DEAR Technical Note IR-11

Compilation of possible x-ray transitions in electronic, pionic, kaonic and sigmaonic aluminum, titanium and zirconium, and in kaonic nitrogen and kaonic neon.

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2nd February 1999

1) General considerations:

All the measurements to be done in the DEAR experiment will have a target cell made of aluminum. This hopefully prevents from having intense electronic X rays in the region of interest. Anyhow, it does not necessarily mean that there are no background peaks visible. Especially one has to take into account all the induced X rays in aluminum. These are kaonic, pionic and sigmaonic transitions. The kaons are directly coming from DAΦNE, the pions and sigmas are decay products from K^- and K^-N interactions. The actual relevance of these transitions can only be checked experimentally, but the energy spectrum shown in figure 1 (observed in a previous experiment at higher energies [1]) gives a hint of what can be expected.

From figure 1 we can learn, that for kaonic aluminum transitions with $\Delta n=1$ are the most important ones, but transitions with $\Delta n\neq1$ can also be observed. Additionally, pionic and sigmaonic atoms can also be seen. But the intensities of all these lines tend to be much (~ a factor of 10) smaller than the $\Delta n=1$ transitions. This does not necessarily mean that these transitions will not be observed in our target cells.

Due to their kinetic energy, the decay products will only be stopped in the aluminum walls to form other exotic atoms, so they will induce only aluminum X rays and will not produce exotic atoms in the target gas.

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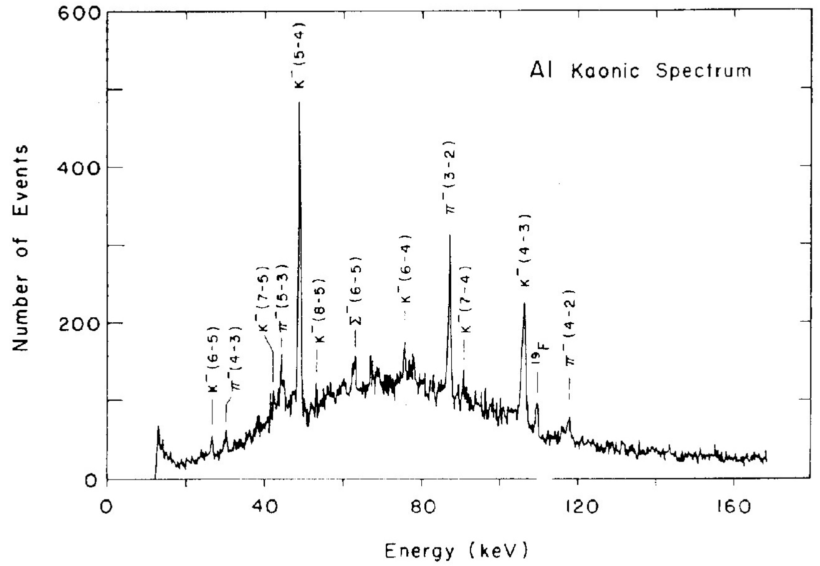

Fig. 3. Al kaonic X-ray spectrum.

Fig.1: Energy spectrum obtained with kaons in aluminum taken from Ref. [1]. Clearly many different transitions can be seen.

2) Induced x-ray transitions in aluminum

In the tables 1, 2 and 3 of this section a compilation of the important transitions in aluminum is given. For all the tables, the listed transition energies were calculated by using a simple Bohr-formula. The energies of all lines within the CCD detection range should be quite accurate, as strong interaction and relativistic effects are small for transitions at high n levels..

Table 1:

Electronic aluminum	
transition	Energy (keV)
2-1 (K_α)	1.486
3-1 (K_β)	1.557

According to Ref.[2] in aluminum the intensity of the electronic K_β line is 1.8 % of the electronic K_α intensity.

