Plural Theories for the Shower Component in High Energy Nuclear Disintegrations

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Detailed numerical results are presented for the average numbers of protons and mesons emitted as shower particles in high energy nuclear disintegrations. The results for two schemes of plural production of mesons are compared with results previously obtained using the Heitler-Janossy(1) model in which it was assumed that the nucleus is transparent to the mesons emitted in the individual nucleon-nucleon collisions. It is concluded that this latter model best fits the limited experimental data available. The results presented for mesons are based on the assumption that the shower particles consist of π-mesons and protons only. This assumption is not essential, as the energy going into the meson component could be considered as producing mesons of various types. Some recent criticisms of the cascade theory are also answered.

INTRODUCTION

IN a previous publication[1] (henceforth referred to as I) the cascade theory for the production of meson and proton shower particles in high energy nuclear disintegrations was developed for a general model embracing three schemes of plural production of mesons as special cases. The three models were called the HJ(1),[2] HJ(2)[3] and MPM.[1] In the HJ(1) model it was assumed: (1) Every high energy nucleon-nucleon collision leads to the creation of one and only one meson. (2) The primary nucleon makes on the average more than one collision in traversing the nucleus. The effect of recoil nucleons is fully taken into account. (3) Many-body collisions do not occur. (4) The mesons produced are emitted without any interaction with the nucleons of the nucleus in which they were created. In the HJ(2) model the assumptions (1)–(3) were made, but instead of (4) it was postulated that a π-meson may give a large fraction of its energy to a nucleon inside a nucleus and that the nucleon then gives rise to a shower via the cascade process. Finally, in the MPM model, assumptions (1)–(3) were made as well as: (4) Very high energy mesons cascade within a nucleus in a manner entirely analogous to that for nucleons. (5) For high energies, each meson-nucleon collision gives rise to two mesons and one nucleon; thus

(A) meson+nucleon→meson+meson+nucleon.
(B) nucleon+nucleon→nucleon+nucleon+meson.

(6) The cross sections for processes A and B are equal.

TABLE I. The values of the functions q, $l(s)$, $k(s)$, $\lambda_1(s)$, and $\lambda_2(s)$ which are to be used in Eq. (1) when deriving the average numbers of nucleons and mesons for the three schemes of plural production.

Scheme	q	$l(s)$	$k(s)$	$\lambda_1(s)$	$\lambda_2(s)$
HJ(1)	0	0	0	$\alpha(s)$	0
HJ(2)	1	$\frac{6}{(s+2)(s+3)}$	$\frac{6}{(s+2)(s+3)}$	$1-W(0,s)-\frac{1}{2}k(s)+\{W^2(0,s)+\frac{1}{4}k^2(s)\}^{\frac{1}{2}}$	$1-W(0,s)-\frac{1}{2}k(s)-\{W^2(0,s)+\frac{1}{4}k^2(s)\}^{\frac{1}{2}}$
MPM	1	$2W(0,s)$	$W(0,s)$	$1-W(0,s)$	$1-3W(0,s)$

[1] Messel, Potts, and McCusker, Phil. Mag. **43**, 889 (1952).
[2] W. Heitler and L. Janossy, Proc. Phys. Soc. (London) **A62**, 374 (1949).
[3] W. Heitler and L. Janossy, Helv. Phys. Acta **23**, 417 (1950).

In I a full discussion was given of these assumptions in the light of recent experiments carried out on high energy nuclear disintegrations, and detailed numerical results were presented for the average number of shower particles on the HJ(1) model. It is the purpose of this paper to present numerical results for the remaining models, HJ(2) and MPM, thus providing experimentalists with theoretical results with which they may compare their data. Hitherto, mainly because of the lack of detailed theoretical results for various models of meson production, authors have sometimes arrived at conclusions which were not justified. The present results are submitted in an attempt to remedy this situation and not to prove or disprove either the plural or multiple theories of meson production. A recent paper by Treiman[4] is also commented upon.

