermal shock.
3. Heating of non-fissile material by neutron capture or inelastic scattering.
4. Radiation damage to sensitive components — total dose effect.
5. γ-ray irradiation damage from nitrogen capture γ's.

2.5.2 Interference Effects

Formation of an ionized layer at 30-40 km altitude from a high altitude burst. The ionized layer contributes to radar blackout and communications interference.

2.5.3 Phenomena

1. Fluorescence of the atmosphere in the visible due to neutron energy deposition.
2. Neutron decay into a proton, an electron and a neutrino. Since the neutron is neutral, in a

high altitude explosion it is not affected by the geomagnetic field, whereas charged particles are. After the neutron decay, charged particles may then appear along magnetic field lines which cannot be reached by the usual charged particles such as β-rays from the weapon.

SECTION 3

ELECTRONS FROM REACTIONS IN NUCLEAR WEAPONS

3.1 Electrons from the Fission Reaction

The fission reaction is a principal source of electrons from nuclear weapons. Although usually only the electrons from the beta decay of the fission daughters are considered, there are other sources of fission electrons. This section follows the sequence of events in fission in a manner analogous with the objective of isolating the processes which may directly give rise to free electrons.

3.1.1 Electron Emission in Compound Nucleus Formation

Fission is initiated by capture of a neutron to form a compound nucleus. Both the spin and size of the nucleus are changed by this capture. There is a weak interaction of the nuclear spin with the orbital electrons, the same interaction which is responsible for the hyperfine structure of spectral lines in the optical region. Since the change in nuclear spin occurs suddenly, in about the time for the neutron to traverse the Bohr orbit of the electrons, the effect of the interaction can be treated by the sudden approximation. Ionization of an orbital electron is possible even though the change in spin interaction energy itself is so very much less than the ionization potential. Of course, conservation of energy in this reaction is not violated, because the energy actually comes from the kinetic energy of the incoming neutron, which certainly is more than adequate for the reaction. The probability of excitation due to change in nuclear spin is of the order of $(H^1/\Delta E)^2$, where H^1 is the interaction energy and ΔE the difference in the energy levels between the initial and final states. The interaction energies are of the order of 10^{10} cps while the ionization energy is of the order of 3×10^{15} cps so that the excitation probability is only 10^{-12}, quite negligible. The result is derived in a

formal manner in Appendix A-3.

The increase in nuclear size caused by absorption of the neutron also changes the atomic energy levels in a sudden fashion, causing ionization of the orbital electrons for the same reason, as did the change in nuclear spin. The effect is of comparable order of magnitude, i.e., negligible.

3.1.2 The Probability of β-Decay During Deformation and Splitting of the Nucleus

The time for fission being of the order of 10^{-21} sec, and the time for beta decay being typically very much longer, 10^{-3} seconds or more. Due to the weak interaction involved, there is only a negligible chance, 10^{-18} or less, for emission of a beta particle of the usual energy range during the deformation and splitting of the fissionable nucleus. Fission, however, is a very violent process, with sufficient energy to give much higher log Ft values than usual in beta decay, and consequently the emission of betas may be more probable than estimated above. No estimates have been made of this effect. The probability of emission must still be quite small, at most of the order of the ratio of the coupling constants in the beta decay to those in the nuclear field.

3.1.3 Electrons Accompanying Prompt Neutron Emission

After the fission daughters are formed, they separate, retaining an appreciable amount of internal energy. Some of this energy is removed by neutron emission. In the process, just as in neutron absorption to form the original compound nucleus, the orbital electrons of the daughters are disturbed by the sudden change in nuclear spin and size, and this disturbance can lead to ionization. The probability for this ionization is very small, being of the same order as estimated in Section 3.1.1 for

compound nucleus formation, that is about 10^{-12}.

Another cause of electron emission is a remote possibility, that is the direct interaction of the neutron with the orbital electrons due to a specifically nuclear contribution. This interaction is in addition to that of the anomalous magnetic moment of the neutron with the spin and orbital moment of the electron which is of electromagnetic origin and has already considered in the effect of the change of nuclear spin. This process as measured in the laboratory does take place but with low probability at high momentum transfers corresponding to electron energies in the 100 Mev range. The orbital electrons of the fission daughters have very much smaller kinetic energies than this, so the direct interaction probability will be negligible.

3.1.4 Prompt Internal Conversion Electrons from Fission Daughters

A part of the excitation energy of the fission daughters is emitted as γ-rays in about 10^{-15} seconds. These γ-rays are accompanied by internal conversion electrons. Compared to γ-ray emission, internal conversion is an alternate mode of decay of the excited states of the daughter nuclei. In this mode, the nucleus makes a transition emitting a virtual photon which is then virtually absorbed by an orbital electron, thereby transferring the energy of the nuclear transition to the electron. The energy spectrum of the internal conversion electrons is very similar to that of the prompt γ-rays except for a small correction due to the binding energy of the electrons, namely $n(E)dE = a \exp(-aE)dE$ where $a = 1(\text{Mev})^{-1}$. The ratio of conversion electrons to nuclear γ-rays is discussed in detail in the report by Horning et al* on the beta spectrum from fission.

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* "The Beta Spectrum from Nuclear Weapons", Horning, Hunter, and Lynn, E. H. Plesset Associates Report No. 55634 for DASA, February 1963, Secret RD.

These internal conversion electrons have some importance in studies of the Argus effect. The electrons usually discussed in relation to this effect come from beta decay and therefore appear relatively much later than these internal conversion electrons. Therefore location and efficiency of injection into Argus type orbits is significantly different for these two sources of electrons. Moreover the lifetime of electrons in the Argus orbits is energy dependent and the internal conversion electrons have higher mean energy and higher maximum energy than the beta decay electrons, resulting in longer lifetimes. Although most of the fissions in a bomb reaction occur in a geometry for which the conversion electrons cannot get outside the bomb, there is a short period of time during disassembly when some fissions, initiated by the residue of prompt neutrons, take place in a configuration dilute enough for the conversion electrons to emerge into the outside world.