Table 2:

Kaonic aluminum	
Δn = 1	
Transition	Energy (keV)
2-1	~1634
3-2	~303.
4-3	~106.
5-4	49.0
6-5	26.6
7-6	16.0
8-7	10.42
9-8	7.144
10-9	5.110
11-10	3.781
12-11	2.876
13-12	2.238
14-13	1.776
15-14	1.433

Δn = 2		Δn = 3	
Transition	Energy (keV)	Transition	Energy (keV)
9-7	17.56	11-8	16.04
10-8	12.25	12-9	11.77
11-9	8.891	13-10	8.895
12-10	6.657	14-11	6.890
13-11	5.114	15-12	5.447
14-12	4.014	16-13	4.381
15-13	3.208	17-14	3.577
16-14	2.605	18-15	2.959
17-15	2.144	19-16	2.475
18-16	1.786	20-17	2.092
19-17	1.503	21-18	1.784
20-18	1.278	22-19	1.534
		23-20	1.328

Table 3:

Pionic aluminum		Sigmaonic aluminum	
$\Delta n = 1$			
Transition	Energy (keV)	Transition	Energy (keV)
2-1	~468.	2-1	~3857.
3-2	~87.	3-2	~714.
4-3	~30.	4-3	~250.
5-4	14.05	5-4	~115.
6-5	7.632	6-5	~63.
7-6	4.602	7-6	37.9
8-7	2.987	8-7	24.6
9-8	2.048	9-8	16.87
10-9	1.465	10-9	12.06
11-10	1.084	11-10	8.926
		12-11	6.789
		13-12	5.284
		14-13	4.192
		15-14	3.382
		16-15	2.768
		17-16	2.294
		18-17	1.922
		19-18	1.627
		20-19	1.389

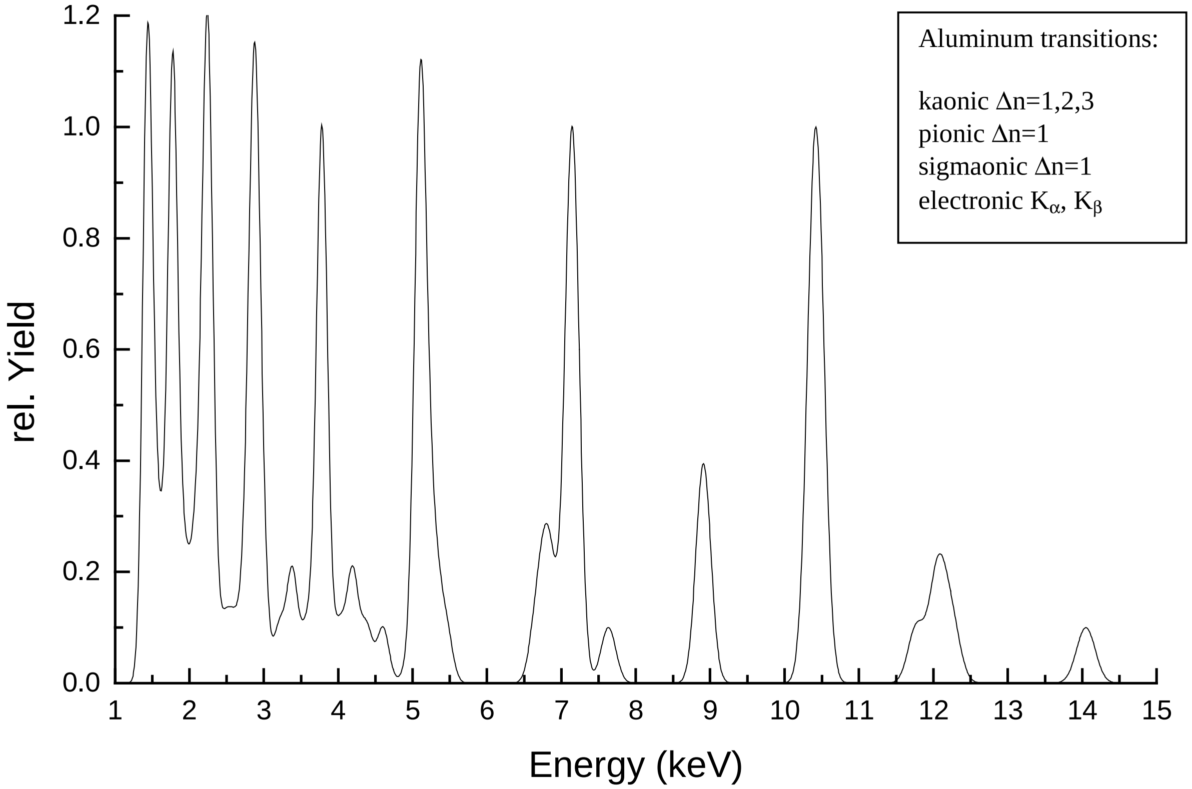

Fig.2: Simulated energy spectrum of all tabulated x-ray transitions induced in aluminum (kaonic, pionic, sigmaonic, electronic lines) which fall within the detection range of the CCDs. Relative intensities are arbitrary, according to the text.

