Proposal to Study the Reaction $d + p \rightarrow He^3 + \gamma$ at $T_d = 460$ MeV.

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Summary

We propose to study the reaction $d + p \rightarrow He^3 + \gamma$ as a supplement to the study of $p + d \rightarrow He^3 + \gamma$ presently being conducted at the 184" cyclotron by the LRL-Cal Tech collaboration. The maximum energy of the deuteron beam is 460 MeV which is equivalent to a 230 MeV proton beam in the p + d reaction. Thus the proposed experiment would provide data at a lower energy than is presently being studied.

The low energy under consideration allows a complete kinematic separation of $d + p \rightarrow He^3 + \gamma$ from $d + p \rightarrow He^3 + \pi^0 \rightarrow He^3 + \gamma + \gamma$ for center of mass angles from about 35° to 150° for the first reaction.

This experiment can be done with the apparatus for the p + d experiment without modification. We estimate that 10,000 events could be collected in the angular range as above in 36 hours of running time with a beam of 10^8 deuterons per second and a hydrogen target $\frac{1}{2}$" thick.

This experiment could be run simultaneously with the LRL-UCLA investigation of d + p elastic scattering.

Experimental Configuration

The He^3 is observed in a telescope consisting of (in order of increasing distance from the hydrogen target) two 3-gap spark chambers, a 0.125" thick scintillation counter, a 4.1875" thick total absorption counter and a veto scintillation counter. This array extends from 3.6° from the central beam line to about 18°. The trigger is appropriate (see below) pulse heights in the first two scintillation counters and none in the third (veto) counter.

The photon is observed in either one of two shower telescopes consisting of a veto scintillation counter, a 2 radiation length lead-glass counter, a $\frac{1}{4}$" scintillation counter, four 1-gap spark chambers, and either an 8 or 14 radiation length lead-glass counter. The trigger would be no pulse in the veto counter and pulses from either or both of the front lead-glass slab and the rear block. With a minimum of 10 radiation lengths of lead glass to initiate a shower, the photon conversion efficiency is essentially 100%. If a shower originates in the front lead-glass slab so that there is a signal in the second scintillation counter, the spark chambers may be fired yielding additional information on the photon position. This should occur for about 40-60% of the events. The telescopes may be positioned at 11 lab angles from 23° to 140°.

The pulse heights from both He^3 trigger counters as well as those from all of the lead-glass counters are pulse-height analyzed. The time of flight difference between the He^3 and photon detection is measured. These data, along with the spark coordinates from a magnetostrictive readout and various quantities accumulated in scalers are recorded on magnetic tape for each event by means of an Alpha-63 Data Processing Unit.

Kinematics and Backgrounds

Appended to the proposal are kinematics tables for the reactions $d + p \rightarrow He^3 + \gamma$, $d + p \rightarrow He^3 + \pi^{\circ}$, and d + p elastic scattering. For the first reaction, note the the He^3 lab angle "folds", attaining a maximum of only 6.6°. The center of mass angles corresponding to a lab He^3 angle greater than 3.7° range from about 38° to 150° -- the sensitive region of the proposed experiment. The He^3 kinetic energies range from 230 to 360 MeV. The photons range from 20° to 125° and from 110 to 230 MeV in energy. The He^3 will be stopped in the 4" total absorption counter yielding a 3% energy determination from the resulting light output. The r.m.s error in the He^3 trajectory angle due to multiple scattering varies from 0.2° to 0.36°. The light output from the photon shower in the lead-glass yields a determination of the photon energy with a resolution between

10 and 20%.

The most troublesome background in this type of experiment is the production of pi-zeros in place of the photon since the pi-zero promptly decays into two photons. At the proposed energy the He^3 from the $He^3 + \pi^0$ final state is limited to a lab angle of 3.2^o (see the kinematics table). These He^3 suffer multiple scattering of r.m.s. angle 0.3^o. Since the apparatus does not accept He^3 of angles less than 3.7^o this background is suppressed. The requirement of a shower from one of the π^0 decay photons further suppresses this background. For a decay photon to yield an appreciable shower it must be heading in the same direction as the π^0. From the kinematics table, only photons in the range 30 to 60^o correspond to He^3 with large enough lab angles to be detected. However, in $d + p \rightarrow He^3 + \gamma$, 30 to 60^o photons all correspond to He^3 with lab angles greater than 5^o. A further check on the separation of the π^0 type background comes from those events for which the shower could be observed in the sparks chambers, allowing a coplanarity requirement to be made.