THEORY AND RESULTS

The expressions[5] for the average number of nucleons $N^{(j)}(E)$ and the average number of π-mesons $\Pi^{(j)}(E)$ with energies greater than E emitted from a nucleus of atomic weight A, due to a collision by a primary particle j ($j=1$ refers to a nucleon, $j=2$ to a meson) of energy E_0 were given in I in matrix form:

$$\begin{bmatrix} N^{(1)}(E) & N^{(2)}(E) \\ \Pi^{(1)}(E) & \Pi^{(2)}(E) \end{bmatrix}$$
$$=\mathbf{I}_1\left\{\frac{V\{D_A\lambda_1(s)\}}{\lambda_2(s)-\lambda_1(s)}\begin{bmatrix} q-\lambda_1(s)-l(s) & k(s) \\ W(0,s) & \alpha(s)-\lambda_1(s)\end{bmatrix}\right.$$
$$\left.+\frac{V\{D_A\lambda_2(s)\}}{\lambda_1(s)-\lambda_2(s)}\begin{bmatrix} q-\lambda_2(s)-l(s) & k(s) \\ W(0,s) & \alpha(s)-\lambda_2(s)\end{bmatrix}\right\}, \quad (1)$$

[4] S. B. Treiman, Phys. Rev. **86**, 917 (1952).
[5] We assume here that the energy going into the meson component is converted entirely into π-mesons. This assumption is not completely valid, for at very high energies it is well known that mesons with masses greater than that of a π-meson are created. This does not raise any serious difficulty, as one could assume that the energy going into the meson component produces, for instance, kappa-mesons, etc. This would, of course, require a change in the energy ranges used in the calculation.

TABLE II. Theoretical results for high energy nucleon-nucleus collisions in heavy elements (silver and bromine) based on the HJ(2) model ($D_A=3.8$).

E_0 Bev	P_1	P_2	P_3	π_1	π_2	π_3	n_s	$\pi+P$	$P_3+\pi_3$	π_3/n_s	P_3/n_s	$(\pi+P)/n_s$	π_1/n_s	$P_2/(\pi+P)$
5	0.70	0.44	0.26	1.16	0.22	0.94	1.86	0.66	1.20	0.51	0.14	0.35	0.63	0.67
7	0.94	0.60	0.34	1.53	0.30	1.23	2.47	0.90	1.57	0.50	0.14	0.36	0.62	0.67
10	1.29	0.86	0.43	1.99	0.42	1.57	3.28	1.28	2.00	0.48	0.13	0.39	0.61	0.67
12	1.48	1.00	0.48	2.25	0.52	1.73	3.73	1.52	2.21	0.46	0.13	0.41	0.60	0.66
15	1.77	1.23	0.54	2.58	0.65	1.93	4.35	1.88	2.47	0.44	0.12	0.43	0.59	0.65
20	2.17	1.52	0.65	3.07	0.87	2.20	5.24	2.39	2.85	0.42	0.12	0.46	0.59	0.64
30	2.84	2.06	0.78	3.85	1.23	2.62	6.69	3.29	3.40	0.39	0.12	0.49	0.58	0.63
50	3.80	2.85	0.95	4.95	1.75	3.20	8.75	4.62	4.15	0.37	0.11	0.53	0.57	0.62
100	5.50	4.30	1.20	6.83	2.95	3.88	12.33	7.25	5.08	0.31	0.097	0.59	0.55	0.59
200	7.54	6.14	1.40	8.80	4.20	4.60	16.34	10.34	6.00	0.28	0.086	0.63	0.54	0.59
300	8.82	7.30	1.52	10.05	5.15	4.90	18.87	12.45	6.42	0.26	0.081	0.66	0.53	0.59
500	10.65	9.00	1.65	11.70	6.45	5.25	22.35	15.45	6.90	0.23	0.074	0.69	0.52	0.58
1000	13.40	11.50	1.90	14.00	8.40	5.60	27.40	19.90	7.50	0.20	0.070	0.73	0.51	0.58
1500	15.00	13.05	1.95	15.48	9.60	5.88	30.48	22.65	7.83	0.19	0.064	0.74	0.51	0.58
2000	16.16	14.20	1.96	16.45	10.50	5.95	32.61	24.70	7.91	0.18	0.060	0.76	0.50	0.58

