The Inelastic Scattering of Fast Neutrons

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In a previous communication[1] we have given the values of the energy levels and cross sections for the inelastic scattering of $2\frac{1}{2}$-Mev neutrons by fluorine, magnesium, and sulfur. The absolute γ-ray yield from the excited nuclei due to a known fast neutron flux was investigated with a pair of calibrated Geiger-Müller counters operated in coincidence. The energy of the γ-radiation was determined by the method of Bleuler and Zunti[2] from the absorption in aluminium of the secondary electrons produced by a polystyrene radiator. The absolute value of the neutron flux was measured with a proton recoil ionization chamber.[3] In this way the elements, beryllium, copper, chromium, and iron have also been investigated.

The method of Bleuler and Zunti permits the γ-ray energy to be found both from the form of the absorption curve and from the range of the secondary electrons. When the values of energy obtained in these two ways agree the γ-radiation is homogeneous, thus indicating the excitation of a single nuclear level only. Such homogeneity was found for the γ-radiation from chromium, magnesium, fluorine, and sulfur.

If the radiation is complex, agreement between the two values will not be obtained. However, the method of Bleuler and Zunti can be extended to the analysis of γ-ray spectra when two components are present. The high energy component is found from the range of the secondary electrons, and this value then enables the low energy component to be determined from the form of the absorption curve. Copper and iron both exhibited complex spectra.

Table I. Gamma-ray energies and inelastic scattering cross sections.

Element	γ-ray energy (Mev)	Inelastic scattering cross section
Beryllium	...	$<0.014\times10^{-24}$ cm^2
Chromium	$1.4\ \pm0.1$	$1.2\ \pm0.4$
Copper	$1.1\ \pm0.1$ $2.2\ \pm0.1$	$1.2\ \pm0.6$ 0.34 ± 0.12
Fluorine	$1.3\ \pm0.1$	0.52 ± 0.18
Iron	$0.8\ \pm0.1$ $2.2\ \pm0.2$	$1.8\ \pm1.3$ 0.14 ± 0.05
Magnesium	$1.4\ \pm0.1$	0.75 ± 0.23
Sulfur	2.35 ± 0.15	0.38 ± 0.1

The copper spectrum could be resolved into two components: that of iron could be accounted for by two components but statistical uncertainty did not exclude the possible presence of γ-rays of intermediate energy. The analysis of the iron spectrum has been made on the basis of these two components. From considerations of the available energy it appears that these levels are separately excited.

The earlier results for fluorine, magnesium, and sulfur have been revised and are included in Table I. The cross sections given are for the naturally occurring elements.

[1] Beghian, Grace, Preston, and Halban, Phys. Rev. **77**, 286 (1950).
[2] E. Bleuler and W. Zunti, Helv. Phys. Acta **19**, 375 (1946).
[3] L. E. Beghian and H. Halban, Proc. Phys. Soc. (London) **62A**, 395 (1949).

On the Theory of Beta-Decay

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It has been found possible to write the matrix elements of standard beta-decay theory[1] in a way which not only gives the beta-spectra and angular distributions for arbitrary degree of forbiddenness, but also yields very simply the selection rules appropriate to any chosen type of interaction.

Table I. Degrees of forbiddenness f of transitions creating the system electron plus neutrino in states JSL. Even values of f refer to parity change no, odd values (underlined) to parity change yes. An * denotes that the term vanishes.

Dirac operators and values of S		$J=0$	1	2	3	4
		$L=0, 1$	0, 1, 2	1, 2, 3	2, 3, 4	3, 4, 5
$1, \beta$	(0)	$0, \underline{*}$	$*, \underline{1}, *$	$*, 2, *$	$*, \underline{3}, *$	$*, 4, *$
$\boldsymbol{\alpha}, \beta\boldsymbol{\alpha}$	(1)	$\underline{*}, 2$	$\underline{1}, 2, \underline{3}$	$2, \underline{3}, 4$	$\underline{3}, 4, \underline{5}$	$4, 5, 6$
$\boldsymbol{\sigma}, \beta\boldsymbol{\sigma}$	(1)	$*, \underline{1}$	$0, \underline{1}, 2$	$\underline{1}, 2, \underline{3}$	$2, \underline{3}, 4$	$\underline{3}, 4, \underline{5}$
$\gamma_5, \beta\gamma_5$	(0)	$\underline{1}, *$	$*, 2, *$	$*, \underline{3}, *$	$*, 4, *$	$*, \underline{5}, *$

Thus, to anticipate, Table II enables the degree of forbiddenness of any emission with nuclear spin change $J_i\rightarrow J_f$ and parity change "yes" or "no" to be read off, for the three commonly used interactions.

States of the system $e+\nu$ (electron plus neutrino) are expressed as superpositions of wave functions $\psi(JM, j_e j_\nu)$ specified by the following quantities: total angular momentum J of the system as a whole, with z-component M, angular momentum j_e of the electron, angular momentum j_ν of the neutrino. J, of course, can have any integral value 0, 1, 2, etc. . . .