The reaction $d + p \rightarrow He^3 + \pi^0$ is the only one likely to correctly simulate the trigger requirements. The problem of chamber flooding due to other reactions remains. In $d + p \rightarrow$ anything, d + p elastic scattering has the largest cross-section. In the LRL-UCLA proposal to study d + p elastic scattering with much of the same apparatus, it is felt that the charged particle flux resulting from a beam of 10^8 deuterons per second and a ½" target are low enough for reliable operation of the spark chambers. Beyond the rate, there is another troublesome feature of d + p elastic scattering at backward center of mass angles. Both the deuteron and proton in the final state have very forward angles, and the deuteron has only about 50 MeV. kinetic energy. This can lead to large pulse heights in the He^3 counters from the deuteron while the forward protons miss the shower telescope veto counters. This problem can be eliminated

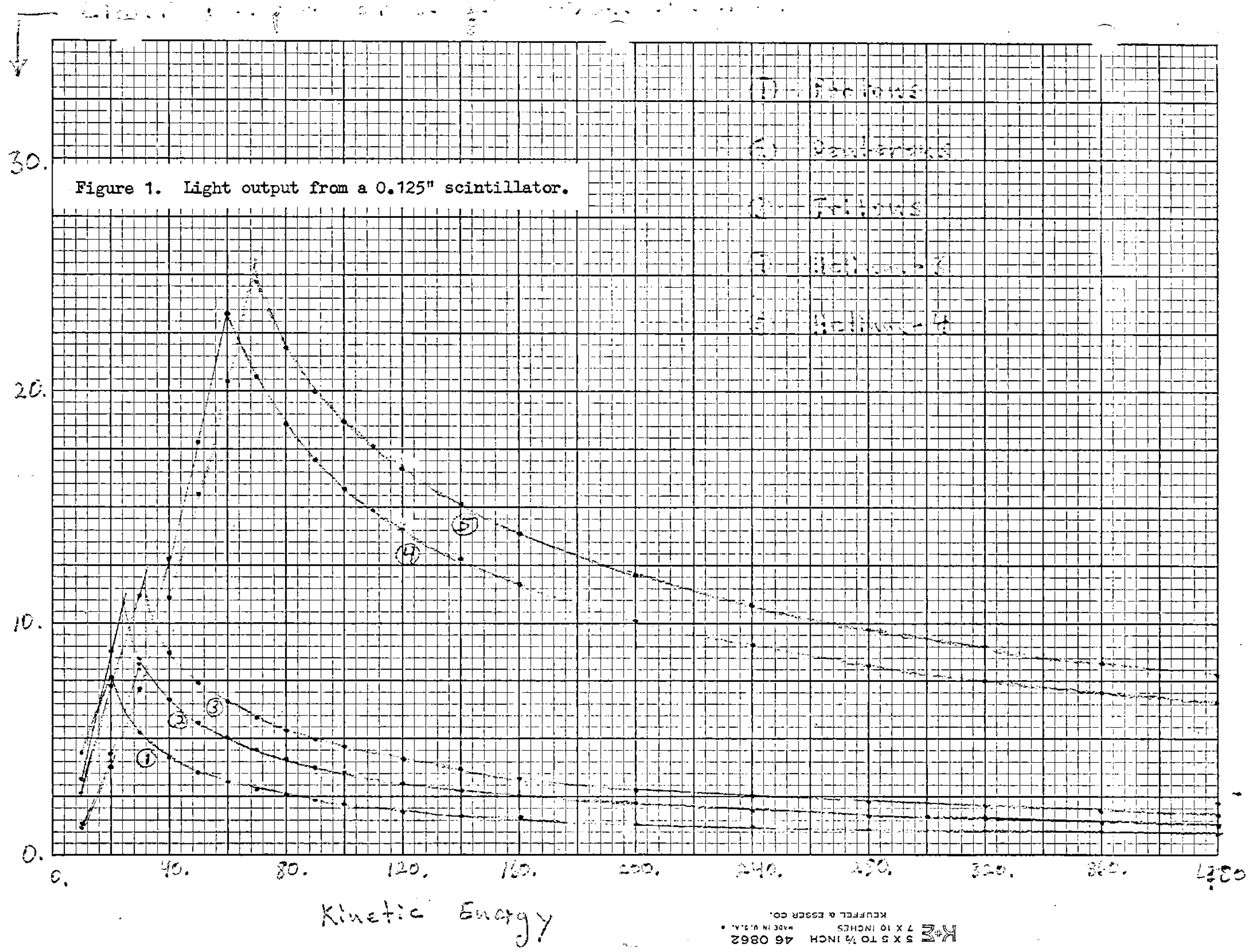

Figure 1. Light output from a 0.125" scintillator.

KE 10 X 10 TO THE CENTIMETER 46 1510
10 X 25 CM. MADE IN U.S.A.
KEUFFEL & ESSER CO.