where

$$\left.\begin{matrix}\lambda_1(s)\\ \lambda_2(s)\end{matrix}\right\}=\tfrac{1}{2}\{q+\alpha(s)-l(s)\}$$

$$\pm\left[\tfrac{1}{4}\{q+\alpha(s)-l(s)\}^2+k(s)W(0,s)-\alpha(s)\{q-l(s)\}\right]^{\frac{1}{2}}, \quad (2)$$

$$\mathrm{I}_1=\frac{1}{2\pi i}\int_{s_0-i\infty}^{s_0+i\infty}(E_0/E)^s ds/s, \quad (3)$$

$$\alpha(s)=1-2W(0,s), \quad (4)$$

$$W(0,s)=120\{(s+2)(s+3)(s+4)(s+5)\}^{-1}, \quad (5)$$

$$V(\lambda)=2[1-(1+\lambda)e^{-\lambda}]/\lambda^2, \quad (6)$$

and D_A is the average number of collisions suffered by a particle in making a diametrical passage through a nucleus of atomic weight A.

If, in the HJ(2) model, we assume that in a meson-nucleon collision the cross section for the production of a nucleon of energy η and a meson of energy $1-\eta$ is $k(\eta)=6\eta(1-\eta)$, then $k(s)=6\{(s+2)(s+3)\}^{-1}$. In Table I the values of q, $l(s)$, $k(s)$, $\lambda_1(s)$, and $\lambda_2(s)$ are tabulated for the three schemes.

Results for the average numbers of protons and mesons for a primary nucleon of energy E_0 are given in Tables II and III for the HJ(2) and MPM models, respectively. The symbols are those used previously,[1] namely:

P_1, P_2 = average number of protons with kinetic energy greater than 500 and 800 Mev, respectively.

π_1, π_2 = average number of charged mesons with kinetic energy greater than 80 and 1100 Mev, respectively.

$P_3=P_1-P_2$, $\pi_3=\pi_1-\pi_2$, $n_s=\pi_1+P_1$, $\pi+P=\pi_2+P_2$.

In deriving the results it was assumed that one-half of the nucleons were protons and two-thirds of the mesons were charged.

The results apply to the heavy nuclei silver and bromine. As has been pointed out by Messel,[6] the value of D_A previously used, *viz.*, $D_A=6.8$, gives for the HJ(1) model a possible total number of nucleons in

TABLE III. Theoretical results for high energy nucleon-nucleus collisions in heavy elements (silver and bromine) based on the MPM model ($D_A=3.3$).

E_0 Bev	P_1	P_2	P_3	π_1	π_2	π_3	n_s	$\pi+P$	$P_3+\pi_3$	π_3/n_s	P_3/n_s	$(\pi+P)/n_s$	π_1/n_s	$P_2/(\pi+P)$
5	0.68	0.43	0.25	1.27	0.24	1.03	1.95	0.67	1.28	0.53	0.13	0.34	0.65	0.64
7	0.89	0.59	0.30	1.69	0.34	1.35	2.58	0.93	1.65	0.52	0.12	0.36	0.65	0.64
10	1.17	0.81	0.36	2.20	0.47	1.73	3.37	1.28	2.09	0.51	0.11	0.38	0.65	0.63
12	1.34	0.94	0.40	2.48	0.56	1.92	3.82	1.50	2.32	0.50	0.10	0.40	0.65	0.63
15	1.54	1.10	0.44	2.86	0.70	2.16	4.40	1.80	2.60	0.49	0.10	0.41	0.65	0.61
20	1.85	1.35	0.50	3.39	0.93	2.46	5.24	2.28	2.96	0.48	0.096	0.42	0.65	0.59
30	2.37	1.78	0.59	4.40	1.35	3.05	6.77	3.13	3.64	0.45	0.087	0.46	0.65	0.57
50	3.16	2.42	0.74	5.82	2.00	3.82	8.98	4.42	4.56	0.43	0.082	0.49	0.65	0.55
100	4.50	3.58	0.92	8.04	3.17	4.87	12.54	6.75	5.79	0.39	0.074	0.54	0.64	0.53
200	6.12	4.92	1.20	10.74	4.82	5.92	16.86	9.74	7.12	0.35	0.071	0.58	0.63	0.51
300	7.28	6.01	1.27	12.40	6.00	6.40	19.68	12.01	7.67	0.33	0.065	0.60	0.63	0.50
500	8.77	7.46	1.31	14.70	7.70	7.00	23.47	15.16	8.31	0.30	0.056	0.64	0.63	0.49
1000	11.04	9.52	1.52	18.22	10.32	7.90	29.26	19.84	9.42	0.27	0.052	0.68	0.62	0.48
1500	12.56	10.88	1.68	20.50	12.00	8.50	33.06	22.88	10.18	0.26	0.051	0.69	0.62	0.48
2000	13.62	11.92	1.70	22.05	13.20	8.85	35.67	25.12	10.55	0.25	0.048	0.70	0.62	0.47