The magnitudes of the individual orbital angular momenta are not constants of the motion owing to relativistic effects. However an expansion of the form

$$\psi(JM, j_e j_\nu)=\sum_{L,S} A(L,S;j_e,j_\nu)\phi(JM,LS)$$

is possible, each term of which may be regarded as representing a state of the system $e+\nu$ having a definite total orbital angular momentum L and total spin $S=0$ or 1 ("spins anti-parallel" or "parallel"), combined vectorially to yield the resultant J, M.

The matrix element of a beta-emission can now be expressed as a sum of "matrix terms," each of which contains (besides nuclear functions) one function $\phi(JM, LS)$ and one of the Dirac operators of the chosen interaction.

Such a "matrix term" gives the probability of a transition in which the system $e+\nu$ is created in the state JM, LS, by the operator concerned. Inspection shows that the nonvanishing terms can be picked out, and each one classified with a "degree of forbiddenness" f (see Table I), by the following rules:

1. $S=0$ or 1 according to the operator (Table I, column 2).
2. For given J and S, $L=|J-S|$ to $J+S$ in integral steps.
3. $f=L$ for terms containing the operators $1, \beta, \boldsymbol{\sigma}, \beta\boldsymbol{\sigma}$; while $f=L+1$ for $\boldsymbol{\alpha}, \beta\boldsymbol{\alpha}, \gamma_5, \beta\gamma_5$. Allowed transitions are denoted by $f=0$, first forbidden by $f=1$, etc.
4. If there is (is not) a nuclear parity change on emission, only terms with odd (even) f are nonvanishing.
5. If the nuclear spin change is $J_i\rightarrow J_f$, the possible values of J are $|J_i-J_f|$ to J_i+J_f in integral steps.

Thus from Table I, using rule 5 and selecting the Dirac operators of the chosen interaction, we can enumerate the f-values of all terms contributing to the beta-emission; the least f-value among

Table II. Degrees of forbiddenness f of transitions creating the system electron plus neutrino with total angular momentum J. For nuclear spin change $J_i\rightarrow J_f$, J ranges from $|J_i-J_f|$ to J_i+J_f. The degree of forbiddenness F of the emission as a whole is the least (even or odd) value of f in this range (for parity change no or yes, respectively). 0 = allowed. * = completely forbidden.

	$J=0$	1	2	3	4
Fermi ($1, \boldsymbol{\alpha}$)	$0, \underline{*}$	$\underline{1}, 2$	$2, \underline{3}$	$\underline{3}, 4$	$4, \underline{5}$
Tensor ($\beta\boldsymbol{\sigma}, \beta\boldsymbol{\alpha}$)	$2, \underline{1}$	$0, \underline{1}$	$\underline{1}, 2$	$2, \underline{3}$	$\underline{3}, 4$
Axial vector ($\boldsymbol{\sigma}, \gamma_5$)	$*, \underline{1}$	$0, \underline{1}$	$\underline{1}, 2$	$2, \underline{3}$	$\underline{3}, 4$

these gives the degree of forbiddenness F of the emission as a whole.[2]

Table II is constructed from Table I for use where only the F of the emission as a whole is required. Thus, e.g., for a nuclear spin change $0 \rightarrow 0$, $J=0$ only, and Table II shows that on the Fermi interaction $F=0$ ("allowed") for parity change "no," and completely forbidden ("yes"); for $1 \rightarrow 1$, $J=0, 1, 2$, and on Fermi interaction $F=0$ (no) and 1 (yes), etc.

In a forthcoming paper it will be shown how this formalism can be used to derive the energy spectra and the angular distribution properties of beta-emissions of arbitrary degree of forbiddenness.

[1] E. J. Konopinski and G. E. Uhlenbeck, Phys. Rev. **60**, 308 (1941); C. L. Critchfield, Phys. Rev. **63**, 417 (1943); D. L. Falkoff and G. E. Uhlenbeck, Phys. Rev. **79**, 334 (1950).

[2] Except that for the pure pseudoscalar interaction $\beta\gamma_5$, F is one unit less, owing to the absence of any terms with $f=0$.

Failure of Paschen's Law and Spark Mechanism at High Pressure

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The use of air at high pressures as an insulating medium as, for example, with power cables and high voltage apparatus in nuclear physics, has aroused considerable interest in the electric breakdown of gases at high pressure. Investigations have been made by Howell,[1] and more recently by Skilling,[2] Skilling and Brenner,[3] Trump, Safford, and Cloud,[4] and Trump, Cloud, Mann, and Hanson.[5] These investigations have all revealed a pronounced failure of Paschen's law when the gas pressure p was very high, as was the case when working with high voltage and short gap distances. These conditions involved very high fields F at the electrodes.