3.1.5 Ionization of Orbital Electrons due to Separation of the Fission Daughters

As discussed in Section 1.1.11, the separation of the daughter fragments, which reaches one Bohr radius in about $1/4 \times 10^{-17}$ seconds, drastically changes the potential field in which the electrons of the original fissionable atom move. The inner fast electrons are able to adjust to this changing field adiabatically; the outer electrons are not, and will be shaken off from the fission daughters. In Section 1.1.11 it was estimated that approximately 30 free electrons per fission were formed in this manner from orbitals bound with less than 300 e.v. The energy spectrum of these free electrons is continuous, peaking around 300 ev corresponding to the velocity of the daughter nucleus of 10^9 cm/sec. Higher energy electrons are formed only with very low probability by this mechanism.

Because the adiabatic condition does not hold exactly, a few electrons are

also released from the inner orbitals of the fissioning atom. On the average, per fission, 0.08 electrons are set free from the K shell, .6 electrons from the L shell and 2.2 electrons from the M shell. These electrons have energies distributed from zero up to the order of the kinetic energy in their original orbits, with the distribution function concentrated at the lower end of this range.

3.1.6 Electrons from Beta Decay

The preceding sections on the electrons accompanying fission summarize all the sources of electrons which follow promptly after fission, the slowest process discussed hitherto being internal conversion with a mean time of 10^{-14} seconds. After this time there is an absence of electron production until beta decay occurs, a relatively slow process with a half-life varying from 10^{-3} seconds to 10^{6} seconds.

The beta particles emitted from the fission daughters in beta decay are electrons rather than positrons, since the daughters are neutron rich, and the conversion of a neutron to a proton within the nucleus with the release of an electron (and a neutrino) tends to result in the production of stable isotopes. The experimental observations and theoretical predictions of the beta spectrum and its variation with time are presented in the paper of Horning, et al. There it is found that a total of about 8 Mev per fission is released as betas with a mean energy of 1 Mev. Almost 5/6 of the energy is released after 1 second following a $t^{-1.2}$ time dependence. The remainder is released at early times at an assumed constant rate. However there is no direct evidence experimentally for the beta decay before about 10^{-2} sec. Moreover, theoretical considerations of the beta decay laws make it doubtful that any betas could have mean lifetimes of less than 10^{-3} seconds and still have low enough energy so that the parent nucleus would be stable against neutron emission, precluding beta decay.

3.1.7 Influence of Beta Decay on Orbital Electrons

In the course of beta decay, the orbital electrons of the daughters may be disturbed. One process involved is the swift passage of the beta through the outer electron shells, a process leading occasionally to ionization. Although in principle all of the beta energy could be transferred to a single orbital electron, the most likely energy transfer is of the order of the binding energy of the electrons in the atom, in the 20 to 30 kev range. We have not made estimates of this process.

A second process is the change in nuclear charge causing excitation and ionization of the orbital electrons. In Appendix A-2 the probability of excitation and ionization was found to be about $3/(4\ Z^2)$ per electron, or about 0.1% for an electron of a typical fission daughter. Per beta particle emitted then, one has about .02 orbital electrons excited or ionized with perhaps half of these or .01 in the ionized state. The energies of the freed electrons seldom exceed the original kinetic energy of the orbitals and are typically much lower than that.

3.1.8 Internal Conversion Following Beta Decay

After beta decay, the residual nucleus may be in an excited state. Although de-excitation usually takes place by means of γ-ray emission, the same transition can occur by an internal conversion which gives the energy of the nuclear transition to an orbital electron. In some particular cases, a transition strictly forbidden by the γ-ray selection rules is permitted by the mechanism of internal conversion. The spectrum of the conversion electrons is of course similar to the spectrum of the γ's following the beta decay.

The internal conversion electrons from this source always follow immediately (within 10^{-14} or 10^{-13} seconds) after the beta decay electrons,

have roughly the same spectrum, and are considerably smaller in number. Therefore they cannot be the cause of any qualitatively different nuclear weapons effect, nor indeed do they have much quantitative import.

3.1.9 Auger Electrons from Fission Daughters

A number of processes leading to vacancies in the occupation of inner orbitals of the fission daughters have just been discussed. In each case it is possible to fill the vacancy not only by an X-ray transition, but by an Auger transition exciting or ionizing one electron as a second drops into the vacancy. For fission daughters, Auger transitions are less probable by a factor like 10 to 100 than X-ray transitions. However, a small number of free electrons are formed by this process with energies of the same order as the X-ray energies discussed earlier, typically in the .1 to 1 kev range, with a few as high as 20 kev.

3.1.10 Electrons from Interactions of the Fission Daughters with Other Atoms

As the ionized fission daughters pass through the materials of the nuclear weapon, they gradually deposit their energy. The dominant mechanism for this deposition is that discussed classically by Bohr in his study of the stopping power formula for charged particles. In his theory it is the distant collisions with relatively small energy transfer to the outer electrons of the substrate atoms which accounts for the major energy loss. In these soft collisions, atomic electrons with velocity less than that of the fission fragment are affected; they are with about equal probability excited or ionized. On the average about 30 ev per ion pair, or per free electron, are required in most substances. The fission fragments of initial velocity 10^9 cm/sec are slowed down to about 10^8 cm/sec by this mechanism, depositing 99% of their kinetic energy or about 160 Mev per fission. As a result about 5×10^6 free electrons are formed per fission, mainly of

energy between zero and 30 electron volts.

