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THE LASER ELECTRON ACCELERATOR
AS A NEUTRON SOURCE

D. W. Glasgow

April 1968

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April 1968

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ABSTRACT

An analysis was made of the feasibility of producing intense photoneutron sources by bombarding thick, heavy-metal targets with nuclear-pumped, laser-accelerated electrons. The maximum neutron yield per electron is obtained by bombarding thick lead or uranium targets with electrons of energy ≥ 100 MeV. There is a tendency for the photoneutrons to be focused in the forward direction at high electron energies. The neutron energy distribution is maxwellian in shape with a pronounced high-energy tail. If the efficiency for converting energy from a 3000 MW reactor to accelerated electrons $\geq 1\%$, then source intensities $\geq 10^{17}$ n/sec are possible. A number of important physics experiments, now impossible or limited by neutron flux, provide further justification for intense neutron sources.

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THE LASER ELECTRON ACCELERATOR AS A NEUTRON SOURCE

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INTRODUCTION

Neutrons have been used for some time as a research tool in nuclear, atomic, molecular, solid state, and reactor physics. The increasing complexity and sophistication of this research has inevitably led to increasing demands on the nature of the neutron source.

The possibility of accelerating electrons to high energies by a laser-generated photon beam^(1,2,3) makes this topic extremely interesting from the standpoint of photoneutron sources as well as from the high and low energy physics standpoint. If a sizable fraction of the nuclear energy from a 3000 megawatt reactor could be transformed into electron kinetic energy by multiple laser accelerators and the resulting multiple electron beams focused onto a thick target, then an intense photoneutron source would result. Such an intense source would have great value to the Transplutonium Program as a producer of heavy isotopes such as ^{244}Cm , ^{248}Cm , ^{252}Cf , ^{254}Cf , and other isotopes of berkelium, einsteinium, and fermium. An intense photoneutron source would also be of value to fundamental research.

PHOTONEUTRON YIELD

Assumed for the purpose of the following experimental situation is a beam of photons produced by a laser which has been pumped by nuclear energy.^(4,5) The photon beam is used to accelerate electrons, in vacuo, to high energies. The electrons are then allowed to strike a slab or cylindrical target, as in Figure 1.

FIGURE 1. Slab and Cylindrical Source Assembly

Electrons passing through matter lose energy by ionizing the atomic electrons and by emitting radiation (bremsstrahlung) in the field of the nucleus. Below a certain critical energy, E_c , ionization losses are dominant whereas, above E_c , radiation losses are dominant. Typical critical energies are 6.9, 24, and 103 MeV for Pb, Fe, and C, respectively. For effective production of photons, the electron energy E should be $>E_c$. The high-energy electron in passing through matter, will create an electron positron-photon shower somewhat as follows: As the primary electron loses energy by bremsstrahlung, Compton electrons and electron-positron pairs thus are produced with about equal probability until the atomic number of the target reaches $Z = 20$, at which point pair production becomes the dominant process. The pairs, and to a lesser extent the Compton electrons, in turn radiate energy by bremsstrahlung, creating more pairs and so on into a full-blown cascade shower.

Neutrons are produced by the photons interacting with the nucleus. In the photonuclear reaction, a nucleus interacts with a photon whose energy is greater than the separation energy of a nuclear particle. In the process, the photon is absorbed, a radiative transition occurs between the ground state and an unbound excited state (virtual state), and the virtual state decays with the emission of a particle or particles such as a neutron, proton, etc. Figure 2 indicates in an approximate manner how the photoneutron cross section varies with energy for nuclei in the vicinity of $Z = 92$.

FIGURE 2. A Typical Photonuclear Cross Section

The cross-section curve in Figure 2 shows a maximum probability for a (γ, n) interaction at an energy between 10 and 20 MeV. The position of the resonant energy E_{res} varies with the mass number A according to

$$E_{\text{res}} = 40 A^{-0.2} \text{ MeV} \quad (1)$$

The yield of neutrons from any target can be calculated approximately, using cosmic-ray shower theory and the

photonuclear cross section. The general outline of the calculation follows the work of Levinger.⁽⁶⁾ The yield Y of photoneutrons/electron of energy E may be expressed as

$$Y(E, Z, t) = N(Z) \int_{E_{th}}^E \sigma_{\gamma, n}(Z, h\nu) \ell(E, h\nu, Z, t) d(h\nu), \quad (2)$$

where

E_{th} = energy threshold for neutron emission $\equiv$ neutron separation energy,