[6] H. Messel, *Progress in Cosmic Ray Physics* (North-Holland Publishing Company, Amsterdam (to be published)), Vol. II.

TABLE IV. Theoretical results for high energy nucleon-nucleus collisions in heavy elements (silver and bromine) based on the HJ(1) model ($D_A=5.8$).

E_0 Bev	P_1	P_2	P_3	π_1	π_2	π_2	n_s	$\pi+P$	$P_3+\pi_3$	π_3/n_s	P_3/n_s	$(\pi+P)/n_s$	π_1/n_s	$P_2/(\pi+P)$
5	0.33	0.22	0.11	2.25	0.55	1.70	2.58	0.77	1.81	0.66	0.04	0.30	0.87	0.28
7	0.45	0.30	0.15	2.76	0.78	1.98	3.21	1.08	2.13	0.62	0.05	0.33	0.86	0.28
10	0.59	0.40	0.19	3.34	1.06	2.28	3.93	1.46	2.47	0.58	0.05	0.37	0.85	0.27
12	0.68	0.47	0.21	3.69	1.24	2.45	4.37	1.71	2.66	0.56	0.05	0.39	0.85	0.27
15	0.80	0.56	0.24	4.12	1.46	2.66	4.92	2.02	2.90	0.54	0.05	0.41	0.84	0.28
20	0.98	0.70	0.28	4.71	1.79	2.92	5.69	2.49	3.20	0.51	0.05	0.44	0.83	0.28
30	1.28	0.94	0.34	5.64	2.32	3.32	6.92	3.26	3.66	0.48	0.05	0.47	0.82	0.29
50	1.72	1.30	0.42	7.03	3.15	3.88	8.75	4.45	4.30	0.44	0.05	0.51	0.80	0.29
100	2.57	1.97	0.60	9.10	4.48	4.62	11.7	6.45	5.22	0.40	0.05	0.55	0.78	0.30
200	3.58	2.84	0.74	11.3	6.00	5.3	14.9	8.84	6.0	0.36	0.05	0.59	0.76	0.32
300	4.23	3.47	0.76	12.8	7.20	5.6	17.0	10.7	6.4	0.33	0.05	0.62	0.75	0.33
500	5.30	4.40	0.90	14.8	8.90	5.9	20.1	13.3	6.8	0.29	0.05	0.66	0.74	0.33
1000	6.90	5.70	1.20	17.8	11.0	6.8	24.7	16.7	8.0	0.28	0.05	0.67	0.72	0.34
1500	8.00	6.70	1.30	19.7	12.5	7.2	27.7	19.2	8.5	0.26	0.05	0.69	0.71	0.35
2000	8.80	7.45	1.35	21.0	13.6	7.4	29.8	21.0	8.8	0.25	0.05	0.70	0.71	0.35

excess of the number available in the nucleus. This phenomenon, explained by "phantom collisions" and the finite size of the nucleus, plays a greater role for the HJ(2) and MPM models because of the greater number of collisions which may occur. Accordingly, the values of D_A were chosen to be $D_A=3.8$ for the HJ(2) model and $D_A=3.3$ for the MPM model, as these values normalized the results to a total number of nucleons equal to 93, the average for silver and bromine. To facilitate direct comparison between the three models, the results for the HJ(1) model with $D_A=5.8$ which normalizes the total number of nucleons to the same value 93 are given in Table IV. (It should be noted that the various ratios tabulated in this table are very much the same as given in I, Table IV for the HJ(1) model with $D_A=6.8$.) The decreasing of the value of D_A in passing from HJ(1)→HJ(2)→MPM and keeping the total numbers of nucleons the same can be roughly explained in the following manner. In the HJ(2) model both the nucleons and the mesons knock out nucleons so that there are fewer nucleons remaining in the nucleus with which the nucleons and mesons can collide. This situation is naturally accentuated in the MPM model.

