PHYS/ENPH 453 - Advanced Physics Laboratory
Energy Loss of Charged Particles

Winter 2018

1 Learning Goals

- Investigate the energy loss and straggling of charged particles through gaseous media.
- Understand the Bethe-Bloch formula for calculating the energy loss of charged particles through materials.

2 Introduction

This experiment investigates how alpha (α) particles slow down as they travel through a variety of gases. Energy loss is dominated by Coulomb interactions between the α's and atomic electrons in the material, which result in the ionization of atoms in the material.

The theory is contained in the *Bethe-Bloch formula* for energy loss. The amount of energy charged particles (electrons, positrons, α particles, heavy nuclei) lose as they travel through a material is proportional to $1/v^2$ of the charged particle. The Bethe-Bloch formula tells you the average amount of energy lost in a material; however, particles with the same energy traveling through the same thickness of material can lose different amounts of energy. This is because a relatively small number of high energy transfer collisions can significantly impact the total energy loss. This spread in energy loss is known as *straggle*.

The derivation of the Bethe-Bloch formula is given in [1]. You should go through this and understand it in detail. There are additional terms added to compensate for relativistic and atomic structure effects. A practical summary of the Bethe-Bloch formula is found in the *Particle Data Group Book (PDG)* in [2] under *"Passage of charged particles through matter"* in the section on *"Experimental Methods and Colliders"*. The first 15 pages cover energy loss and straggling relevant for this investigation. Calculations of stopping power for α particles in various materials can also be obtained from NIST [3].

3 Lab Safety

- The experiment uses a surface ^{241}Am alpha source. To avoid damage and contamination, do not touch the source, nor the Si detector, in the chamber.
- The silicon detector requires approximately 50 V to operate. To avoid voltage breakdown at low pressures, when you pump the chamber to vacuum or let the chamber up to air, turn OFF the bias voltage of the detector.
- You will be using a variety of compressed gas cylinders. The gas in these chambers is highly pressurized, and a 2-stage regulator is used to fill the experimental chamber in a controlled manner. Ask the TA or instructor to show you how to operate the regulator before use.

4 Designing Your Lab

You will be using a surface ^{241}Am alpha source, which produces approximately 5.5 MeV α particles. The source is mounted in a small vacuum chamber across from a silicon surface barrier detector. When an alpha particle travels through the detector it produces ionizations, which relax to form electron-hole pairs [4]. These allow a current pulse to flow which is collected, integrated, and amplified. The output of the preamplifier-amplifier combination is a pulse with a voltage proportional to the integrated charge over the previous few microseconds. This pulse is fed into a multichannel analyzer (MCA), which consists of an analog to digital converter (ADC) that measures the height of each pulse, and a digital memory that counts the number of pulses of each pulse height.

Using the available equipment in Section 5, investigate how alpha particles slow down the presence of different gases.

Theoretical Considerations

T.1 The Bethe-Bloch equation is not dependent on the pressure/density of the gas. How do you relate the experimentally variable parameters to those that are used in the Bethe-Bloch equation?

T.2 How do you decouple *straggling* from intrinsic energy resolution [5], see P.2?

T.3 How will you compare experimental data to the Bethe-Bloch formula (ignoring high-density and relativistic terms) and/or data tables [6]?

T.4 CO_2 is a molecule. How do you handle the difference the stopping power for each atomic species?

T.5 As the velocity of the charged particle decreases with every collision with atoms in the medium, the effect of Coulomb interactions becomes stronger, increasing the stopping power. How does one relate the Bethe-Bloch equation to the range or travel distance?

T.6 What is happening as the charge particle travels through a material? Come up with a intuitive picture of what the Bethe-Bloch equation is describing.

Experimental Considerations

E.1 What is the relevant energy range for this experiment? How should the gain be set to maximize resolution with the limited number of MCA channels?

E.2 What is the resolution of the Si detector?

E.3 What gases (Ar, N_2, CO_2, and He) and pressures should be used to investigate the Bethe-Bloch equation over the largest range?

Predictions

P.1 What happens to the energy of the α particles as a function of gas pressure in the chamber?

P.2 What is the shape of the energy spectrum from the ^{241}Am alpha source? How will it relate to the measured shape after the α particles traverse the gas?

Design

D.1 How do you calibrate the Si detector over the relevant energy range?

D.2 How do you calibrate the pressure transducer?