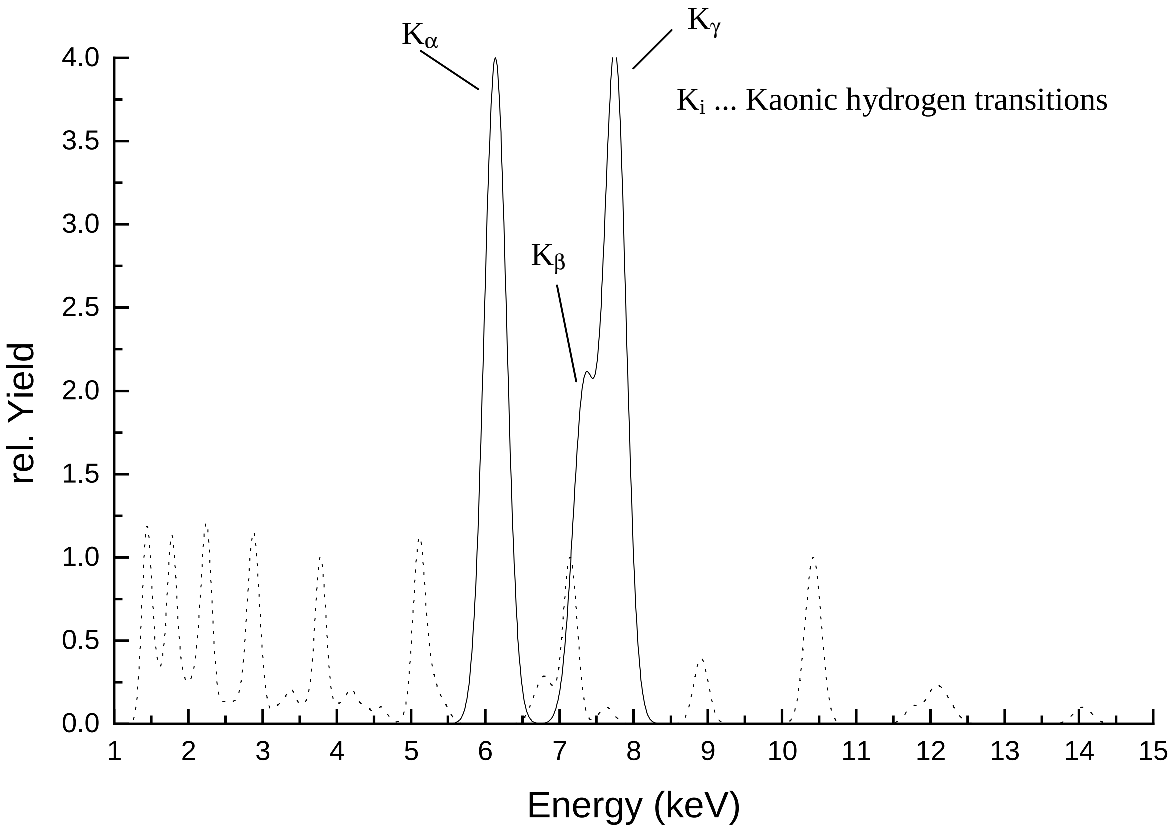

Fig.3: Simulated energy spectrum of all tabulated x-ray transitions induced in aluminum (kaonic, pionic, sigmaonic, electronic lines) which fall within the detection range of the CCDs (same as Fig.2, dotted line). The kaonic hydrogen 2-1 (K_α), 3-1 (K_β) and 4-1 (K_γ) transitions (full lines) are also included. Relative intensities are arbitrary, according to the text.