E = energy of the bombarding electron,

$N(Z)$ = number of nuclei/cm²/radiation length "t" of a target with mass number A and density ρ ,

t = the distance over which the electron has its energy reduced by $e = 2.71828$,

$$= \left[\frac{4\alpha N_0 Z^2 r_e^2 \ln(183 Z^{-1/3})}{A} \right]^{-1},$$

Z = atomic number,

α = fine structure constant = $e^2/\hbar c = 1/137$,

N_0 = number of target atoms/cm³,

r_e = classical electron radius = e^2/mc^2 ,

$\sigma_{\gamma, n}$ = photoneutron cross section for a bombarding photon of energy $h\nu$,

$\ell(E, h\nu, Z, t)$ = photon track length = total distance traversed by photons, with energy lying between $h\nu$ and $h\nu + d(h\nu)$, in a cascade shower triggered by an original photon whose energy is equal to E .

In the above yield equation, the shower is assumed to be completely absorbed. Levinger has applied this equation to a very thick Pb target and obtained the yield

$$Y(E, 82, \text{many } t) = 2.0 \times 10^{-4} E(\text{MeV}) \quad . \quad (3)$$

Equation 3 shows that the neutron yield from a thick target at

electron energies $>E_{\text{res}}$ is proportional to the electron beam power. This fact has been experimentally verified⁽⁷⁾ for photo-neutron production from a thick uranium target bombarded by electrons of energy 10-80 MeV.

Barber and George⁽⁸⁾ have further considered the problem of neutron yield versus Z of the target. According to cosmic ray shower theory, the track length is proportional to $E/(h\nu)^2$. Since this quantity varies slowly over the region of the giant resonance, it may be considered to be constant and removed outside the integral sign of Equation 2. The energy $h\nu$ is now the photon energy at the peak of the "giant resonance" in the photo-nuclear cross section. This energy, $(h\nu)_{\text{res}}$ is proportional to $A^{-1/5}$. The integrated cross section

$$\int_{E_{\text{th}}}^E \sigma_{\gamma,n}(Z, h\nu) d(h\nu) \quad , \quad (4)$$

may be estimated from the Sum Rules of Levinger and Bethe.⁽⁹⁾ The estimate indicates that

$$\int_{E_{\text{th}}}^E \sigma_{\gamma,n}(Z, h\nu) d(h\nu) = \frac{2\pi^2 e^2 \hbar}{mc} \cdot \frac{Z(A-Z)}{A} \propto \frac{Z(A-Z)}{A} \quad , \quad (5)$$

where e is the electron charge, $\hbar$ is Planck's constant, m is the electron mass, c is the velocity of light, Z the atomic number, and A the mass number. Substituting Equation (5) into Equation (2), and remembering that $(h\nu)_{\text{res}}^2 \propto A^{-2/5}$, one observes that the yield of neutrons/electron is given by

$$Y(E, Z, t) \propto \frac{E(A-Z)}{Z A^{3/5} \ln(183 Z^{-1/3})} \quad . \quad (6)$$

This expression decreases rather slowly as Z increases, whereas the experimental yields increase faster than this expression. The discrepancy results from the fact that the Sum Rules are not correct for light nuclei with few levels, and because

ionization losses are ignored in estimating the shower track length. The estimated value of the yield can be improved by using measured values for the integrated photoneutron cross section and considering ionization losses in determining the track length. Barber and George write the track length as

$$\ell(E, h\nu, Z, t) \propto \frac{R(Z)}{I(Z) + R(Z)} \cdot \frac{E}{(h\nu)_{\text{res}}^2},$$

where $I(Z)$ and $R(Z)$ are experimental values of the ionization and radiation losses. When this expression is substituted into Equation (2) the neutron yield/incident electron is given by

$$Y(E, Z, t) = N(Z) \cdot \frac{R(Z)}{I(Z) + R(Z)} \cdot \frac{E}{[h\nu(Z)]_{\text{res}}^2} \cdot \int_{E_{\text{th}}}^E \sigma_{\gamma, n}(Z, h\nu) d(h\nu) \quad (7)$$

$R(Z)$, $I(Z)$, $[h\nu(Z)]_{\text{res}}$, and the integrated cross section in Equation (7) are now measured values. Agreement with the experiment is shown in Figure 3.