D.3 What are potential backgrounds and sources of error?

D.4 How do you determine the resolution of the Si detector as a function of energy (see T.2)?

D.5 Create a block diagram of the vacuum/experimental chamber and gas system.

5 Equipment

- 1 Ortec silicon surface barrier detector
- 1 Tektronix TDS 1012 Oscilloscope
- 1 Computer running Genie-2000 MCA software
- 1 Canberra DSA1000 MCA Multichannel Analyzer
- 1 MXP100D Pressure Transducer
- 1 Keithley 169 Multimeter
- 1 Vacuum/Experimental Chamber
- Vacuum/gas hoses and band clamps
- 4 Pressurized gas canisters with 2-stage regulators (Argon, Helium, Carbon Dioxide, Nitrogen)
- 1 Nuclear Instrumentation Module (NIM) Rack
- 1 Canberra CI 807 NIM pulser
- Additional NIM modules if needed

References

[1] John David Jackson. Classical electrodynamics.

[2] Particle Data Group. http://pdg.lbl.gov/2010/reviews/rpp2010-rev-passage-particles-matter.pdf.

[3] Alpha Particle stopping power data. http://physics.nist.gov/physrefdata/star/text/astar.html.

[4] Glenn F Knoll. *Radiation detection and measurement*. John Wiley & Sons, 2010.

[5] Segre. Nuclei and particles.

[6] Lee C Northcliffe and R Fo Schilling. Range and stopping-power tables for heavy ions. *Atomic Data and Nuclear Data Tables*, 7(3):233–463, 1970.