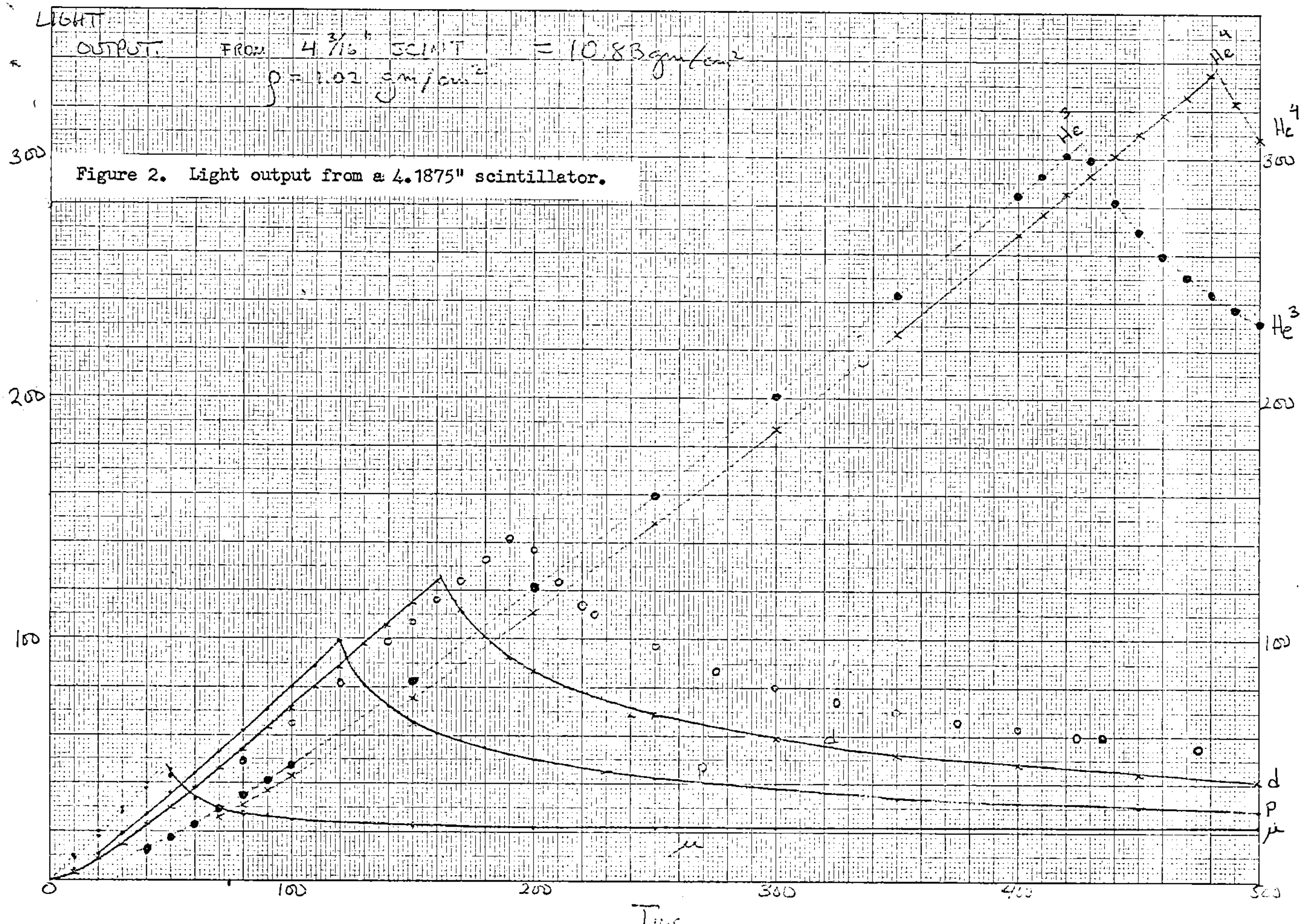

Figure 2. Light output from a 4.1875" scintillator.

with proper bias setting on the two He^3 trigger counters. Figures 1 and 2 show the expected light output in these two counters for various charged particles. The He^3 in the proposed experiment have kinetic energies between 230 and 360 MeV. In the 0.125" counter, only deuterons with energies between 20 and 60 MeV have pulse heights greater than the 360 MeV He^3. However, for the 4" counter only deuterons in the close vicinity of 160 MeV have pulse heights comparable with the 230 MeV He^3. Thus all deuterons (and also protons) can be excluded from the trigger.

With the suppression of the backgrounds as outlined above, the proposed experiment should be nearly background free.

Counting Rate Estimate

The geometric detection efficiency of the apparatus has been calculated using a Monte Carlo program. Typically one setting subtends 1-1.5% of the 4π solid angle viewed in the center of mass frame. This is about double that obtained with the same apparatus for the reaction $p + d \rightarrow He^3 + \gamma$ due to more favorable lab to center of mass transformations.

As an estimate of the differential cross-section, I used a fit to the data of Bachelier et al (Phys. Letters 21, 697 (1966)) normalised to $8 \times 10^{-32} cm^2/sr.$ at $90°$ in the c.m. frame. This is roughly a factor of 2 less than the notorious Frascati data would imply.