FIGURE 3. *Calculated and Experimental Yields of Photoneutrons Per Incident Electron for Various Targets*

The yield as observed in Figure 3 is dependent on the atomic number of the target. Lead is about 10 times as effective a target as carbon, while uranium is approximately 30 times as effective as carbon. The greater effectiveness of uranium results from the fact that additional neutrons are produced by photofission. Figure 4 shows the yield data of Barber and George, plotted as a function of energy for 1 radiation length thick targets of C, Cu, Pb, and U.

FIGURE 4. *Experimental Neutron Yield Versus the Energy of the Incident Electron*

The superiority of the neutron yield from uranium at high energies is quite apparent. Barber and George have also measured the yield for various energies and thickness (see Table I). It is apparent that the yield increases with the atomic number, energy, and target thickness.

TABLE I. Yield (Neutrons/Electron) for Various Incident Electron Energies, Targets, and Thicknesses of Targets.

Target	Target Thickness, radiation lengths	Yield (Neutrons/Electron) x 10 ⁻⁴		
		15, MeV	25, MeV	35, MeV
C	1	0	0.3	1.7
Al	1	0	1.0	4.2
Cu	1	1	5.5	12.5
Cu	2	1	9.5	23
Cu	3	1	12.5	29
Cu	4	1	15.0	34
Ta	1	4	11	18
Pb	1	2	15	17
Pb	2	4	28	47
Pb	3	6	37	65
Pb	4	8	48	80
Pb	6	10	55	90
U	1	7	32	48
U	2.3	18	66	108
U	3.5	18	84	150

There is a paucity of experimental data for the neutron yield above an electron bombarding energy of 35 MeV. Consequently, Alsmiller and Moran^(10,11) have calculated the yield for thick targets of Ta, Pb, and U for incident electron energies of 24 to 200 MeV. A Monte Carlo calculation was made of the three-dimensional development of high-energy electron-photon

cascade showers in order to determine the photon track length. The yield was calculated from Equation (2), using the measured photoneutron cross sections at lower energies, and assuming them to be constant or slowly varying at higher energies. The calculated yields (Figure 5) agreed with the 34 MeV measurements of Barber et al.⁽⁸⁾ for Pb and U (last eight entries in Table I). The yields, indicated to be very nearly proportional to the energy of the incident electron, continue to increase at the higher energies for targets of 10 radiation lengths in thickness. The contribution of high-energy photons to the yield, appreciable for electron energies >100 MeV, is the result of the slowly rising photoneutron cross section above 35 MeV. Typically, 15 to 20% of the yield comes from these photons which are well collimated in the forward direction. The increase in yield, from uranium, as compared to tantalum and lead, is due to photofission, which may contribute as much as 40% to the yield.

It is now apparent that the maximum yield of neutrons results from bombarding a thick (>10 radiation lengths) uranium target with electrons whose energy >100 MeV.

THE ENERGY AND ANGULAR DISTRIBUTION OF PHOTONEUTRONS

The energy and angular distributions of photoneutrons emitted by a compound nucleus can be described reasonably well by the evaporation or statistical theory of Weisskopf and Ewing.⁽¹²⁾ The energy distribution of the photoneutrons is given by the expression

$$N(E_n)dE_n \propto E_n dE_n \sigma(E_n) \int_{E_B + E_n}^{E_{\max}} \frac{\omega(E_R) \sigma_{\gamma n}(E_\gamma) I(E_\gamma, E_{\max}) dE_\gamma}{\int_0^{E_\gamma - E_B} E_n \sigma(E_n) \omega(E_R) dE_n}, \quad (8)$$

where

E_n = neutron energy,

FIGURE 5. Neutron Yield Versus Target Thickness for Various Targets and Bombarding Electron Energies

$\sigma(E_n)$ = cross section for formation of the compound nucleus by absorption of a neutron of energy E_n ,

E_B = binding energy of the neutron or, alternatively, the photoneutron threshold,

$E_{\max}$ = maximum energy of the photon,

$\omega(E_{\text{ex}})$ = energy level density in the residual nucleus with excitation energy $E_{\text{ex}} = E_\gamma - E_B - E_n$;
 $= \omega(0)e^{(E_{\text{ex}}/T)}$,

$\omega(0)$ = energy level density at zero excitation,

T = nuclear temperature ≈ 1.0 MeV,

E_γ = photon energy,

$\sigma_{\gamma n}(E_\gamma)$ = cross section for the (γ, n) process, and

$I(E_\gamma, E_{\max})$ = bremsstrahlung spectrum with maximum energy $E_{\max}$.