A further function which has been computed is $G(E_0)$, which expresses the average amount of energy available for the production of particles other than shower particles, that is, gray and evaporation tracks:

$$G(E_0)=-\int_0^{0.5} E\frac{dN^{(i)}(E)}{dE}dE-\int_0^{0.22} E\frac{d\Pi^{(i)}(E)}{dE}dE. \quad (7)$$

The results for $G(E_0)$ for the HJ(1) model with $D_A=5.8$ and a primary nucleon are given in Table V.

DISCUSSION

In I it was pointed out that the surprising feature of the numerical results presented for the HJ(1) model was their apparent agreement with the limited experimental data available on high energy nucleon disintegrations (see Camerini *et al.*[7]). We say "surprising" since experimental evidence[8,9] appeared to support the hypothesis that the π-mesons do interact with nucleons in a manner analogous to that for the nucleons themselves, whereas in the HJ(1) model it was assumed that the nucleus was transparent to the mesons created within it. Heitler (private communication) has suggested that this apparent anomaly would be resolved if the interaction cross section for π-mesons with nucleons were to decrease with increasing primary energy. Although it is true that a large number of meson-nucleus interactions have been observed for primary meson energies $\leqslant 1$ Bev, there is little evidence for such behavior for meson energies >1 Bev.

Since the HJ(1) model *appears* to fit the experimental facts, we shall discuss the results for the HJ(2) and MPM models in relation to those for the HJ(1) model. In I, results for HJ(1) were presented both for light and heavy nuclei. Because the results for heavy nuclei exhibit the main features of the models more strongly than do those for light nuclei, the latter have not been considered in this paper.

Although an inspection of Tables II, III, and IV reveals at first sight a rather strong similarity between the various quantities tabulated, there are a number of outstanding differences which may allow the experimentalist to decide the relative merits of the models. We note that the number of P_1 particles is greatest for the HJ(2) model. This would be expected because in this case the nucleons are given a large preference over the mesons, the mesons themselves contributing to the number of nucleons and at their own expense. In the MPM model the number of P_1 particles is greater than in the HJ(1). This is because the mesons contribute to the number of nucleons. It should be remembered, however, that in this instance the mesons *gain* as well.

[7] Camerini, Lock, and Perkins, *Progress in Cosmic Ray Physics*, edited by J. G. Wilson (North-Holland Publishing Company, Amsterdam, 1952), Vol. I, Chap. 1.
[8] W. O. Lock and G. Yekutieli, Phil. Mag. **43**, 231 (1952).
[9] W. G. V. Rosser and M. W. Swift, Phil. Mag. **42**, 856 (1951).

The fact that on the HJ(2) model the nucleons are given preference over the mesons leads to a smaller π_1/n_s ratio than on the HJ(1) model. Furthermore, on the HJ(2) model, the relative number of $\pi+P$ particles is greater and the number of protons among the unidentifiable shower particles is very high. This fact would tend to disagree with the Bristol[7] estimate that the protons constitute roughly 30 percent of the $\pi+P$ particles. The significance which one can attach to this difference depends, of course, upon the amount of confidence one places in the Bristol figure.

The behavior of the $\pi+P$ particles and the P_2 particles on the MPM model is much the same as on the HJ(2) model. One feature of the results makes the validity of this model rather dubious, namely, the constancy of the π_1/n_s ratio. Both the Bristol results and those of Barker and Butler[10] indicate that with increasing primary energy the π_1/n_s ratio decreases.