Figure 2 and 3 show simulated energy spectra. There, all the given aluminum lines which fall within the detection range of the CCDs are displayed. Following the lesson of Fig.1, the intensities for the kaonic Δn=1 transitions were assumed, for simplicity, to be equal, the same intensity was assumed for the electronic K_α line. The pionic, sigmaonic and kaonic Δn=2 and Δn=3 transitions were assumed to be a factor of 10 less. No effects of detector efficiency, cascade yields, stopping distribution etc. have been taken into account.

In figure 3 the yield of the kaonic hydrogen lines was assumed to be 4 times higher than that of the background (just for display reasons). In reality the background is hopefully much lower. Luckily, none of the mentioned aluminum transitions are around 6 keV. So we can see in figure 3, that the kaonic hydrogen K_α-transition is totally unaffected. However, higher lines (K_β, K_γ) could be contaminated. For the measurement of kaonic deuterium, where the line energies are higher, this possible background must be a matter of thorough studies, excluding evidently an empty-target measurement due to the integrated luminosity requested. Finally, it should be clearly stated, that the intensities of the shown aluminum transitions are just guesses and especially their relative intensities in comparison with the kaonic hydrogen lines are not known.

3) Induced x-ray transitions in titanium and zirconium

In tables 4-8 of this section a compilation of the important transitions in titanium and zirconium is given. To have an online energy calibration throughout the measurement, it was decided to cover the inside of the cryo-target cell with titanium and zirconium foils. There, electronic X rays will be induced and will give nice calibration lines. However, one should not forget about the possibility to induce kaonic, pionic and sigmaonic lines in these materials, too. Therefore we list in tables 4-8 the possible transitions in the energy region of CCD detection.

Table 4:

Electronic	**titanium**	**zirconium**
transition	Energy (keV)	Energy (keV)
2-1 ($K_{\alpha1}$,$K_{\alpha2}$)	4.511 (4.505)	15.775 (15.691)
3-1 ($K_{\beta1}$,$K_{\beta2}$)	4.930	17.66 (17.97)

Following Ref.[2], the intensity of the sum of the electronic K_β transitions compared to the sum of the electronic K_α transitions is 13.5 % for titanium and 19.2 % for zirconium.

Table 5:

Kaonic titanium	
Δn = 1	
Transition	Energy (keV)
10-9	14.76
11-10	10.92
12-11	8.306
13-12	6.464
14-13	5.129
15-14	4.138
16-15	3.386
17-16	2.807
18-17	2.352
19-18	1.990
20-19	1.699

Δn = 2		Δn = 3	
Transition	Energy (keV)	Transition	Energy (keV)
13-11	14.77	15-12	15.73
14-12	11.59	16-13	12.65
15-13	9.267	17-14	10.33
16-14	7.524	18-15	8.545
17-15	6.193	19-16	7.149
18-16	5.159	20-17	6.042
19-17	4.342	21-18	5.152
20-18	3.690	22-19	4.430
21-19	3.162	23-20	3.836
22-20	2.730	24-21	3.344
23-21	2.374	25-22	2.933
24-22	2.076	26-23	2.587
25-23	1.827	27-24	2.293
26-24	1.616	28-25	2.042
		29-26	1.826
		30-27	1.640
		31-28	1.478

Table 6:

Kaonic zirconium			
Δn = 1			
Transition	Energy (keV)	Transition	Energy (keV)
15-14	13.75	23-22	3.675
16-15	11.25	24-23	3.225
17-16	9.327	25-24	2.846
18-17	7.816	26-25	2.524
19-18	6.615	27-26	2.249
20-19	5.647	28-27	2.012
21-20	4.860	29-28	1.808
22-21	4.212	30-29	1.630

Δn = 2			
Transition	Energy (keV)	Transition	Energy (keV)
19-17	14.43	30-28	3.438
20-18	12.26	31-29	3.105
21-19	10.51	32-30	2.813
22-20	9.072	33-31	2.558
23-21	7.887	34-32	2.332
24-22	6.900	35-33	2.132
25-23	6.071	36-34	1.954
26-24	5.370	37-35	1.795
27-25	4.773	38-36	1.654
28-26	4.261	39-37	1.526
29-27	3.820		