The theoretical energy distribution, maxwellian in shape, is maximum at about 1 MeV (of the order of the nuclear temperature) for virtually all elements. Superimposed upon the maxwellian distribution is a high-energy tail produced by the direct interaction of a photon with a neutron in the nucleus.⁽¹³⁾ The experimental⁽¹⁴⁾ and theoretical distribution for lead (Figure 6) is very similar to that of any other element, including uranium. Superimposed upon the energy distribution of uranium will be that due to photofission. The dashed curve of Figure 6 shows the energy distribution of photofission neutrons, where the number of neutrons per unit energy interval $N(E)$ is given by

$$N(E) = \text{constant} \cdot e^{-E/0.965} \sinh \sqrt{2.29E} \quad (9)$$

The fission spectrum is normalized so that its peak is equal to the photoneutron peak. The energy spectra of neutrons

from the two processes are very much alike; namely, a maxwellian distribution with a high-energy tail.

FIGURE 6. Neutron Energy Versus the Number of Neutrons Per Unit Energy Interval

The angular distribution of photoneutrons from lead as well as from uranium is expected to be isotropic. Experimental measurements,⁽¹⁴⁾ using 70 MeV bremsstrahlung and accepting all neutron energies, show the distribution to be approximately isotropic. If only high-energy neutrons (>4 MeV) are considered, the distribution is anisotropic and goes as $a + b \sin^2 \theta$, where θ is the angle formed by the neutron and photon beam directions. This distribution results from the direct interaction mentioned earlier. The anisotropic component accounts for about 30% of the neutrons. The angular distribution for photofission neutrons from uranium and lead is expected to be isotropic. In summary, one may state that the neutron flux produced in a thick lead or uranium target by electrons with energies < 100 MeV has an approximate Maxwellian energy distribution and an isotropic angular distribution. However, for electron energies ≥ 100 MeV, the neutrons are produced predominantly by the direct photoeffect. The energy distribution will show a peak at between 1 and 2 MeV, but the high-energy tail will be much more pronounced. The angular distribution will be peaked in the forward direction. The effect would be to concentrate high-energy neutrons forward of the slab target, or onto the axis of the cylindrical target.

CONVERSION OF REACTOR POWER TO NEUTRONS PER SECOND

The intensity "N" of the neutron source resulting from the bombardment of thick U or Pb targets with nuclear-pumped, laser-accelerated electrons may be estimated from

$$N = \frac{P}{V} \cdot E_{ff \rightarrow e} \cdot Y \quad , \quad (10)$$

where

P = power level of the reactor,

- V = potential difference corresponding to an electron kinetic energy of E ,
 $E_{ff \rightarrow e}$ = efficiency for converting total reactor nuclear energy (via laser) to accelerated electrons, and
 Y = photoneutron yield.

Figure 7 illustrates the neutron source intensity versus the efficiency for converting nuclear energy to accelerated electrons for U and Pb targets. The electron energy is 100 MeV, the power level is that of a 1970 commercial power reactor (3000 thermal megawatts), and the photoneutron yield for U and Pb is 0.064 n/e and 0.044 n/e, respectively. The efficiency for converting total reactor energy to accelerated electrons is a function of the type and number of lasers associated with the reactor, the efficiency for pumping the laser with nuclear energy, and the electron acceleration mechanism.

A comparison may be made between this type of neutron source and various other intense sources (see Table II). The High Flux Irradiation Reactor (HFIR)⁽¹⁵⁾ was designed primarily for the production of transplutonium elements necessary to the heavy-element research program of the United States. The core is composed of three concentric cylinders consisting of a target zone surrounded by light water, a cylindrical fuel element surrounding the target and water, and a cylindrical beryllium reflector surrounding the fuel element and control rods. The entire assembly is immersed in a light-water reflector. The Savannah River High Flux Demonstration (SRHFD)⁽¹⁵⁾ is a modified production reactor in which the high flux is attained by reducing the absorption in the core and operating at a high power level. This reactor is used for research and assists the Transplutonium Program by preirradiation of ^{242}Pu for the High Flux Irradiation Reactor. The proposed Chalk River, Canada Intense Neutron Generator (ING)⁽¹⁶⁾ is a high current (65 mA at

FIGURE 7. Neutron Source Intensity Versus the Efficiency for Conversion of Nuclear Energy to Electron Energy

1 GeV) proton linac to be used in generating an intense neutron source by the spallation reaction $\text{Bi}(p, n^{\prime s})$. The target will consist of a molten-metal lead-bismuth eutectic surrounded by a beryllium reflector and a D_2O moderator. The thermal flux at 12 cm distance from the target is 10^{16} n/cm²/sec, a factor of 5 greater than the two high flux reactors.