The recent investigators[2-5] agree that the failure of Paschen's law was due to the significant occurrence of a source of ionization which did not depend on the discharge parameter F/p, being instead a function of F and the nature of the cathode surface. It follows that the electron emission from the cathode must play an important and significant part in the breakdown mechanism, which cannot then be accounted for in terms of gas processes alone. The results of Skilling and Brenner,[3] and those of Trump *et al.*[5] all indicated that the electron emission from the cathode contributed strongly (exponentially in the case of an aluminium cathode) to the prebreakdown current, and this emission became, in fact, the controlling secondary process at the very highest pressures investigated. The mechanism of cathode emission suggested was the field emission of electrons from the cathode at high values of F, but no estimates of the magnitude of the field current under such circumstances have been given.

Prebreakdown cold emission of electrons from the cathode in spark gaps at atmospheric pressure in air has been studied during recent years in this laboratory.[6,7] The effect of different surface conditions was examined when the macroscopic electric intensity at the cathode was $\sim 10^5$ volts/cm, corresponding to breakdown, and it was shown that the surface condition and the previous treatment of the cathode exerted a considerable influence on the rates of electron emission. The electron emission was found to follow the Fowler-Nordheim[8] field law which gives the number of electrons emitted per second i in terms of the electric field F by the relation

$$r=i/F^2=A\exp(-6.8\times 10^7\phi^{\frac{3}{2}}/F),$$

where ϕ is the work function of the cathode surface in volts, and F is the field in volts/cm. From this equation estimates of ϕ for the emitting surface and of the emitting area for various values of F and i were made. Cold emission currents of the order of 10^4 and 10^5 electrons/sec were readily produced in the prebreakdown phase. If a value of $\phi \sim 4.5$ ev for the common metals such as nickel is taken, the above equation shows that fields of at least 3×10^7 volts/cm are required to produce the observed emission. However, such emission was obtained with values of the macroscopic field in the gap as low as 10^5 volts/cm. Clearly then, either the microscopic field F at the cathode surface is much greater than the measured macroscopic field in the gap (gap voltage/gap distance), or the work function of the region from which the electrons were extracted is much less than 4.5 ev. Allowing for possible local intensification (up to 10 times[9]) of the field at microscopic points on the surface, estimates of ϕ lay within the range 0.1 ev to 0.5 ev, the emitting area was estimated $\sim 10^{-14}$ cm^2. These values appear to suggest that the electrons were obtained from the surface oxide layer (which is always present on electrodes in air). This result shows that high electron emission is possible by field extraction processes from cathodes in air. For breakdown in very small gaps and high air pressures, this process would be very important, and could predominate as a source of ionization when extremely high pressures (and therefore fields) are employed, just as indicated by measurements in air at high pressures.[1-5] Further, this ionization process depends on the field F and also on the nature of the surface which itself to a certain extent might depend on the air pressure. However, the far most important factor in the mechanism is certainly the field F, so that this ionization process is bound to lead to deviations from Paschen's law, which holds only for processes dependent, not on F, but on F/p.

It is now of interest to consider whether such field processes can influence the secondary ionization mechanism[10] in such a way as to produce a modification of Paschen's law. Trump *et al.*[5] have suggested that the high fields employed in small gaps at high gas pressures may enhance the secondary ionization coefficient γ, and that such enhancement would lead to a lowering of the sparking potential V_s and to failure of Paschen's law. In this connection Germer and Haworth,[11] and Newton[12] have already shown how greatly the efficiency of positive ion electron extraction from metal surfaces is increased in the presence of high electric surface fields, and it is likely that this process of electron extraction would be greatly enhanced if electrons were available from regions of low work function, such as oxide layers.[6,7]

However, there is another aspect of this question. It has been established that considerable field emission is obtainable from oxide layers on a cathode surface, and it is interesting to consider whether the presence of positive ions on such layers could produce an enhancement of the microscopic field there and thus produce increased field emission in accordance with the equation above. The net result of this would be a comparatively high electron emission due to the incidence of the positive ions on the cathode or, in other words, an enhancement of the effective value of γ as compared with the (very low) values found in low pressure work when the field F is low. Our previous results[6,7] have shown how rapidly the electron emission i increases with the field F, so that an enhancement of F due to the presence of positive ions on cathode surface layers could lead to greatly increased electron emission. It should be noticed that such a mechanism outlined above would be taking place during the whole prebreakdown process and would appear as a greatly enhanced γ.

Support for this view has been found from the results of recent work in this laboratory on the enhancement of prebreakdown field emission from the cathode due to the presence of positive ions on the surface. In these experiments, residual ions from a previous spark were swept on to the cathode surface and the resulting emission measured. Owing to the difficulties involved in estimating quantitatively the positive ion concentration at the cathode, it is difficult at present to give an accurate estimate of the degree of enhancement obtained in these measurements. It is not, however, unreasonable to consider that the efficiency of the effective γ-process would be considerably increased by a factor $\sim 10^4$ by the enhanced field emission produced by the presence of the positive ions on thin surface cathode layers. This would be especially the case when there was considerable prebreakdown concentration of positive ions in the gap during the time when the sparking potential was being measured.

This effect could lead to an enhancement of γ of about the order required to account for the observed deviation from Paschen's law.