Occasionally much harder collisions occur between a fission fragment and a close substrate atom. Although a great deal of kinetic energy can be transferred in these collisions, the maximum recoil velocity of the struck atom is only the velocity of the fission fragment itself, about 10^9 cm/sec. The acquired velocity of the substrate atom results in the shaking off of these outer electrons with velocity less than the recoil velocity. These shake off electrons, perhaps 10 or so for each hard collision, have velocities up to several hundred volts, in contrast to the few tens of volts of the electrons per distant collision. Typically, however, only a few percent of the fission energy is transferred in the hard collisions; thus there is a hard collision probability of only a few percent per fission, giving on the average less than one shake off electron of the 100 ev energy range per fission compared to the 5×10^6 electrons in the 10 ev range due to distant collisions.

The electrons discussed in this subsection can only be emitted into the outside world during a phase in the disassembly of the weapon when the materials are so mixed up and so dilute that fissions occur near the boundary surface of the weapon.

3.1.11 Multi-Particle Fission

Occasionally more than two particles are formed in fission. When ternary fission occurs, the third particle in addition to two medium atomic weight daughters is usually an alpha. Since the α particle is relatively lighter, it may be emitted with much higher velocity, say even 5×10^9 cm/sec, compared to the velocity of the usual fission daughters. The fast α may cause more high energy electrons in its interactions with the bomb materials than the more massive daughters.

3.2 Electrons from Elastic Scattering of Neutrons

It is unusual for free electrons to be produced in the elastic scattering of neutrons by most nuclei. The electrons are not produced by the direct nuclear interaction, but rather by effects on the orbital electrons. The first such effect results from the interaction of the magnetic moment of the neutron with the spin and orbital magnetic moment of the electrons. Because the collision with the neutron is relatively rapid compared with the electron orbital period, this interaction can ionize electrons as well as merely split and shift electronic levels. This effect was discussed in connection with the neutron forming a compound nucleus prior to fission and is of the same order as estimated there, completely negligible.

A second effect results from the recoil of the scattering nucleus after being struck by the neutron. If the recoil is rapid, it will shake off some bound electrons, if slow it will nevertheless occasionally cause ionization. After an elastic collision in the center of mass system, the recoil nucleus must have the same magnitude momentum as the scattered neutron. Therefore a nucleus of mass number A will have a velocity $v_A = v_{n/A}$ where v_n is the neutron velocity in the center of mass system. A typical value for v_n is 10^9 cm/sec. For large values of A, say A > 10, the recoiling nucleus will be moving slowly compared to the bound electrons and the probability of ionization will be of the order of $v_A/v_e = v_n/(A\,v_e)$. For light elements like H, Li, Be and B, which are very important constituents in nuclear weapons, v_A is greater than the velocity of the valence electrons, and those electrons will be ionized. A large number of electrons are formed by this process, usually several per elastic scattering. Their energy however is low, not often exceeding that corresponding to the velocity of the recoil nucleus, which can be 100 ev and is most likely to be about 10 ev.

3.3 Electrons from the Inelastic Scattering of Neutrons

The same mechanisms leading to free electrons from the elastic scattering of neutrons, the most important of which is the shake off of orbital electrons by the recoil nucleus, also operate in the case of inelastic scattering. But in addition, there are other mechanisms. Inelastic scattering leaves the recoil nucleus in an excited internal state, often with the major fraction of the incident neutron energy. De-excitation is brought about by γ-ray emission, usually in cascade. Accompanying the γ-ray transitions are internal conversion transitions. Since the typical spectrum of γ-rays from inelastic scattering in weapon materials is very much the same as the spectrum of the γ-rays from the fission daughters, the spectrum of the internal conversion electrons is also similar and may be roughly approximated by $N(E)dE = (a)e^{-aE}dE$ where $a = 1(\text{Mev})^{-1}$.

Like the fission reaction, inelastic scattering gives an early source of high energy electrons due to this internal conversion process. Actually the inelastic scattering contribution will usually be more significant than the fission contribution, since the former has a larger over-all cross section in weapon materials, and the scattering usually occurs closer to the surface of the weapons enabling the electrons to escape into the outside world.

In addition to the internal conversion electrons, there will be accompanying low energy Auger electrons as the inner atomic shells vacated in the conversion are filled from the outer shells.

3.4 Electrons from the Thermonuclear Reactions

Neutron reactions such as fission, or inelastic scattering, take place equally well in cold material or materials already heated by the considerable

energy release of a nuclear explosion. In cold materials orbital electrons may become ionized, as discussed in the previous sections. In most cases the heated materials which give important neutron reactions contain relatively heavy elements which retain some of their orbital electrons under thermal conditions, and therefore may also give some additional free electrons accompanying the neutron processes. In contrast, thermonuclear reactions by definition do not occur in cold materials. The thermonuclear fuel must first be heated by some form of energy deposition, usually a combination of hydrodynamic, radiative transfer, and nuclear radiation deposition, and only then can it react. As a result, all the electrons of the light elements participating in the reactions are already ionized before the thermonuclear reactions take place. The reactions then occur between bare nuclei in a free electron plasma, and no new free electrons are produced directly.

The thermonuclear reactions of course do give energy to the plasma of free electrons, changing its energy distribution. The mechanism by which this process takes place is the interaction of the fast product ions with the plasma, both in close binary collisions and in many particle collisions. Because of the mass difference between the heavy ions and electrons, the fraction of the ion energy transferred per collision is small. However, because of its comparatively small mass the increase in the energy of the colliding electron is large. For example, consider a head-on collision of a 2.4 Mev proton from the reaction D + D = T + P with a 1 kev electron. Inititally the electron has velocity of $v = 1.9 \times 10^9$ cm/sec, the proton $V = 2.2 \times 10^9$ cm/sec. After the head-on collision the velocity of the electron is $v' = v + 2V = 6.3 \times 10^9$ cm/sec corresponding to an energy of 10.7 kev. In most weapon designs, it will be impossible for the 10 kev type electrons to get out of the weapon, so that this reaction is not important.

In addition there are other interactions such as the Compton collisions which increase the energy of the electrons in the thermonuclear plasma. In some special design cases, however, the higher energy electrons may indeed escape, and the thermonuclear reactions are then an additional source of electrons.