TABLE II. *Intense Neutron Sources*

Source	Mean Thermal Flux, n/cm ² /sec
High Flux Irradiation Reactor (HFIR) Power level = 100 MW	2.0×10^{15}
Savannah River High Flux Demonstration (SRHFD) Power level = 735 MW	2.2×10^{15}
Proposed Chalk River, Canada Intense Neutron Generator (ING). Line power = 130 MW	1×10^{16}

The high fluxes of the ING are generated by converting ≈ 130 MW of electrical line power to 65 MW of beam power, 38 MW of which are expended as thermal energy in the target. The spallation reaction produces 20 neutrons per proton at 1 GeV, whereas the $\text{U}(e, n)$ or $\text{Pb}(e, n)$ produces 0.4 and 0.3 neutrons per electron, respectively, at 1 GeV. The spallation reaction is 50 to 60 times more productive per unit energy output. Limitations on intense neutron sources result from the thermal energy generated per produced neutron and the capability of removing this wasted energy from the source. It is obvious, after comparing the values of the thermal energy generated in the target per neutron "Q" (see Table III) for photoneutron, (d, n), fission,

TABLE III. *Thermal Energy Generated in the Target Per Neutron and Efficiency for Different Nuclear Reactions**

<u>Nuclear Reaction</u>	<u>Thermal Energy(Q), MeV/n</u>	<u>Efficiency = 1/Q, n/Meg Joule</u>
Pb(e,n) (E = 34 MeV, t = 10 rad. lengths)	3200	1.95×10^{15}
Pb(e,n) (E = 100 MeV, t = 10 rad. lengths)	2280	2.74×10^{15}
U(e,n) (E = 34 MeV, t = 10 rad. lengths)	1765	3.54×10^{15} ,
U(e,n) (E = 100 MeV, t = 10 rad. lengths)	1562	4.0×10^{15}
Be ⁹ (d,n)B ¹⁰ (Ed = 15 MeV)	1200	5.20×10^{15}
U fission	167	3.74×10^{16}
Bi(p,n' ^s)	20	3.12×10^{17}
H ³ (d,n)He ⁴ (fusion)	3.5	1.78×10^{18}
H ² (d,n)He ³ (fusion)	2.4	1.2×10^{18}
H ² (d,t)H ¹ (fusion)		

* The thermal energy deposited in the target does not include kinetic energy transported outside the target by neutrons, gamma rays, and neutrinos.

and spallation reactions, that heat removal from the target would be a problem for an intense photoneutron source. Nevertheless, advanced research reactor designs indicate power densities of 1 to 3 MW/liter, and advanced cooling technology using molten metals may allow power densities of 5 MW/liter. If a sizable fraction of the nuclear energy from a 3000 MW reactor were transferred by a laser-accelerator system to a molten metal Pb-Bi target (this probably eliminates uranium) with a volume ≤ 100 liters, then power densities ≤ 10 MW/liter could probably be tolerated.

Figure 7 indicates that if $E_{ff \rightarrow e} = 1\%$ (primary intensity $\geq 10^{17} \text{ n}'\text{s}/\text{sec}$) the laser-accelerator photoneutron source would be competitive with the present generation of high-flux reactors. An $E_{ff \rightarrow e}$ of $>15\%$ would be necessary to be competitive with the proposed spallation neutron source.

Further effort is required in order to obtain the energy and spatial distributions of the neutrons in the moderator. Such an effort would entail an approximate solution to the Boltzman equation.

FURTHER JUSTIFICATION FOR MORE INTENSE NEUTRON SOURCES

Neutron sources of more extreme intensity than those presently available must be provided before various important physics experiments can be performed. In addition, sources of this type would enable the experimentalist, in performing currently feasible experiments, to utilize small and rare samples, measure small cross sections, and improve experimental resolution and precision in much shorter time intervals. Some of the experiments require low energy ($\ll 1 \text{ eV}$) steady-state neutron sources, while others require higher energy (eV-MeV) pulsed-sources for timing purposes. Some of these experiments, although not ideally compatible with neutron sources produced by high-energy electrons, nevertheless are discussed, because of their importance to many physical theories, under the following classifications.