Δn = 3			
Transition	Energy (keV)	Transition	Energy (keV)
22-19	14.72	34-31	3.670
23-20	12.75	35-32	3.350
24-21	11.11	36-33	3.067
25-22	9.746	37-34	2.814
26-23	8.595	38-35	2.589
27-24	7.619	39-36	2.387
28-25	6.785	40-37	2.205
29-26	6.069	41-38	2.041
30-27	5.450	42-39	1.894
31-28	4.912	43-40	1.760
32-29	4.443	44-41	1.638
33-30	4.032	45-42	1.528

Table 7:

Pionic titanium		**Sigmaonic titanium**	
$\Delta n = 1$			
Transition	Energy (keV)	Transition	Energy (keV)
6-5	21.91	12-11	19.84
7-6	13.21	13-12	15.44
8-7	8.576	14-13	12.25
9-8	5.880	15-14	9.882
10-9	4.206	16-15	8.088
11-10	3.112	17-16	6.703
12-11	2.367	18-17	5.617
13-12	1.842	19-18	4.754
		20-19	4.059
		21-20	3.493
		22-21	3.027
		23-22	2.641
		24-23	2.318
		25-24	2.045
		26-25	1.814
		27-26	1.616

Table 8:

Pionic zirconium		**Sigmaonic zirconium**	
$\Delta n = 1$			
Transition	Energy (keV)	Transition	Energy (keV)
10-9	13.92	19-18	15.91
11-10	10.30	20-19	13.59
12-11	7.836	21-20	11.69
13-12	6.098	22-21	10.13
14-13	4.839	23-22	8.842
15-14	3.904	24-23	7.760
16-15	3.195	25-24	6.847
17-16	2.648	26-25	6.072
18-17	2.219	27-26	5.410
19-18	1.878	28-27	4.841
20-19	1.603	29-28	4.349
		30-29	3.921
		31-30	3.548
		32-31	3.221
		33-32	2.932
		34-33	2.677
		35-34	2.451
		36-35	2.250
		37-36	2.070
		38-37	1.909
		39-38	1.764
		40-39	1.633

4) Induced x-ray transitions in nitrogen - the case of the NTP-target

In the case of the NTP-target, nitrogen will be filled into the target cell. This will be on one hand a kind of quantitative measurement to test our setup and to test the kaon production of the accelerator, on the other hand, it will be the first mesurement of kaonic nitrogen lines, as no publication can yet be found. Information about the kaonic cascade can be deduced. Important transitions in kaonic nitrogen are listed in table 9.

Table 9:

Kaonic nitrogen	
$\Delta n = 1$	
Transition	Energy (keV)
2-1	~466.
3-2	~86.
4-3	30.2
5-4	**13.98**
6-5	**7.596**
7-6	**4.580**
8-7	**2.973**
9-8	**2.038**
10-9	**1.458**
11-10	1.079
12-11	0.820

Some of the kaonic nitrogen lines are overlapping with the kaonic aluminum, as can be seen in figure 4 which shows a simulated energy spectrum. The spectrum was calculated assuming a factor of 4 higher intensities for the kaonic nitrogen lines as for electronic and kaonic ($\Delta n=1$) transitions in aluminum. Kaonic $\Delta n \neq 1$, pionic and sigmaonic transitions in aluminum were added with an assumed 10% intensity with respect to kaonic $\Delta n=1$ lines. No effects of detector efficiency, kaon stopping distribution etc. have been taken into account.