6 Appendix

$^{4}_{2}$He IONS

ENERGY PER MASS UNIT	ELECTRONIC STOPPING POWER IN UNITS OF MEV/(MG/SQ CM)												ENERGY FOR A=4
MEV/AMU	BE	C	AL	TI	NI	GE	ZR	AG	EU	TA	AU	U	MEV
0.0125	0.877	0.726	0.532	0.354	0.287	0.261	0.241	0.223	0.142	0.121	0.112	0.096	0.0500
0.0160	0.993	0.821	0.602	0.400	0.325	0.295	0.273	0.253	0.161	0.137	0.126	0.108	0.0640
0.0200	1.110	0.918	0.673	0.447	0.363	0.330	0.305	0.282	0.180	0.154	0.141	0.121	0.0801
0.0250	1.241	1.026	0.752	0.500	0.406	0.368	0.341	0.316	0.201	0.172	0.158	0.135	0.1001
0.0320	1.403	1.163	0.852	0.566	0.461	0.419	0.387	0.358	0.227	0.195	0.180	0.154	0.1281
0.0400	1.554	1.294	0.945	0.631	0.514	0.469	0.432	0.400	0.254	0.219	0.201	0.173	0.1601
0.0500	1.704	1.428	1.040	0.697	0.571	0.520	0.479	0.444	0.282	0.245	0.226	0.194	0.2001
0.0600	1.819	1.539	1.115	0.751	0.617	0.561	0.518	0.480	0.308	0.267	0.247	0.212	0.2402
0.0700	1.906	1.631	1.173	0.795	0.657	0.596	0.551	0.511	0.328	0.287	0.266	0.229	0.2802
0.0800	1.972	1.709	1.219	0.832	0.689	0.624	0.576	0.536	0.347	0.305	0.282	0.243	0.3202
0.0900	2.020	1.773	1.254	0.863	0.715	0.649	0.598	0.557	0.365	0.319	0.296	0.255	0.3602
0.1000	2.054	1.827	1.280	0.887	0.737	0.668	0.614	0.575	0.379	0.332	0.307	0.265	0.4003
0.1250	2.094	1.932	1.317	0.927	0.774	0.702	0.645	0.604	0.405	0.354	0.331	0.286	0.5003
0.1600	2.077	2.018	1.323	0.948	0.797	0.723	0.663	0.622	0.424	0.372	0.349	0.304	0.6404
0.2000	2.010	2.040	1.299	0.944	0.799	0.723	0.664	0.622	0.431	0.380	0.357	0.312	0.8005
0.2500	1.901	1.999	1.248	0.922	0.784	0.711	0.651	0.610	0.431	0.381	0.357	0.312	1.0007
0.3200	1.745	1.896	1.170	0.881	0.752	0.686	0.626	0.585	0.419	0.372	0.349	0.307	1.2808
0.4000	1.587	1.762	1.086	0.827	0.712	0.651	0.594	0.555	0.404	0.359	0.338	0.296	1.6010
0.5000	1.424	1.601	0.996	0.770	0.667	0.613	0.558	0.520	0.384	0.343	0.322	0.284	2.0013
0.6000	1.268	1.428	0.904	0.708	0.617	0.568	0.515	0.480	0.359	0.321	0.302	0.269	2.4016
0.7000	1.148	1.288	0.832	0.657	0.575	0.530	0.480	0.448	0.338	0.302	0.285	0.253	2.8018
0.8000	1.050	1.171	0.773	0.616	0.541	0.500	0.452	0.422	0.320	0.288	0.271	0.241	3.2021
0.9000	0.972	1.074	0.724	0.581	0.512	0.475	0.429	0.399	0.306	0.275	0.260	0.232	3.6023
1.0000	0.905	0.991	0.682	0.552	0.487	0.457	0.409	0.380	0.293	0.264	0.250	0.223	4.0026
1.2500	0.775	0.830	0.598	0.490	0.436	0.407	0.366	0.340	0.267	0.241	0.228	0.204	5.0033
1.6000	0.649	0.680	0.512	0.428	0.382	0.357	0.322	0.297	0.238	0.216	0.204	0.183	6.4042
2.0000	0.548	0.572	0.442	0.374	0.336	0.316	0.283	0.262	0.212	0.194	0.183	0.165	8.0052
2.5000	0.459	0.481	0.379	0.325	0.294	0.277	0.247	0.230	0.189	0.172	0.163	0.148	10.007
3.2000	0.378	0.399	0.318	0.276	0.252	0.237	0.212	0.196	0.164	0.150	0.142	0.129	12.808
4.0000	0.316	0.336	0.270	0.237	0.217	0.205	0.184	0.170	0.144	0.132	0.125	0.114	16.010
5.0000	0.264	0.283	0.229	0.203	0.187	0.176	0.159	0.147	0.126	0.115	0.110	0.100	20.013
6.0000	0.228	0.246	0.200	0.178	0.164	0.156	0.141	0.130	0.111	0.103	0.098	0.090	24.016
7.0000	0.202	0.218	0.178	0.159	0.147	0.140	0.127	0.117	0.101	0.093	0.089	0.082	28.018
8.0000	0.181	0.196	0.161	0.145	0.134	0.127	0.116	0.107	0.093	0.086	0.082	0.076	32.021
9.0000	0.165	0.179	0.147	0.133	0.123	0.117	0.107	0.099	0.086	0.080	0.076	0.071	36.023
10.0000	0.152	0.165	0.136	0.123	0.114	0.109	0.099	0.092	0.080	0.074	0.072	0.066	40.026
11.0000	0.141	0.153	0.127	0.115	0.107	0.102	0.093	0.086	0.075	0.070	0.068	0.062	44.029
12.0000	0.132	0.143	0.118	0.108	0.100	0.096	0.087	0.082	0.071	0.066	0.064	0.059	48.031