NEUTRON FUNDAMENTAL PROPERTIES, INTERACTIONS, AND THE LÜDERS-PAULI CPT THEOREM

Dineutron, Trineutron, and the Tetra-neutron

The existence of a bound state of the di, tri, and tetra-neutron is forbidden by the hypothesis of charge independence. However, experiments establishing the hypothesis are not of such accuracy as to rule out small differences between the n-p, n-n,

and p-p interactions which would permit bound states of these neutron nuclei. A recent experiment⁽¹⁷⁾ attempted to detect the dineutron (n_2) by searching for a "Wigner Cusp" at the threshold for dineutron production in the n-d total cross section. The effect was not observed. Further analysis indicated that the effect, if it existed, might be a 0.1-1 mb effect superimposed upon a 1 barn n-d total cross section. The analysis also indicated that the experimental system must be extremely stable over a period of a week or more. Stability requirements possibly could be met for periods of an hour if the available neutron flux (electron, proton, or deuteron produced) could be increased by a factor of 10^4 . The dineutron has been sought in various other experimental studies of secondary reactions believed to result from its existence. One such experiment⁽¹⁸⁾ used the $^{27}\text{Al}(n_2, p)^{28}\text{Mg}$ reaction as a detector of the dineutron. The ^{27}Al was exposed to the neutron flux ($\approx 10^{11}$) at a point 8 cm from the ends of the fuel elements in a nuclear reactor. The results of this experiment indicated that, if the dineutron is produced in fission, the number produced/fission is $< 5 \times 10^{-9}$. However, in view of the fact that the dineutron would be weakly bound (< 50 keV), its radius ($> 14 \times 10^{-13}$ cm) would compare to a giant nucleus of $A = 1500$. A strong probability of the dineutrons undergoing diffraction breakup in passing through the fuel elements, moderator, etc, and escaping detection in this experiment could be concluded. It seems fair to say that no one has conclusively proven the nonexistence of the dineutron. A number of other experiments could be used to search for the dineutron.⁽¹⁹⁾ If the reaction

occurs, then one might observe the reaction

or (n_2, α) reactions on other light nuclei. It is obvious that the ${}^9\text{Be}$ target must be very thin, i.e. $\approx 10 \text{ ug/cm}^2$. Another possibility is shown in Figure 8.

FIGURE 8. *Experimental Geometry for Possible Dineutron Detection*

Since the dineutron has such a large radius, there will be a high probability of diffraction breakup as it traverses the scatterer. The two separated neutrons will exhibit a strong angular correlation in the forward direction. The probability of recording coincidences between the two neutrons will vary as $1/L^2$. Only chance coincidences varying as $1/L^4$ will be observed if the dineutron does not exist. The parameters of the experiment might be target thickness, scatterer, L , and θ . The Be target must be very thin to insure that the newly created dineutron will not break apart. Very thin targets necessitate intense neutron sources in order to produce the dineutron in measurable quantities.

Thornton et al.⁽²⁰⁾ have searched for the trineutron (n_3), using neutrons from the $T(d, n){}^4\text{He}$ reaction as the neutron source and the $T(n, p)n_3$ reaction as the detector. Although no evidence of trineutron existence was found, this experiment

suffered from statistical errors of 50%. A more intense neutron source would remove this serious handicap.

Schiffer and Vandenbosch⁽¹⁸⁾ have also searched for the tetra-neutron (n_4) using the $^{27}\text{Al}(n_4, {}^3\text{H})^{28}\text{Mg}$ or $^{27}\text{Al}(n_4, p2n)^{28}\text{Mg}$ reactions as the detecting mechanism. The ^{27}Al was exposed to a neutron flux of 10^{11} n/cm²/sec for one day. Results of the experiment indicate that if the tetra-neutron is produced in fission, the yield would be $<5 \times 10^{-9}$ per fission. A more intense neutron source would make this a more definitive experiment.

Neutron Mean Life for β^- Decay

The coupling constants for beta and muon decay depend upon the lifetimes of the neutron and the muon and, as such, provide a most sensitive test of the universal Fermi interaction. Any experiment measuring neutron lifetime obviously should be conducted in such a manner as to allow the newly created neutron as much time in the detector as possible in order to enhance the probability of decay within the sensitive volume of the detector. The accuracy of such an experiment varies as $n\sqrt{T}$. Since a more accurate value for the neutron decay constant is necessary, a more intense source of cold neutrons is required. An increase in flux of 10^2 to 10^3 over existing sources would be appropriate.