From the above discussion it is obvious that it is difficult at present to decide between the models. As more accurate experimental results become available it should become relatively simple to decide which of the models, if any, is correct. For the present we conclude that not only is the HJ(1) the simplest of the models of plural meson production considered, but also it gives the most satisfactory agreement with the limited experimental data available.

We now turn our attention to a discussion of the results presented in Table V and a recent paper by Treiman.[4]

It is well known that for nucleon energies below 1.5 Bev, less than one-half of the nucleon-nucleon encounters are inelastic and do not lead to the production of mesons. As the primary energies increase above 1.5 Bev, the probability for inelastic nucleon-nucleon collisions increases, and near 5 Bev practically every nucleon-nucleon collision leads to the creation of mesons. It is evident, then, that in nucleon-nucleus encounters in which the primary nucleon energy $E_0 \leqslant 1$ Bev, practically the total primary energy is dissipated in the production of gray and evaporation tracks. For $1.5 \leqslant E_0 \leqslant 5$ Bev, the percentage of energy going into the production of gray and evaporation tracks will decrease sharply. For energies $E_0 \geqslant 5$ Bev, one would expect this percentage to remain substantially constant. That this is actually so may be seen from Table V. For a primary energy $E_0 = 10$ Bev there is on the average 1.62 Bev available for the production of gray tracks and evaporation prongs. For $E_0 = 500$ Bev there is, on the average, 10.8 Bev available. If one takes into consideration the gray tracks, which may have energies in the neighborhood of 400 Mev, it will be seen that the actual energy available for the production of evaporation prongs is nearly independent of the primary energy.

[10] K. H. Barker and C. C. Butler, Proc. Phys. Soc. (London) **A64**, 4 (1951).

TABLE V. $G(E_0)$, the energy available for production of gray and evaporation tracks in a nucleon-heavy nucleus collision on the HJ(1) model.

E_0 in Bev	$G(E_0)$ in Bev	$100G/E_0$
10	1.62	16.2
20	2.27	11.3
50	3.28	6.8
100	4.43	4.4
200	6.71	3.4
500	10.82	2.2

Treiman, in a recent paper[4] on the analysis of cosmic-ray experiments on the neutron component, determined a "specific yield" function. This function gave the production rate of disintegration nucleons at a given atmospheric depth arising from a unit flux of vertically incident cosmic-ray primaries of given atomic weight and given energy per nucleon. Disintegration nucleons were defined as evaporation prongs and slow recoil nucleons with $E < 50$ Mev. He found, within the experimental error, that over a very limited primary energy range (4 to 12.7 Bev per nucleon) the specific yield function was fairly insensitive to primary energy. For primary energies below 4 Bev per nucleon the specific yield function depended strongly on the energy.

Treiman briefly discussed Messel's theory[11] of a nucleon cascade and stated: "Actually the results obtained by Messel predict a specific yield function for small star production which depends strongly on primary proton energy, even for energies above 4.1 Bev." It is readily seen from Table V that this conclusion was not justified even though $G(E_0)$ applies to the heavy nuclei. Recall that the energy of high energy gray tracks is also included in $G(E_0)$.

It should be mentioned here, once again, that the theory of a nucleon cascade, as such, is independent of the model of meson production. The one and only assumption[6] used in this respect is the homogeneity property of the total cross section with regard to the primary and secondary energies. The theory may, however, be specialized to include various models of meson production, as we have done in I and in this paper.

Finally, we should like to comment on one of Treiman's statements which we believe is incorrect. Trieman states (reference 4, page 922) ". . . Messel has obtained fairly good agreement between theory and experiment for the latitude variations of small stars. This must be considered to be spurious, however, since the primary proton energy spectrum adopted by Messel (integral power law exponent$=1.7$) is in serious disagreement with the spectrum deduced from the data of Winckler and Peters (exponent$\simeq 1.0$)." However, in the papers to which Treiman refers,[12] Messel concluded

[11] H. Messel, Comm. Dublin Inst. Advanced Studies, Series A, No. 7 (1951).