The results of the calculation are summarized in Table 1. Note that the counting rate is fairly uniform over the various settings as opposed to the large variations observed in $p + d \rightarrow He^3 + \gamma$. For the present reaction the variations in the cross-section and detector solid angle compensate very nicely.

With the use of the two shower telescopes two of the settings can be used simultaneously. To obtain a unifrom survey of the region from 35 to $150°$ I suggest that data be taken at the following 4 pairs of settings:

1 & 8, 4 & 9, 6 & 10, 7 & 10. Eight hours of running at a beam of 10^8 deuterons per second should suffice to collect 1000-15000 events at each setting.

Table 1

$d + p \rightarrow He^3 + \gamma$ Counting Rate Summary

Setting	θ_{lab}	$\theta_{c.m.}$	Events/day	
1	23.45°	131-153°	3400	
2	28.47	124-146	4000	Assuming a beam intensity of
3	34.47	117-138	3800	10^8 deuterons per second and
4	39.33	111-131	4000	a target thickness = ½"
5	44.47	105-124	4000	
6	59.0	88-105	4500	
7	71.4	76- 91	5000	
8	86.5	61- 75	5000	
9	102.63	48- 60	3900	
10	119.0	35- 47	2700	
11	139.63	29- 32	140	

Compatibility with the d + p Elastic Scattering Experiment

The present experiment is physically compatible with the LRL-UCLA study of d + p elastic scattering. Our He^3 telescope is their deuteron telescope. They will detect the proton in a small proton telescope placed at angles from 4 to 30°. Only setting 1 of the present experiment would overlap the range of their proton telescope.