3.5 Electrons Produced by the Interaction of γ-Rays

3.5.1 High Energy Electrons

During the course of a nuclear explosion, γ-rays are produced; these in turn may produce high energy free electrons. The three most important processes for this production are Compton scattering, photo-electric absorption, and pair-triplet production.

In Compton scattering, the photon is scattered inelastically by the electron, the latter acquiring a fraction of the energy of the former. For the mean γ-ray energy of 1 Mev this fraction is about 0.4 and increases with the energy. In photoelectric absorption, the electron takes all the γ-ray energy, uses a small portion to overcome its binding in the atom, and retains the major portion as kinetic energy. In pair or triplet production, a portion of the incident γ-ray energy, $2\,mc^2 \sim 1.02$ Mev is used to create the positron electron pair, the remainder being available as kinetic energy shared between the two members of the pair or the three members of the triplet. In all three processes, energetic electrons, of the order of 1 Mev, are produced in copious quantities.

Even at the earliest stages of a nuclear explosion, the electrons produced by these γ-ray interactions in the outer layers of the weapon will be able to escape into the outer world. As the weapon disassembles it will be possible for the electrons produced at deeper layers to escape, and the electron

output will increase. Soon, however, the γ- rays will be able to escape before undergoing any collisions, and electron production will fall off.

3.5.2 Low Energy Electrons

In both the photo-electric absorption and the Compton scattering process, vacancies are left in the shells of the atoms hit by the γ-rays. In Compton scattering the vacancies are randomly distributed, while in photo-electric absorption 75 percent of the vacancies are in the K shell and almost all of the remainder in the L shell. Through the Auger effect then, free electrons may be produced as the inner shell vacancy is filled. These electrons are of low energy compared to the initial photo-electron or Compton recoil, having of the order of the binding energy of the K shell electrons or less, typically in the 5 to 50 kev region.

Pair production no doubt also disturbs the atomic electrons by the escape of the pair through the atomic system. The probability of this reaction has not been estimated for this paper. Recoil of the nucleus leads to velocities which are $\sim \frac{m}{M}$ times the mean velocity of the electron positron pair. This is too low to shake off any orbital electrons.

In "triplet" production, the vacancy left by the recoil atomic electron may bring about the creation of additional Auger electrons.

3.6 Electrons Produced by the Interaction of X-Rays

In a nuclear explosion X-rays of kilovolt energy abound. In their interaction with the atoms of the weapon, free electrons are produced by the photoelectric absorption. No other process producing free electrons occurs to any appreciable extent. The cross-section for photoelectric absorption is relatively large compared to say the Compton or Thomson cross-section, so large in fact that essentially no X-ray except those near

the surface can escape the weapon. Instead the X-rays are absorbed, their energy being converted into energy of the photo-electrons. The kinetic energy of the electrons is therefore just the X-ray energy less the binding energy, and is in the neighborhood of a few kilovolts.

Following X-ray absorption, additional free electrons may be formed by the Auger effect. These are somewhat but not very much lower in energy than the photo-electrons themselves.

3.7 Thermal Electrons

Up to this point some specific mechanisms for producting free electrons have been discussed, the mechanisms being restricted to those accompanying the primary energy producing reactions in the weapon such as fission, or the DD reaction, or to those just a few steps removed such as the electrons from the photoelectric absorption of X-rays or of γ-rays. However, by far the largest number of free electrons are produced as a result of a long chain of reactions in the weapon materials; for example a γ-ray accompanying fission has a Compton recoil, producing a secondary electron whose capture is accompanied by the emission of an X-ray, which then causes a photo-electron. In the dense materials contained in weapons the various chains of reactions usually occur sufficiently quickly so that a condition of local thermodynamic equilibrium is established. The details of the chains then need not be calculated to get the free electron population, their energy distribution, and their subsequent emission rate, it being sufficient to calculate the local temperature and the equilibrium electron distribution there.

3.8 Effects of Free Electrons

3.8.1 Influence of Free Electrons on Observation of the Weapon

1. Observation of the weapon by neutron output, γ-ray output, or hard X-rays is unaffected by free electrons produced by the weapon.

2. Observation by the visible, I. R., or U. V. light emitted from the bomb case is seriously effected by the free electrons produced by the weapon.

3. Observation by reflection of radar, maser, or laser beams is determined by state of free electrons around the weapon.

3.8.2 Radiation from the Weapon-Produced Free Electrons

1. Free electrons produce bremsstrahlung X-rays. The thermal X-rays from the bomb surface are in part due to this bremsstrhlung, in part due to free-bound, and bound-bound transitions.

2. Bremsstrahlung from the electrons in the thermonuclear fuel may be observed if the reaction is close to the weapon surface, and if the burn is "runaway", giving high electron temperatures, of energy 20 kev or greater.

3. There is an electromagnetic pulse from a nuclear explosion due primarily to the current associated with Compton recoil electrons. The character, however, of the pulse in atmospheric explosions is determined by electrons from the air rather than from the bomb materials.

4. Electromagnetic noise. At later stages in an explosion there will be electromagnetic noise due to the thermal radiation from the residual low temperature free electrons created by weapon interactions.

3.8.3 Electron Belts from High Altitude Explosions and their Effect

1. Electrons may be injected into Argus type orbits from a high

altitude nuclear explosion.

2. Different times, locations, and mechanisms of electron injected into Argus orbits obtain for the different classes of electrons. One must consider the prompt fast electrons in the Mev energy range resulting from Compton recoils and prompt internal conversion, the prompt kilovolt electrons from deep atomic transitions, and the prompt low energy electrons 10 to 100 ev from "shake off" of the outer orbital electrons, as well as the delayed electrons due to beta decay and processes that follow thereafter.

3. Synchrotron radiation from the Argus belts.

4. Aurora, ionization, radar clutter, blackout, and interference from electrons in Argus belts as they interact with the atmosphere.