MEV/AMU	H	HE	N	O	NE	AR	KR	XE	RN	MYLAR	$(CH_2)_n$	WATER	MEV
0.0125	1.994	0.851	0.564	0.530	0.471	0.311	0.190	0.135	0.089	0.713	0.907	0.692	0.0500
0.0160	2.214	0.934	0.627	0.590	0.525	0.354	0.220	0.156	0.104	0.802	1.020	0.771	0.0640
0.0200	2.408	0.989	0.684	0.644	0.576	0.400	0.250	0.182	0.121	0.889	1.131	0.840	0.0801
0.0250	2.617	1.038	0.746	0.703	0.636	0.456	0.292	0.213	0.154	0.985	1.254	0.916	0.1001
0.0320	2.904	1.102	0.817	0.777	0.710	0.532	0.346	0.261	0.181	1.107	1.412	1.013	0.1281
0.0400	3.167	1.152	0.882	0.849	0.782	0.611	0.405	0.310	0.220	1.224	1.562	1.106	0.1601
0.0500	3.442	1.211	0.956	0.930	0.865	0.698	0.470	0.366	0.265	1.346	1.716	1.208	0.2001
0.0600	3.723	1.274	1.033	0.999	0.944	0.777	0.528	0.416	0.305	1.450	1.851	1.302	0.2402
0.0700	3.977	1.347	1.103	1.071	1.016	0.847	0.577	0.459	0.339	1.542	1.966	1.394	0.2802
0.0800	4.229	1.420	1.171	1.138	1.084	0.910	0.624	0.497	0.369	1.623	2.068	1.482	0.3202
0.0900	4.451	1.493	1.235	1.204	1.146	0.967	0.665	0.532	0.394	1.695	2.155	1.565	0.3602
0.1000	4.685	1.572	1.303	1.262	1.201	1.018	0.703	0.559	0.415	1.757	2.235	1.642	0.4003
0.1250	5.227	1.745	1.442	1.389	1.327	1.121	0.772	0.615	0.457	1.888	2.403	1.816	0.5003
0.1600	5.863	1.955	1.604	1.546	1.466	1.222	0.838	0.667	0.495	2.021	2.568	2.025	0.6404
0.2000	6.376	2.117	1.734	1.665	1.574	1.279	0.870	0.691	0.510	2.096	2.660	2.188	0.8005
0.2500	6.764	2.239	1.816	1.748	1.632	1.290	0.872	0.684	0.503	2.114	2.679	2.306	1.0007
0.3200	6.947	2.268	1.844	1.760	1.610	1.234	0.823	0.642	0.469	2.061	2.617	2.337	1.2808
0.4000	6.775	2.237	1.776	1.688	1.529	1.141	0.755	0.587	0.428	1.947	2.479	2.254	1.6010
0.5000	6.355	2.112	1.640	1.561	1.396	1.027	0.677	0.529	0.385	1.786	2.280	2.094	2.0013
0.6000	5.742	1.926	1.458	1.385	1.238	0.905	0.600	0.468	0.343	1.593	2.044	1.869	2.4016
0.7000	5.110	1.756	1.292	1.227	1.098	0.802	0.537	0.418	0.309	1.427	1.834	1.659	2.8018
0.8000	4.540	1.593	1.152	1.098	0.982	0.718	0.486	0.379	0.282	1.287	1.652	1.480	3.2021
0.9000	4.056	1.446	1.036	0.987	0.878	0.647	0.442	0.349	0.259	1.170	1.500	1.328	3.6023
1.0000	3.676	1.329	0.949	0.900	0.802	0.594	0.409	0.326	0.242	1.073	1.374	1.209	4.0026
1.2500	2.971	1.113	0.792	0.756	0.672	0.504	0.354	0.286	0.216	0.895	1.137	1.003	5.0033
1.6000	2.316	0.907	0.655	0.626	0.561	0.428	0.307	0.250	0.193	0.730	0.914	0.814	6.4042
2.0000	1.830	0.750	0.556	0.530	0.479	0.372	0.272	0.223	0.175	0.610	0.751	0.674	8.0052
2.5000	1.432	0.616	0.470	0.447	0.413	0.327	0.242	0.202	0.161	0.510	0.617	0.557	10.007
3.2000	1.112	0.494	0.392	0.374	0.347	0.281	0.214	0.178	0.143	0.420	0.501	0.456	12.808
4.0000	0.891	0.403	0.329	0.316	0.297	0.243	0.186	0.157	0.127	0.352	0.415	0.380	16.010
5.0000	0.728	0.331	0.277	0.266	0.251	0.208	0.162	0.137	0.112	0.296	0.347	0.318	20.013
6.0000	0.621	0.282	0.240	0.231	0.219	0.183	0.143	0.121	0.100	0.256	0.299	0.274	24.016
7.0000	0.546	0.248	0.213	0.206	0.194	0.163	0.128	0.110	0.091	0.228	0.265	0.243	28.018
8.0000	0.489	0.221	0.192	0.186	0.175	0.148	0.116	0.100	0.083	0.205	0.238	0.219	32.021
9.0000	0.443	0.201	0.175	0.169	0.160	0.135	0.107	0.092	0.077	0.187	0.217	0.200	36.023
10.0000	0.407	0.186	0.162	0.156	0.148	0.125	0.099	0.085	0.071	0.172	0.199	0.184	40.026
11.0000	0.376	0.172	0.151	0.146	0.138	0.116	0.092	0.079	0.066	0.160	0.185	0.171	44.029
12.0000	0.350	0.161	0.141	0.136	0.129	0.109	0.087	0.075	0.062	0.149	0.172	0.160	48.031