The present experiment would use the electronics now used for the study of $p + d \rightarrow He^3 + \gamma$ without major modifications.

Relation to the Reaction $\gamma + He^3 \rightarrow p + d$

The purpose of the proposed experiment is to provide a test of time reversal invariance in the electromagnetic interaction by comparison with its inverse reaction, $\gamma + He^3 \rightarrow p + d$. The 460 MeV incident deuteron beam in $d + p \rightarrow He^3 + \gamma$ corresponds to a 157 MeV incident photon in $\gamma + He^3 \rightarrow p + d$. This is well below the energy region in which an $N^*(1236)$ might be excited in an intermediate, leading to a possible time reversal violation. It is also below the energy range of the Cal Tech experiment on the reaction $\gamma + He^3 \rightarrow p + d$, for which data does not extend below 200 MeV incident photons. There is some as yet unpublished data for $\gamma + He^3 \rightarrow p + d$ at 140 and 160 MeV taken by L.J. Koester at Illinois.

In addition to comparison with its inverse reaction, the present experiment is justified as an extension of the LRL-Cal Tech study of $p + d \rightarrow He^3 + \gamma$. Complete anglular cross-sections for the latter will be collected only for T_p = 462 MeV, an energy where the $N^*(1236)$ should be present. The shape of the angular distribution should be markedly influenced by the presence of the N^* which would be confirmed of denied by the additional data provided by the proposed experiment. This would be the clearest evidence for the presence of the N^* in the reaction $p + d \rightarrow He^3 + \gamma$, not relying on a comparison with the inverse reaction.

D + P = HE3 + PHOTON

MASSES INCIDENT 1875.58100
TARGET 938.25600
C 2808.34300
D 0.

INCIDENT MOMENTUM 1391.810 INCIDENT KINETIC ENERGY 460.000

CENTER OF MASS PARAMETERS
TOTAL ENERGY 2963.254 BETA .4251 GAMMA 1.1048 S 87.808742E+05
PARTICLE A TOTAL ENERGY 1926.658 MOMENTUM 440.689
PARTICLE B TOTAL ENERGY 1036.596 MOMENTUM 440.689
PARTICLE C TOTAL ENERGY 2812.392 MOMENTUM 150.862 BETA .0536 OMEGA
PARTICLE D TOTAL ENERGY 150.862 MOMENTUM 150.862 BETA 1.0000 OMEGA