3.8.4 Ionization and Excitation of the Atmosphere by Electrons from High Altitude Explosions

1. Layers of ionization at 60 to 90 km altitude due to high energy electrons from high altitude explosions. Radar attenuation by these layers, and effect on high frequency communications.

2. Visible fluorescence of ionized layers.

3. I. R. excitation processes in ionized layers.

4. Higher altitude ionization from the lower energy electrons.

5. Excitation of plasma waves by high density of low energy electrons.

3.8.5 Explosion at Low Altitudes

1. Local ionization due to electrons and radar reflection from the ionized region.

2. Preionization of the atmosphere before shock wave arrival, attenuating EM and visible from the weapon.

Table I - The Fission Reaction

Ia - γ-ray Emissions
Ib - X-ray Emissions
Ic - Electron Emissions
Id - Neutron Emissions

To use Table I, fold out pages 59 and 60, which contain the process relevant for each line in the emission tables.

Table II - Reactions Other Than Fission

IIa - γ-ray Emissions
IIb - X-ray Emissions
IIc - Electron Emissions
IId - Neutron Emissions

TABLE Ia - Y-RAY EMISSIONS - 1

Section	Transition Time (sec)	Total Energy (Mev)	Mean Energy per Photon (Mev)	Spectrum and Comments	
1.1.1		None for neutrons of less than about 6 Mev energy			(1)
1.1.3		None			(2)
1.1.5	10^{-17}	Small perhaps 0.2 Mev	Possibly 20 Mev	Broad Process not verified	(3)
1.1.4		None			(4)
1.1.6 A-1	$\tau = E_f/E = 10^{-16}$	.004	0	Bremsstrahlen type, so that energy emitted per unit energy interval is flat to maximum of 200 Mev. Quantum theory calculation of spectrum has not been made.	(5)
	Neutrons dominate over Y-rays 10^{-14}	.006	1	See process 7 below. Spectrum will be a little harder than in 7 after neutron boiloff. No cutoff above 6 Mev.	(6)
1.1.7 1.1.8 1.1.9	10^{-13}-10^{-15}	6	1	$n(E)dE = 6e^{-aE}dE$ $a=1(\text{Mev})^{-1}$ Main source of prompt Y-rays, cutoff above 6 Mev.	(7)

TABLE Ia – Y-RAY EMISSIONS – 2

Section	Transition Time (sec)	Total Energy (Mev)	Mean Energy per Photon (Mev)	Spectrum and Comments	
1.1.10	10^{-11}–1	Forbidden Small	Isomeric transitions ~1/4 Mev	Line spectrum	Few sharp lines of specific nuclear transitions (8)
1.1.12	10^{-14}	6	.5	Complicated line spectrum, many nucleids	(11)

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TABLE Ib-X-RAY EMISSIONS - 1

Section	Transition Time (sec)	Total Energy per Reac. (kev)	Representative or Mean Energy per Photon (kev)	Spectrum and Comments	
3.1.1		10^{-14}	80	Characteristic X-ray spectrum with discrete lines broadened by later interactions.	(1)
1.1.11a	10^{-11}	10^{-14} negligible	80	Same as above.	(2)
	Same as (2) above				(3)
3.1.3		10^{-14}	25	Broad spectrum with many lines from the distribution of possible fission daughters. Individual lines broadened by short lifetime of atomic states in daughters.	(6)

TABLE Ib - X-RAY EMISSIONS - 2

Section	Transition Time (sec)	Total Energy per Reac. (kev)	Representative or Mean Energy per Photon (kev)	Spectrum and Comments	
1.1.11b	10^{-10}	3	.2	Broad continuum from 0 to about 300 ev.	(9)
1.1.11c	10^{-11}	30	~5	Characteristic line spectrum of many elements superimposed. Energies from 0 to ~40 kev.	(10)
1.1.13	10^{-12}	.100 per β	10	Characteristic X-ray spectrum from β decay daughters.	(11)

TABLE Ic - ELECTRON EMISSIONS - 1

Section	Transition Time (sec.)	Number of Electrons per reac.	Total Energy in Electrons per reaction (kev)	Mean Energy per Electron (kev)	Spectrum and Comments	
3.1.1		10^{-12}	10^{-14}	100	Jagged function due to overlay of many ionization edges. No beta emission during these phases.	(1)
1.1.11a	10^{-11}	10^{-15}	10^{-14}	100	Same comment as above.	(2)
		same as (2) above				(3)
3.1.3		10^{-15}	10^{-14}	30	Jagged function due to overlay of many ionization edges of many elements.	(6)
3.1.4	10^{-13}	.05	60	1000	Electrons of definite energy, corresponding to nuclear transitions. Internal conversion electrons	(7)

TABLE Ic - ELECTRON EMISSIONS - 2

Section	Mean Time for Process (sec)	Number of Electrons per fission or other reaction	Total Energy per Reaction (kev)	Representative or Mean Energy per electron (kev)	Spectrum and Comments	
1.1.10		Few	Small	250	Electrons of definite energy, corresponding to sharp nuclear levels in the transition. Internal conversion electrons from forbidden transitions.	(8)
1.1.11b 3.1.5	10^{-16}	30	3	.2	Continuous from 0 to about 500 ev with a slight peak near 300 ev.	(9)
1.1.11c 3.1.5	10^{-17}	6	30	5	Broad groups each centered around ionization energy of atomic shells.	(10)
3.1.6	$>10^{-3}$	8	8000	1000	See Horning et al. for spectrum. Electrons	(11)
3.1.7	10^{-17}	.1	10	10	directly from beta decay. Broad groups of energies centered around binding energies of the various shells in the beta decay products. Orbital electrons.	
3.1.8	10^{-13}	.08	80	1000	The same spectrum as the γ's following the β decay. Internal conversion. Orbital electrons.	
3.1.9	10^{-11}	Small number	1	1	Most electrons have energies from .1 to 1 kev with a few higher up to 20 kev. Auger effect accompanying vacancies in atomic orbitals	(12)

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TABLE Id - NEUTRON EMISSIONS - 1