[12] H. Messel, Phys. Rev. **83**, 21 (1951); **83**, 26 (1951).

that using $\gamma=1.7$, the then accepted value, does *not* yield good quantitative agreement with experiment and suggested that better agreement would be obtained with a smaller value of γ. In a further paper[13] (apparently overlooked by Treiman), Messel presented results adopting "the upper limit $\gamma=1.1$." Instead of the agreement between Messel's theory (with $\gamma=1.7$) and experiment being spurious, the facts are, as stated in the literature, that with $\gamma=1.7$ the theory is not in good quantitative agreement but with $\gamma=1.1$ they are.

[13] H. Messel, Proc. Phys. Soc. (London) A64, 726 (1951).

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The Mechanism of Field Dependent Secondary Emission

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In recent experimental investigations, it was found that secondary emission ratios as high as 10,000 to 1 could be attained utilizing field dependent secondary emission from magnesium oxide. Early tests showed the mechanism causing the high gains to be fundamentally different from the more standard secondary emission phenomenon.

The hypothesis was made that the mechanism of field dependent secondary emission was a process similar to that of the "Townsend avalanche" occurring in gas discharges. As the surface of the dielectric film was bombarded with primary electrons, the high resistivity of the material in combination with the secondary emission current caused the surface to charge to the potential of the collector grid, producing a high field within the dielectric. Electrons released within the material could then gain enough energy to liberate additional electrons, and an avalanche type process resulted.

Experiments were conducted to test this hypothesis and each proved to be consistent with the above theory. The main content of these experiments can be summarized in the following statements:

(1) The high yields appeared to be independent of the base material. This indicated that the surface or volume effects were most important, implying that a Fowler type field emission from the base metal was not a significant factor.

(2) In studying the secondary current as a function of field, the gas discharge equations were found to be correct. These equations predicted a straight line plot of the ln lnδ *vs* $1/E$, and in addition, gave a close estimate of the magnitude of the secondary emission ratio.

(3) By means of retarding potential measurements, the energies and mean free paths of the emitted secondary electrons were determined. These data were in good agreement with the results in item (2).

(4) The rise time for surface charging was determined by using square wave variations of bombarding currents, and was found to be consistent with the original hypothesis.

I. INTRODUCTION

In recent years several workers have reported unusually high secondary emission ratios from thin dielectric films. Their investigations have shown that high dc fields applied across these films cause an enhancement of the secondary emission ratio. In the experiments to be described, high fields were applied across thin films of magnesium oxide while the surface was being bombarded with primary electrons. The secondary emission ratio was found to increase exponentially with field over a wide range of bombardment energy.[1] By applying a square wave variation of field and observing the rise time of surface charging, it was concluded that the enhanced ratios were the result of a high field created within the magnesium oxide by the charged surface. It was further postulated that secondary electrons, liberated in the material, would be accelerated to such high velocities that an effect similar to the "Townsend avalanche" could occur.

The following discussion is an attempt to explain the mechanism of electron multiplication in the dielectric film.

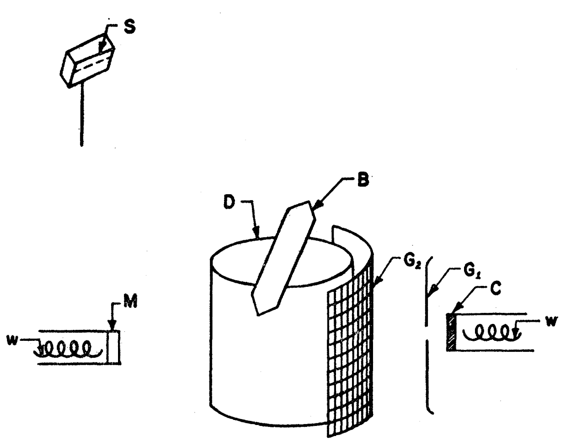

Fig. 1. Experimental tube.

II. EXPERIMENTAL PROCEDURES

Experimental tubes were constructed as shown in Fig. 1. In this design, C represents an oxide coated cathode to be used as the primary emission source; W indicates the tungsten filaments used for heating the cathode sleeves. G_1 is a negatively biased focusing grid consisting of a disk with a small opening. In some tubes, G_1 was omitted with no noticeable difference.

[1] H. Jacobs, Phys. Rev. 84, 877 (1951).