Neutron-Neutron Scattering (Cold Neutrons)

This experiment would give a direct measure of the n-n interaction. At the present time, there are no experimental measurements of the n-n effective range, and the only way of measuring the n-n scattering length is to study the final state interaction in the reactions.

$$\pi^- + d \rightarrow 2n + \gamma,$$

$$n + d \rightarrow 2n + p,$$

$$n + t \rightarrow 2n + d,$$

$$\mu^- + d \rightarrow 2n + \bar{\nu}.$$

(13)

The value of the scattering length is sensitive to the perturbing effects of the third particle in the final state. However, these effects should be minimized in the last reaction since the neutrino is a weakly interacting particle. An accurate direct measurement (extremely flux limited) of the n-n interaction would be pertinent to sensitive testing of the hypothesis of charge independence of nuclear forces. A much more intense source of thermal neutrons is necessary.

Asymmetries in Lepton Emission from Cold Polarized Neutron Decay⁽²¹⁾

The small asymmetries in the emission of leptons from the decay of cold polarized neutrons provide a sensitive measure of the parameters of the fundamental weak interaction. For example, the sign of the ratio of axial-vector to vector coupling may be determined from neutron decay without any of the complexities arising from beta decay of a complex nucleus. The accuracy of the experiment would be greatly improved with an increase in the neutron flux of $10^2 - 10^3$.

Evidence Concerning Time-Reversal Invariance

The importance of establishing time-reversal invariance, or failure thereof, arises from the recent observations at Brookhaven National Laboratory and the Stanford Linear Accelerator Center of a possible failure of charge conjugation - parity invariance in the weak interaction. If the observations are correct, then a violation of time-reversal invariance must exist in order for the Lüders-Pauli "CPT" theorem to be invariant. If the time reversal transformation is invariant, then "CPT" invariance must fall. Although failure of "T" invariance would tend to perpetuate the "CPT" invariance; alteration of the conventional approach to the equilibrium condition in thermodynamics would be required. The possible discovery of a failure of time-reversal

in the decay of the K_2^0 meson has provided the incentive to search for a nucleon electric dipole moment.⁽²²⁾

The argument for the nonexistence of a nucleon electric dipole moment is based on time reversal invariance. The experiment consists of forming a thermalized neutron beam (3×10^{13} n/cm²/sec) via a D₂O moderator placed in a nuclear reactor. An intense beam of cold neutrons is produced at points remote to the reactor by using the large angular acceptance and velocity selection of a bent neutron pipe.

The cold beam is directed into a magnetic-mirror-spin-polarizer. After polarization, the neutron pipe channels the beam into a magnetic resonance spectrometer. The spectrometer consists of a split oscillating magnetic field produced by two rf coils. A phase shift of 90° is introduced between the split coils so as to maximize the rate of change of the spin-flip transition probability with respect to frequency.

Finally, the beam is led to a Fe-Co analyzing magnet and neutron detector. The experimental sensitivity is proportional to the separation of the coils and inversely proportional to the neutron velocity. The properties of neutron pipes are such that the number of neutrons of energy 10^{-8} eV is less than the number of energy 10^{-6} eV by a factor of $10^1 - 10^2$; hence, increased primary flux would increase the sensitivity of the measurement.

Neutron-Electron Interaction

The direct measurement of the neutron-electron interaction⁽²³⁾ provides one of the main sources of information regarding nucleon structure. The nature of the interaction is observed from the asymmetry in the neutron scattering from the electron cloud of noble gas atoms. The experiment is flux-limited.

Gravitational Acceleration of Free Neutrons

The direct measurement of the gravitational acceleration of unbound neutrons⁽²⁴⁾ furnishes a positive test of the premise that the acceleration of gravity is a universal constant of all matter, regardless of whether it is a particle or anti-particle, or whether it is in a bound or free state. In order to improve the accuracy of the present measurements (fall distance per flight path), flight paths of a mile or longer should be used. The longer paths would necessitate an increase in thermal neutron flux of 10^3 .