Section	Transition Time (sec)	Number of Neutrons per reac.	Total Energy (Mev)	Mean Energy per Neutron (Mev)	Spectrum and Comments		TABLE Number
2.1.1	10^{-2}	1	~2	2	From 0 to E_{max} concentrated near 2 Mev. Inelastic scattering before compound nucleus excitation.	(1)	(1)
							(2)
							(3)
							(4)
							(5)
2.1.4 2.1.5 2.1.6	10^{-17}	2-3	6	2	Watt spectrum, $\sqrt{E}\, e^{-E/T}$	(6)	(6)
							(7)

TABLE I - THE FISSION REACTION - 1

and Comments		Number	Process	Time Table (sec)	Mean Time for Process (sec)
concen-	(1)	(1)	Formation of Compound Nucleus	0	10^{-20}
nav. 2 Mev. cattering ound nucleus		(2)	Formation of Daughter Nuclei in Contact	10^{-20}	10^{-20}
		(3)	Coherent Oscillations of Distorted Daughter Nuclei	10^{-20}	$\nu^{-1} = 10^{-22}$
		(4)	Conversion of electrostatic repulsive energy into kinetic energy of daughters as daughters separate	2×10^{-20}	10^{-20}
		(5)	Acceleration radiation of fission daughters	10^{-20}	
rum,	(6)	(6)	Neutron boil-off	10^{-17}	10^{-17}
		(7)	Prompt Y-ray emission	10^{-14}	10^{-14}

2

TABLE Id - NEUTRON EMISSIONS - 2

Section	Transition Time (sec)	Number of Neutrons per reac.	Total Energy (Mev)	Mean Energy per Neutron (Mev)	Spectrum and Comments	
2.1.7	10^{-17}	.01 per fission	.01	$\sim$1	Evaporation spectrum of lower temperature than process 6.	(11)

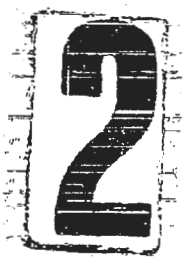

TABLE I – THE FISSION REACTION – 2

Number	Process	Time Table (sec)	Mean Time for Process (sec)
(8)	Quiet interlude until β decay	10^{-13}–10^{-3}	
(9)	Separation of daughter nuclei to 10^{-8} cm. Shakeoff of outer electrons.	10^{-17}	10^{-16}
(10)	Ionization of inner electrons		10^{-17}
(11)	Beta decay	$>10^{-3}$	
(12)	Auger effect	Various	

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ture than

TABLE II - REACTIONS OTHER THAN FISSION - 1

IIa. EMISSIONS: γ-RAYS

Process	Section	Total Energy Per Reaction (Mev)	Mean Energy Per Photon (Mev)	Spectrum	Comments
1. Neutron Capture in Compound Nucleus	1.2.1	7	1	Broad, similar to fission spectrum	
2. Direct Radiative Capture	1.2.2	Binding Energy plus kinetic energy	Higher than 1 Mev	Few discrete lines	Source of most high energy γ-rays with E>7 Mev
3. Reaction Scattering of Neutrons	1.3	Fraction of incident K.E.	<1	Broad	
4. Thermonuclear Reactions	1.4	~Q of reaction	~20	Few lines	

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TABLE II - REACTIONS OTHER THAN FISSION - 1

IIb. EMISSIONS: X-RAYS

Process	Section	Typical Total Energy Per Reaction (Kev)	Mean Energy Per Photon (Kev)	Spectrum
1. Neutron Capture				
Recoil effect	1.2.3	Few tenths or less	~.01	Optical-like spectrum with many lines
Internal conversion effect	1.2.3	.7	Z^2Ry ~30	Characteristic X-ray spectrum
Auger effect after internal conversion		.06	6	Transitions mainly to L shell
2. Elastic Scattering of Neutrons	3.2	Same as recoil effect in neutron capture		
3. Inelastic or Reaction Scattering of Neutrons				
Recoil effect	3.3	Same as recoil effect in neutron capture		
Internal conversion	1.3, 3.3	.7	Z^2Ry ~30	Characteristic X-ray spectrum
Auger effect after internal conversion	1.3, 3.3	.06	6	Transitions mainly to L shell

TABLE II - REACTIONS OTHER THAN FISSION - 1

IIc. EMISSIONS: ELECTRONS

	Process		Section	Number of Electrons Per Reaction
1.	Neutron Capture			
	Recoil effect	Light nuclei A < 10	1.2.3	All but K electrons ~3
		Heavy nuclei A > 10	1.2.3	Few valence electrons ~2
	Internal conversion effect		1.2.3	.01
	Auger effect after internal conversion		3.3	.01
2.	Elastic Scattering of Neutrons			
		Light nuclei A < 10	3.2	All but K electrons
		Heavy nuclei A > 10	3.2	Few valence electrons
3.	Inelastic or Reaction Scattering of Neutrons			
	Recoil effect		3.3	Same as elastic scattering
	Internal conversion		3.3	.01
	Auger effect after internal conversion		3.3	.01
4.	Compton Scattering of γ-Rays			
	High energy electrons		3.4.1	1
	Low energy auger electrons		3.4.2	1
5.	Pair Triplet Production			
	High energy electrons		3.4.1	2 or 3
6.	Photo-Electric Absorption of γ-Rays			
	High energy electrons		3.4.1	1
	Low energy auger electrons		3.4.2	1

TABLE II - REACTIONS OTHER THAN FISSION - 2

IIc. EMISSIONS: ELECTRONS

	Typical Total Energy in Electrons Per Reaction (Kev)	Mean Energy Per Electron (Kev)	Spectrum	Comments
1.	Few tenths	~ .05		
	< .1	~ .01		
	70	1000	Line spectrum	
	.3	30	Groups of energies	
2.	Few tenths	~ .05		
	< .1	~ .01		
3.	70	1000	Line spectrum	
	.30	30	Groups of energies	Depends upon Z
4.	400	400	Continuous and broad 0 to E_γ	
	5	5	Groups of energies	
5.	1000	500	Continuous and broad	
6.	1000	1000	Distributed with edges corresponding to atomic shells	