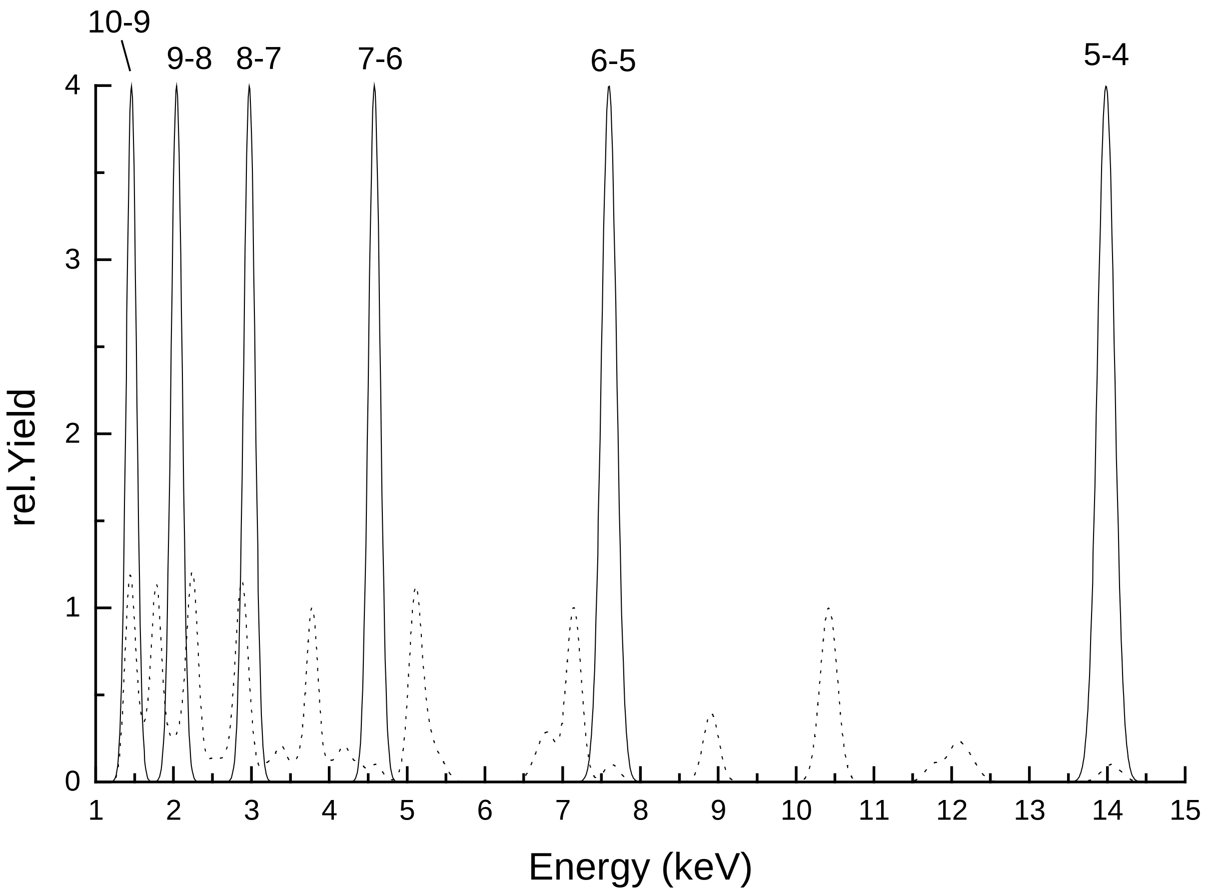

Fig.4: Simulated energy spectrum of kaonic nitrogen (full lines). Kaonic, electronic, pionic and sigmaonic transitions in aluminum are added (dotted lines). Relative intensities are arbitrary, according to the text.

5) Induced x-ray transitions in neon - another possibility for the NTP-target measurements.

A possible extension of the measurement of kaonic nitrogen is kaonic neon: Kaonic neon displays some lines in the detection range; kaonic neon has never been measured before, so it would be a "first measurement". Important transitions in kaonic neon are listed in table 10.

Figure 5 shows a simulated energy spectrum with the neon lines assumed to have intensities a factor of 4 higher than the electronic and kaonic Δn=1 transitions in aluminum. Kaonic Δn≠1, pionic and sigmaonic transitions in aluminum were added with an assumed 10% intensity with respect to kaonic Δn=1 lines. No effects of detector efficiency, kaon stopping distribution etc. have been taken into account.