PARTICLE C

CM ANGLE	LAB ANGLE	KINETIC ENERGY	MOMENTUM	BETA	SOLID ANGLE	U	LAB ANGLE	KINETIC ENERGY
0.	0.	369.678	1487.625	.4681	.0103	70.0525E+04	180.000	95.816
5.00	.507	369.409	1487.049	.4680	.0103	70.0019E+04	172.135	96.089
10.00	1.011	368.602	1485.324	.4675	.0102	69.8505E+04	164.314	96.892
15.00	1.509	367.264	1482.460	.4668	.0101	69.5994E+04	156.578	98.230
20.00	2.000	365.405	1478.474	.4658	.0099	69.2506E+04	148.968	100.089
25.00	2.480	363.040	1473.389	.4646	.0097	68.8067E+04	141.516	102.454
30.00	2.947	360.185	1467.236	.4631	.0094	68.2711E+04	134.252	105.309
35.00	3.398	356.864	1460.049	.4613	.0091	67.6478E+04	127.197	108.630
40.00	3.830	353.101	1451.873	.4592	.0088	66.9417E+04	120.368	112.393
45.00	4.240	348.924	1442.757	.4570	.0083	66.1580E+04	113.777	116.570
50.00	4.627	344.367	1432.756	.4545	.0079	65.3028E+04	107.428	121.127
55.00	4.986	339.463	1421.932	.4517	.0073	64.3825E+04	101.322	126.031
60.00	5.315	334.249	1410.353	.4488	.0067	63.4042E+04	95.456	131.249
65.00	5.612	328.766	1398.093	.4457	.0060	62.3753E+04	89.824	136.728
70.00	5.874	323.055	1385.230	.4424	.0053	61.3036E+04	84.419	142.439
75.00	6.098	317.160	1371.851	.4389	.0045	60.1973E+04	79.230	148.334
80.00	6.281	311.125	1358.045	.4353	.0036	59.0648E+04	74.245	154.369
85.00	6.421	304.996	1343.908	.4317	.0026	57.9148E+04	69.453	160.498
90.00	6.515	298.820	1329.538	.4279	.0016	56.7559E+04	64.841	166.674
95.00	6.562	292.644	1315.041	.4241	.0005	55.5970E+04	60.397	172.850
100.00	6.560	286.516	1300.523	.4202	-.0006	54.4469E+04	56.109	178.978
105.00	6.506	280.481	1286.095	.4164	-.0019	53.3145E+04	51.964	185.013
110.00	6.400	274.585	1271.871	.4126	-.0032	52.2082E+04	47.951	190.909
115.00	6.240	268.874	1257.965	.4088	-.0045	51.1365E+04	44.058	196.620
120.00	6.026	263.391	1244.492	.4051	-.0058	50.1076E+04	40.275	202.103
125.00	5.759	258.178	1231.567	.4016	-.0072	49.1292E+04	36.590	207.316
130.00	5.439	253.273	1219.305	.3983	-.0086	48.2090E+04	32.995	212.221
135.00	5.067	248.716	1207.815	.3951	-.0099	47.3537E+04	29.478	216.778
140.00	4.646	244.540	1197.206	.3922	-.0112	46.5701E+04	26.032	220.954
145.00	4.178	240.776	1187.577	.3895	-.0124	45.8639E+04	22.648	224.718
150.00	3.668	237.455	1179.023	.3871	-.0136	45.2407E+04	19.316	228.039
155.00	3.119	234.601	1171.630	.3850	-.0146	44.7050E+04	16.029	230.893
160.00	2.537	232.235	1165.472	.3833	-.0154	44.2611E+04	12.780	233.259
165.00	1.928	230.376	1160.614	.3819	-.0161	43.9123E+04	9.559	235.118
170.00	1.297	229.038	1157.106	.3810	-.0167	43.6613E+04	6.361	236.456
175.00	.652	228.232	1154.987	.3804	-.0170	43.5098E+04	3.177	237.262
180.00	.000	227.962	1154.278	.3802	-.0171	43.4592E+04	.000	237.532

D + P = HE3 + PI-ZERO

MASSES	INCIDENT	1875.58100
	TARGET	938.25600
	C	2808.34300
	D	134.97400

INCIDENT MOMENTUM 1391.810 INCIDENT KINETIC ENERGY 460.000

CENTER OF MASS PARAMETERS

TOTAL ENERGY 2963.254 BETA .4251 GAMMA 1.1048 S 87.808742E+05

PARTICLE A	TOTAL ENERGY	1926.658	MOMENTUM	440.689		
PARTICLE B	TOTAL ENERGY	1036.596	MOMENTUM	440.689		
PARTICLE C	TOTAL ENERGY	2809.318	MOMENTUM	74.015	BETA .0263	OMEGA
PARTICLE D	TOTAL ENERGY	153.936	MOMENTUM	74.015	BETA .4808	OMEGA