TABLE II - REACTIONS OTHER THAN FISSION - 1

IId. EMISSIONS: NEUTRONS

	Process	Section	Number of Neutrons per Reaction
1.	The (n, 2n) Reaction. Incident Kinetic Energy E_i		
	Direct reaction	2.2	2
	Compound nucleus reaction	2.2	2
2.	Thermonuclear Reactions		
	$D + D \rightarrow He^3 + n$ $D + D \rightarrow T + P$	2.3.2	1/2
	$D + T \rightarrow He^4 + n$	2.3.2	1
3.	Elastic Scattering. Incident Energy E_i	2.4.1	1
	"Kigme" neutrons	2.4.1	1
	(n, n) scattering	2.4.1	2
4.	Inelastic Scattering. Incident Energy E_i	2.4.2	1

TABLE II - REACTIONS OTHER THAN FISSION - 2

IId. EMISSIONS: NEUTRONS

	Total Energy (Mev)	Mean Energy Per Neutron (Mev)	Spectrum	Comments
1.	$E_i - E_b$	$\frac{E_i - E_b}{2}$	Flat between 0 and max.	Most important for $E_i >> E_b$
	$E_i - E_b$	1	Evaporation type $n(E) = ae^{-aE}$	Most important for $E_i \sim E_b$
2.	2.4	2.4	Gaussian with fractional breadth of $3.4\sqrt{kT/E}$	
	14.1	14.1	Gaussian with fractional breadth of $3.4\sqrt{kT/E}$	Breadth is 1.4 Mev for kT = 10 kev
3.	$E_i(1-\frac{1}{2}A)$	$E_i(1-\frac{1}{2}A)$	Relatively flat between E_i and $E_i(1-\frac{1}{A})$	Increase of energy possible in some scattering
	$2E_i$	E_i	Maximum of $2E_i$	
4.	(kT) ~ 1 nuclear	(kT) ~ 1 nuclear	Evaporation type $n(E) = ae^{-aE}$	

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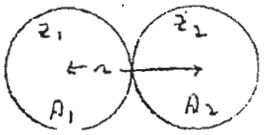
ATOMIC ENERGY ACT 1954

APPENDIX A-1

γ-Rays from Separating Fission Fragments

The emission of γ-rays due to the acceleration of the two fission daughters upon separation will be considered classically, since the acceleration radiation is a classical effect. Assume that the fission process results in two daughters, each of mass number A_1 and A_2 and charge number Z_1 and Z_2, with center separation r when in contact. The acceleration of daughter (1) is



$$a = \frac{Z_1 Z_2 e^2}{MA_1 r^2} \qquad (1)$$

with a similar equation for the acceleration of daughter (2).

In equation (1), M is the proton mass.

Classically an accelerated charge radiates. In fission, there are two daughters whose motion is coherent and the resultant radiation must be calculated with this in mind. Indeed for precisely symmetrical fission there would be no dipole radiation. For unsymmetrical fission the radiation is due to the net changing dipole moment of the system, equivalent to an accelerated charge of magnitude $(\Delta Z)e = (Z_1 - Z_2)e$, so that the energy radiated per unit time is

$$S = \frac{2}{3} \frac{(\Delta Z)^2 e^2}{c^3} a^2 \qquad (2)$$

As (1) shows, the acceleration diminishes as the daughters separate, and lasts sensibly only until the separation has increased to about 2r. The time τ during which the acceleration lasts is of the order of

$$\tau = \left(\frac{2r}{a}\right)^{1/2} . \qquad (3)$$

The energy emitted during the time τ is then

$$E = S\tau = \frac{2}{3}\frac{(\Delta Z)^2 e^2}{c^3} a^{3/2}\sqrt{2r} . \qquad (4)$$

Now the distance r is about

$$r = \frac{r_o}{2}(A_1^{1/3} + A_2^{1/3}), \qquad (5)$$

where the classical electron radius is $r_o = e^2/mc^2 = 2.8 \times 10^{-13}$ cm. Substituting (5) and (2) into (4) gives the total energy E radiated as

$$\frac{E}{mc^2} = \frac{2^4}{3}\frac{(\Delta Z)^2 (Z_1 Z_2)^{3/2}}{A_1^{3/2}(A_1^{1/3} + A_2^{1/3})^{5/2}}\left(\frac{m}{M}\right)^{3/2} \qquad (6)$$

For a common assymetric fission $Z_1 = 35$, $Z_2 = 57$, $Z = 22$, and $A = 2.62$. The numerical result from (6) is

$$\frac{E}{mc^2} = .780 \times 10^{-2} \qquad (7)$$

Hence only a negligible amount of γ-ray energy is released by the acceleration of the fission daughters.

Appendix A-2

Excitation of Orbital Electrons by Discontinuous Change in Nuclear Charge

Consider that at time $t = 0$ the nuclear charge of a hydrogenic atom changes discontinuously from the value Ze to $Z'e$ as for example in beta decay. Then, according to the sudden approximation, the probability amplitude for an electron with wave function u_i before $t = 0$ to have the wave function v_j after a long period of time is

$$b_{i \longrightarrow j} = \int v_j^* \, u_i \, d\tau . \qquad (1)$$

In particular the probability that a K electron for the nucleus Z will remain a K electron for the nucleus Z' is

$$P_{K \longrightarrow K} = \left[\int u_K^* (Z') \, u_K(Z) d\tau \right]^2 \qquad (2)$$

where

$$u_K(Z) = \frac{1}{\sqrt{\pi}} \left(\frac{Z}{a_o} \right)^{3/2} e^{-\frac{Zr}{a_o}} . \qquad (3)$$