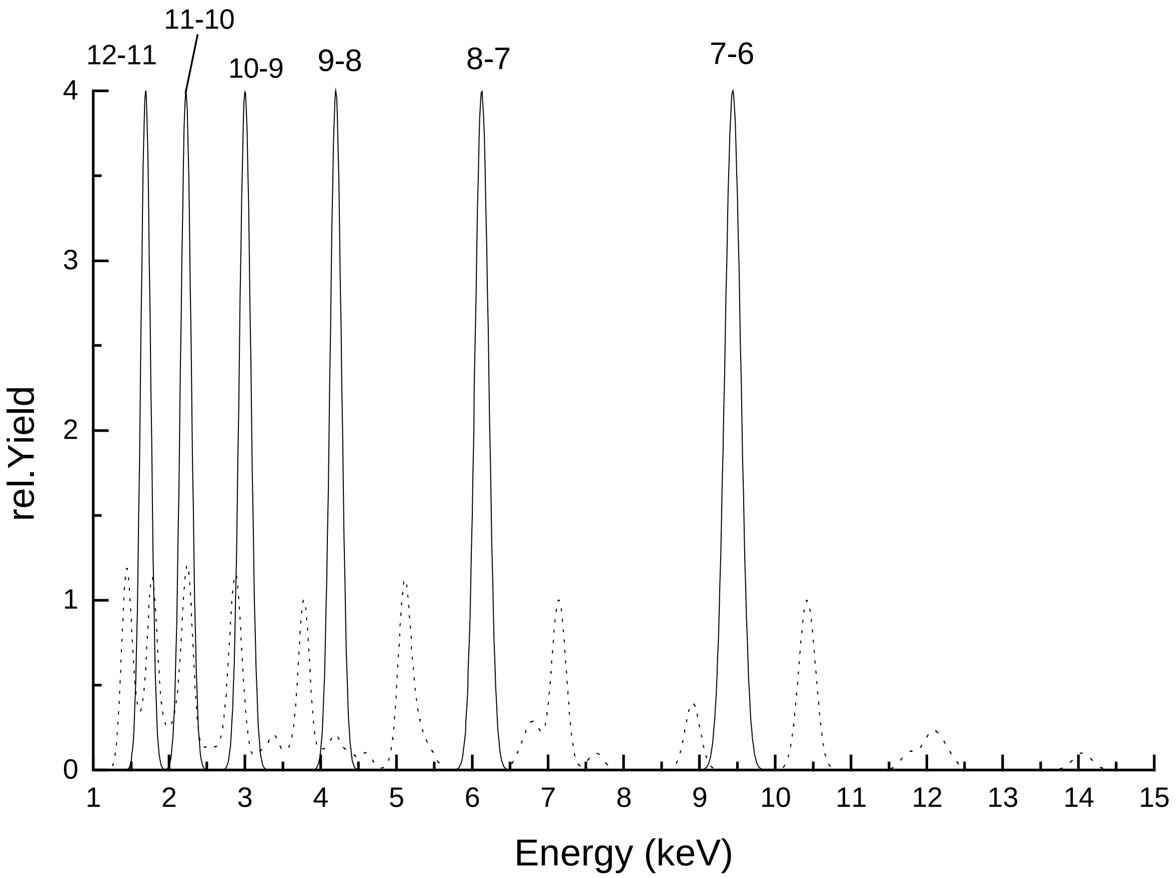

Fig.5: Simulated energy spectrum of kaonic neon (full lines). Kaonic, electronic, pionic and sigmaonic transitions in aluminum are added (dotted lines). Relative intensities are arbitrary, according to the text.

Table 10:

Kaonic neon	
Δn = 1	
Transition	Energy (keV)
2-1	~961.
3-2	~178.
4-3	~62.
5-4	28.8
6-5	15.65
7-6	**9.439**
8-7	**6.126**
9-8	**4.200**
10-9	**3.004**
11-10	**2.223**
12-11	**1.691**
13-12	1.316
14-13	1.044

6) Conclusions

For all our measurements, especially for the cryo-target, it is necessary to know very well the background structure. We have shown the possibility of many different induced x-ray transitions in the detection range of the CCDs. Although Ti and Zr foils, used for the calibration of the energy scale, may shield some lines originating from transitions in aluminum, they may themselves contribute to the background.

References:

[1] P.D. Barnes et al. Nucl. Phys. A231 (1974) 477.

[2] S.I. Salem, T.H. Falconer and R.W. Winchell, Phys. Rev. A6 (1972) 2147.