PARTICLE C

CM ANGLE	LAB ANGLE	KINETIC ENERGY	MOMENTUM	BETA	SOLID ANGLE	U	LAB ANGLE	KINETIC ENERGY
0.	0.	330.188	1401.281	.4465	.0028	64.4639E+04	180.000	.332
5.00	.264	330.056	1400.984	.4464	.0028	64.4391E+04	144.844	.464
10.00	.526	329.660	1400.097	.4462	.0028	64.3648E+04	122.628	.860
15.00	.785	329.004	1398.625	.4458	.0027	64.2416E+04	109.236	1.515
20.00	1.039	328.092	1396.579	.4453	.0027	64.0705E+04	100.166	2.428
25.00	1.286	326.931	1393.970	.4446	.0026	63.8527E+04	93.310	3.589
30.00	1.525	325.531	1390.818	.4438	.0025	63.5899E+04	87.703	4.989
35.00	1.754	323.901	1387.142	.4429	.0024	63.2842E+04	82.860	6.619
40.00	1.971	322.055	1382.968	.4418	.0023	62.9377E+04	78.522	8.455
45.00	2.176	320.006	1378.324	.4406	.0021	62.5532E+04	74.535	10.514
50.00	2.366	317.770	1373.241	.4393	.0020	62.1336E+04	70.805	12.750
55.00	2.541	315.364	1367.755	.4379	.0018	61.6821E+04	67.270	15.156
60.00	2.698	312.806	1361.903	.4363	.0016	61.2022E+04	63.890	17.714
65.00	2.836	310.116	1355.727	.4347	.0014	60.6974E+04	60.635	20.404
70.00	2.955	307.314	1349.270	.4331	.0012	60.1716E+04	57.485	23.206
75.00	3.052	304.422	1342.577	.4313	.0010	59.6288E+04	54.425	26.098
80.00	3.128	301.461	1335.698	.4295	.0007	59.0732E+04	51.441	29.059
85.00	3.181	298.454	1328.682	.4277	.0005	58.5089E+04	48.526	32.066
90.00	3.211	295.424	1321.582	.4258	.0002	57.9404E+04	45.671	35.096
95.00	3.216	292.394	1314.450	.4239	-.0001	57.3718E+04	42.870	38.126
100.00	3.196	289.387	1307.342	.4220	-.0004	56.8076E+04	40.119	41.133
105.00	3.152	286.426	1300.310	.4202	-.0006	56.2520E+04	37.413	44.094
110.00	3.082	283.534	1293.411	.4183	-.0009	55.7092E+04	34.747	46.986
115.00	2.988	280.732	1286.699	.4165	-.0012	55.1834E+04	32.118	49.788
120.00	2.870	278.042	1280.227	.4148	-.0015	54.6786E+04	29.523	52.478
125.00	2.728	275.484	1274.048	.4131	-.0018	54.1986E+04	26.959	55.036
130.00	2.562	273.078	1268.213	.4116	-.0021	53.7471E+04	24.422	57.442
135.00	2.375	270.842	1262.771	.4101	-.0023	53.3275E+04	21.910	59.679
140.00	2.168	268.793	1257.766	.4087	-.0026	52.9431E+04	19.421	61.727
145.00	1.941	266.947	1253.243	.4075	-.0028	52.5966E+04	16.951	63.573
150.00	1.698	265.317	1249.239	.4064	-.0030	52.2908E+04	14.498	65.203
155.00	1.439	263.917	1245.789	.4055	-.0032	52.0280E+04	12.060	66.603
160.00	1.167	262.756	1242.924	.4047	-.0033	51.8103E+04	9.633	67.764
165.00	.885	261.844	1240.669	.4041	-.0034	51.6391E+04	7.217	68.676
170.00	.594	261.188	1239.044	.4037	-.0035	51.5160E+04	4.807	69.332
175.00	.299	260.792	1238.063	.4034	-.0036	51.4417E+04	2.402	69.728
180.00	.000	260.660	1237.735	.4033	-.0036	51.4168E+04	.000	69.860

D + P = D + P

MASSES INCIDENT 1875.58100
TARGET 938.25600
C 1875.58100
D 938.25600

INCIDENT MOMENTUM 1391.810 INCIDENT KINETIC ENERGY 460.000

CENTER OF MASS PARAMETERS
TOTAL ENERGY 2963.254 BETA .4251 GAMMA 1.1048 S 87.808742E+05
PARTICLE A TOTAL ENERGY 1926.658 MOMENTUM 440.689
PARTICLE B TOTAL ENERGY 1036.596 MOMENTUM 440.689
PARTICLE C TOTAL ENERGY 1926.658 MOMENTUM 440.689 BETA .2287 OMEGA
PARTICLE D TOTAL ENERGY 1036.596 MOMENTUM 440.689 BETA .4251 OMEGA