The integral in (2) gives

$$P_{K \longrightarrow K} = \left[4 \left(\frac{Z \, Z'}{a_o^2} \right)^{3/2} \int_o^\infty e^{\frac{-(Z + Z')r}{a_o}} \, r^2 dr \right]^2$$

$$P_{K \longrightarrow K} = 8^2 \, \frac{(Z \, Z')^3}{(Z + Z')^6} . \qquad (4)$$

The probability that the K electron will be excited due to the nuclear transition is

$$P_{K \longrightarrow \text{ ex}} = 1 - P_{K \longrightarrow K} . \qquad (5)$$

Putting $Z' = Z + \xi$ and expanding to the first non-vanishing term in ξ, one obtains

$$P_{K \longrightarrow \text{ ex}} = \frac{3}{4} \left(\frac{\xi}{Z} \right)^2 . \qquad (6)$$

For beta decay $\xi = 1$, and for typical fission daughters $Z = 40$. Then

$$P_{K \longrightarrow \text{ ex}} = 3/6400 = 4.68 \times 10^{-4} .$$

The calculation may be extended to other orbitals besides that of the K electron. But rather than performing the calculation in detail, one may note that a simple approximate form for the radial wave function for the orbital with principal quantum number n can be obtained from (3) by replacing Z with Z/n. The integral analogous to (4) will show that n cancels out in the result. Therefore, the probability of excitation is approximately independent of the initial orbital.

Appendix A - 3

Electron Transitions Induced by the Neutron Magnetic Moment

When a neutron interacts with a nucleus, the orbital electrons feel a perturbation from the neutron's magnetic moment. This perturbation occurs rapidly compared to orbital times, so that the sudden approximation can be used.

The electronic wave function before the neutron-nucleus interaction is taken to be a hydrogenic wave function perturbed by the original nuclear moment; that after, a hydrogenic function perturbed by the nuclear plus neutron magnetic moment. That is,

$$(H_o + H')\, V_n' = E_n'\, V_n' \tag{1}$$

before, and

$$(H_o + H'')\, V_n'' = E_n''\, V_n'' \tag{2}$$

after, where

$$H_o\, u_n = E_n\, u_n \tag{3}$$

the usual hydrogenic functions.

To get the probability P_x of a transition, we first determine the probability of the electron remaining in the ground state, $|a_o|^2$; then $P_x = 1 - |a_o|^2$. The ground state probability amplitude is given in the sudden approximation by

$$a_o = \int \bar{V}_o'' V_o'\, d^3x \tag{4}$$

Applying second-order perturbation theory we obtain for the wave

functions

$$V_0' = u_0\left(1 - \tfrac{1}{2}\sum_{k\neq 0}\frac{|H'_{k0}|^2}{(E_0-E_k)^2}\right) + \sum_{k\neq 0}\frac{H'_{k0}}{(E_0-E_k)}u_k + \sum_{k\neq 0}\left\{\sum_{\ell\neq 0}\frac{H'_{k\ell}H'_{\ell 0}}{(E_0-E_k)(E_0-E_\ell)} - \frac{H'_{k0}H'_{00}}{(E_0-E_k)^2}\right\}u_k \tag{5}$$

and V_0'' is similarly given by replacing H'_{ij} by H''_{ij}. Then, to order $|H'_{ij}|^2$, (4) gives

$$a_0 = 1 - \tfrac{1}{2}\sum_{k\neq 0}\frac{|H'_{k0}|^2}{(E_0-E_k)^2} - \tfrac{1}{2}\sum_{k\neq 0}\frac{|H''_{k0}|^2}{(E_0-E_k)^2} + \sum_{k\neq 0}\frac{H'_{k0}H''^{*}_{k0}}{(E_0-E_k)^2} \tag{6}$$

and the probability of a transition, P_x, is

$$P_x = 1 - |a_0|^2 = \sum_{k\neq 0}\frac{|\Delta H_{k0}|^2}{(E_0-E_k)^2} \tag{7}$$

where $\Delta H_{k0} = H'_{k0} - H''_{k0}$ and terms high than $|\Delta H_{k0}|^2$ have been dropped.

It is difficult to evaluate a sum like (7), but we can place an upper limit on P_x by noting that $(E_0-E_k)^2 \leq (E_0-E_1)^2$ and that the completeness of states gives us

$$\sum_{k\neq 0}|\Delta H_{k0}|^2 = (\Delta H)^2_{00} - |\Delta H_{00}|^2 \tag{8}$$

so that

$$P_x \leq \frac{1}{(E_0-E_1)^2}\left\{(\Delta H^2)_{00} - |\Delta H_{00}|^2\right\} \tag{9}$$

ΔH is given in terms of the hyperfine separation constant by

$$\Delta H = \tfrac{1}{2}\hbar\,\Delta\nu_0\,\vec{\sigma}_n\cdot\vec{J}_e \tag{10}$$

Evaluating the neutron spin operator and the electron angular momentum in the ground state,

$$P_x \leq \frac{1}{2(E_0 - E_1)^2} \left(\frac{1}{2} h \Delta\nu_0\right)^2 \tag{11}$$

The separation constant is given by

$$\frac{1}{2} h \Delta\nu_0 = \frac{8\pi}{6} u_0(0)^2 g_e g_n \mu_n \mu_e \tag{12}$$

where the magnetic moments are

$$\mu_a = \frac{e\hbar}{2 m_a c} \tag{13}$$

For the Lande' constants, $g_n = 3.8$, $g_e = 2.0$, and

$$u_0(0) = 2\left(\frac{Z}{a_0}\right)^{\frac{3}{2}} \tag{14}$$

where a_0 is the Bohr radius. Substituting these values for $\Delta\nu_0$ and noting that $E_0 - E_1 = \frac{3}{4} Z^2$ Rydberg, we have

$$P_x \leq 3.05 \times 10^{-12} Z^2 \tag{15}$$

Therefore the upper bound on the total probability of transition is very small, even for rather large effective nuclear charge Z.

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