Neutron Charge

Experimental studies that set accurate limits on the neutron charge are important to the theory of fundamental particles.⁽²⁵⁾ There has been much speculation concerning the consequences of a finite electron-proton charge difference, $\delta q = |q_e| - |q_p|$, upon the expansion rate of the universe.^(26,27) If one assumes charge conservation in the neutron decay, $n \rightarrow p + \beta^- + \bar{\nu}_e$, and that the neutrino is uncharged, then the electron-proton charge difference must equal the charge on the neutron q_n . Consequently, each atom in the universe would have a net charge, $q(\text{atom}) = Z \delta q + N q_n = (Z + N)q_n$, where Z is the number of electron-proton pairs and N is the number of neutrons. If the neutron charge is of the order of 2×10^{-18} electron charges, then the observed expansion rate of the universe would be explained. Shull et al.⁽²⁸⁾ have made direct measurements of the neutron charge by measuring the electrostatic deflection of a monoenergetic neutron beam. While the experiment improved the lower limit of the charge over previously published results, the experiment still is not sufficiently sensitive to resolve the questions associated with fundamental particle theory and the expansion rate of the universe. A more intense source of thermal neutrons is necessary in order to obtain colder neutrons and allow a larger path for electrostatic deflection and detection of the neutron.

ADDITIONAL NUCLEAR PHENOMENA EXPERIMENTS

Polarization and Triple Scattering

Experiments involving the polarization of neutrons are used to probe the spin-orbit dependence of nuclear forces and the spin-orbit potential of the optical model. The triple scattering experiment provides information on the spin-spin interaction of the neutron with the nucleus. These experiments now are highly limited by flux.

Intermediate Structure

Recent experimental data indicate in various neutron cross sections a structure much wider than compound nuclear resonances, yet narrower than the optical model structure. These so-called intermediate structures are pertinent to reaction theory and, as such, must be studied in greater detail. A detailed study requires a more intense neutron source similar to that produced by pulsed high-energy electron beams.

Neutron Capture, Fission, and Multiparameter Cross Sections

Neutron capture provides a technique for the study of nuclear structure by exciting low lying states. More intense neutron sources are required in extending the studies to all isotopes with low capture cross sections. The neutron sources may be produced by pulsed high-energy electron beams.

Successful detailed studies of the dependence of fission fragment mass and kinetic energy on fragment charge, of neutron energies and numbers, and of gamma quanta energies and numbers must rely on the highest possible increases in the primary neutron flux.

Many multiparameter cross-section experiments requiring higher energy, higher intensity sources are contemplated. These sources may be produced by pulsed high-energy electron beams.

SOLID AND LIQUID STATE PHYSICS

It is a well known fact that the neutron has many advantages (zero charge, appropriate wave length, magnetic moment) over other types of physical probes for the investigation of the dynamical properties of liquids and solids, crystal structure, radiation damage, etc. Many of these experiments require more intense thermal neutron sources.

SUMMARY AND CONCLUSIONS

An analysis has been made of the feasibility of concentrating a sizable fraction of the available energy of a 3000 MW reactor into a 50 to 100 liter volume in order to produce an intense neutron source. Multiple beams of electrons accelerated by the photons from multiple lasers which, in turn, are pumped with nuclear energy, are used to bombard a slab or cylindrical target. The resultant cascade shower of photons produces neutrons by the direct photoeffect, photonuclear, and photofission reactions.

The neutron yield per electron indicates that the electron energy should be of the order of 100 MeV, and the thick (>10 radiation lengths) target should be made of Pb or U.

The angular distribution of the neutrons is essentially isotropic for electron energies $\ll 100$ MeV. The anisotropic angular distribution for electron energies ≥ 100 MeV is due to the fact that the high-energy photons in the cascade shower are directed predominantly forward from the original direction of the electron beam. These high-energy photons interact directly with the neutrons in the nucleus and eject them in the forward direction. Such phenomena effectively focus the higher energy neutrons forward from the slab target, or onto the axis of the cylindrical target.

The neutron energy distribution, maxwellian in shape, has a high-energy tail for electron energies $\ll 100$ MeV. The

distribution has a maximum at about 1 to 2 MeV. The energy distribution retains the evaporation peak at 1 to 2 MeV for electron energies ≥ 100 MeV, although the high-energy tail is much more pronounced.

An estimate of the neutron source intensity indicates that an efficiency of $\geq 1\%$ for converting nuclear energy to electron kinetic energy would produce source intensities $\geq 10^{17}$ n/sec and render the device competitive with the present generation of high-intensity sources as an isotope generator and research tool. An efficiency of $\geq 15\%$ would be required to compete with the proposed proton-linac neutron-generator at Chalk River, Canada. It now seems fair to say that this device deserves further experimental and theoretical study in view of its potential as a production and research tool.

A number of important physics experiments, now impossible or limited by neutron flux currently available, provide further justification for intense neutron sources.

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