PARTICLE C

CM ANGLE	LAB ANGLE	KINETIC ENERGY	MOMENTUM	BETA	SOLID ANGLE	U	LAB ANGLE	KINETIC ENERGY
0.	0.	460.000	1391.810	.5959	.1003	0.	0.	.000
5.00	1.583	459.212	1390.488	.5956	.1003	-14.7803E+02	87.238	.788
10.00	3.164	456.855	1386.526	.5945	.1004	-59.0088E+02	84.479	3.145
15.00	4.741	452.947	1379.942	.5926	.1006	-13.2349E+03	81.724	7.053
20.00	6.313	447.517	1370.759	.5901	.1008	-23.4242E+03	78.976	12.483
25.00	7.877	440.607	1359.015	.5867	.1011	-36.3914E+03	76.237	19.393
30.00	9.431	432.269	1344.756	.5827	.1015	-52.0376E+03	73.509	27.731
35.00	10.972	422.567	1328.036	.5779	.1018	-70.2439E+03	70.794	37.433
40.00	12.499	411.574	1308.921	.5723	.1022	-90.8716E+03	68.094	48.426
45.00	14.007	399.375	1287.486	.5659	.1025	-11.3764E+04	65.410	60.625
50.00	15.493	386.062	1263.813	.5588	.1028	-13.8746E+04	62.743	73.938
55.00	16.953	371.736	1237.994	.5509	.1030	-16.5629E+04	60.096	88.264
60.00	18.384	356.506	1210.128	.5422	.1029	-19.4207E+04	57.468	103.494
65.00	19.778	340.489	1180.324	.5326	.1027	-22.4263E+04	54.860	119.511
70.00	21.131	323.807	1148.696	.5223	.1020	-25.5568E+04	52.275	136.193
75.00	22.436	306.585	1115.368	.5111	.1009	-28.7885E+04	49.710	153.415
80.00	23.683	288.956	1080.470	.4992	.0992	-32.0966E+04	47.168	171.044
85.00	24.863	271.053	1044.142	.4864	.0965	-35.4561E+04	44.648	188.947
90.00	25.965	253.013	1006.533	.4729	.0927	-38.8414E+04	42.149	206.987
95.00	26.976	234.973	967.798	.4586	.0874	-42.2266E+04	39.672	225.027
100.00	27.879	217.070	928.108	.4435	.0801	-45.5861E+04	37.217	242.930
105.00	28.656	199.441	887.643	.4278	.0702	-48.8943E+04	34.781	260.559
110.00	29.284	182.219	846.603	.4114	.0568	-52.1259E+04	32.366	277.781
115.00	29.737	165.536	805.205	.3945	.0389	-55.2565E+04	29.969	294.464
120.00	29.983	149.519	763.693	.3771	.0150	-58.2621E+04	27.591	310.481
125.00	29.984	134.290	722.341	.3594	-.0166	-61.1199E+04	25.229	325.710
130.00	29.695	119.964	681.466	.3415	-.0582	-63.8081E+04	22.883	340.036
135.00	29.065	106.651	641.435	.3236	-.1126	-66.3064E+04	20.552	353.349
140.00	28.035	94.452	602.681	.3059	-.1831	-68.5956E+04	18.234	365.548
145.00	26.539	83.459	565.715	.2888	-.2729	-70.6584E+04	15.928	376.541
150.00	24.510	73.757	531.144	.2725	-.3847	-72.4790E+04	13.633	386.243
155.00	21.884	65.419	499.676	.2574	-.5188	-74.0436E+04	11.346	394.581
160.00	18.618	58.509	472.121	.2441	-.6768	-75.3403E+04	9.068	401.491
165.00	14.704	53.079	449.359	.2330	-.8288	-76.3593E+04	6.795	406.921
70.00	10.197	49.170	432.277	.2246	-.9720	-77.0927E+04	4.528	410.830
75.00	5.226	46.813	421.659	.2193	-1.0740	-77.5350E+04	2.263	413.187
180.00	.000	46.026	418.053	.2176	-1.1112	-77.6828E+04	.000	413.974