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线聚焦激光辐照 Al 靶所产生的紫外 X 射线谱线

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本文叙述了采用线聚焦激光辐照 Al 靶所产生的高离化态离子的紫外 X 射线（XUV）谱线。利用 Cowan[1] 的原子能级程序计算了不同离化态的离子谱线的波长和振子强度 gf，辨认出 140 条离子谱线，其中有 82 条新谱线.

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一、引 言

为了研究高离化态离子谱线，目前，国内外主要利用高功率激光器进行打靶. 由于采用高纯度的靶材料，所产生的谱线基本上不含杂质元素谱线，便于对谱线的辨认. 此外，通过调节激光打靶的功率密度，使得所产生的等离子体具有不同的离化态，有利于对不同离化态的离子谱线的研究. 目前，国外通常采用点聚焦激光打靶，由于激光与物质相互作用所产生的等离子体向外膨胀，使所测得的谱线有明显的 Doppler 加宽. 为了减小谱线的 Doppler 加宽，我们采用线聚焦激光打靶，在柱状等离子体的轴向用掠入射光栅谱仪来测量离子谱线，所测得的谱线宽度明显变窄. 由于在柱状等离子体中，有很多光性薄的跃迁谱线沿柱状等离子体轴向得到线性放大，其强度比点聚焦激光打靶时所测得的要强，由此，可以获得新谱线.

二、实验条件与结果

LF-11 装置是由中国科学院上海光学精密机械研究所研制的高功率激光器，它由一台波长为 1.06μm 的钕玻璃激光器经过多级放大，输出功率可达 10^{11}W. 实验布局如图 1 所示，线聚焦由柱透镜组产生，掠入射光栅谱仪瞄准柱状等离子体轴向，距离焦线端点为 20mm. 针孔相机距离焦线另一端为 15mm，用于测量激光焦线的宽度. 掠入射光栅谱仪是我们自己研制，测量时间积分 XUV 谱线，光栅曲率半径为 998mm，刻划线为 1200 条/

mm，闪耀角为 2°15′，入射角为 88°，谱仪测量范围为 20—320 Å，狭缝宽度选取 30 μm. 激光能量为 20J，脉冲宽度为 250ps，线聚焦焦线长为 11mm，宽度为 100 μm（由针孔相机测量），靶面激光平均功率密度为 8.0×10^{12} W/cm^2. Al 靶厚度为 1.0 μm，纯度为 99.99%. 用高灵敏度 Kodak SWR X 射线底片记录单次打靶所产生的谱线，底片用 D19 显、定影液处理. 所测得的谱线如图 2. 另外几次打靶的结果与此相同.

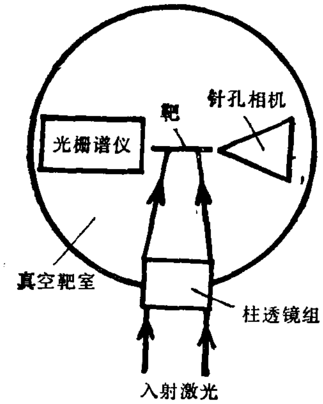

图 1 实验装置示意图

将所测得的谱线用微密度计扫描，得到谱线的相对强度和相对位置，利用光栅方程，可以得到这些谱线的实验波长 λ_{exp}，测量误差为 ±0.04 Å，谱仪对 200 Å 的谱分辨率为 0.06 Å. 利用 Cowan[1] 的原子能级程序计算了不同离化态的谱线波长 λ_{cal} 和振子强度 gf 值，该程序采用 Hatre-Fock 自洽场加相对论修正，可以同时计算多个组态，计算值 λ_{cal} 与 Kelly[2] 编制的波长表相差±1‰. 由于谱线的强度正比于 gf 值和粒子的占据数密度 N_i，在计算中，只取 $gf > 0.001$ 的谱线. 将实验测得的 λ_{exp} 和相对强度 I 与计算值 λ_{cal} 和 gf 及文献[2]的波长表进行对比，辨认出所测得的谱线.

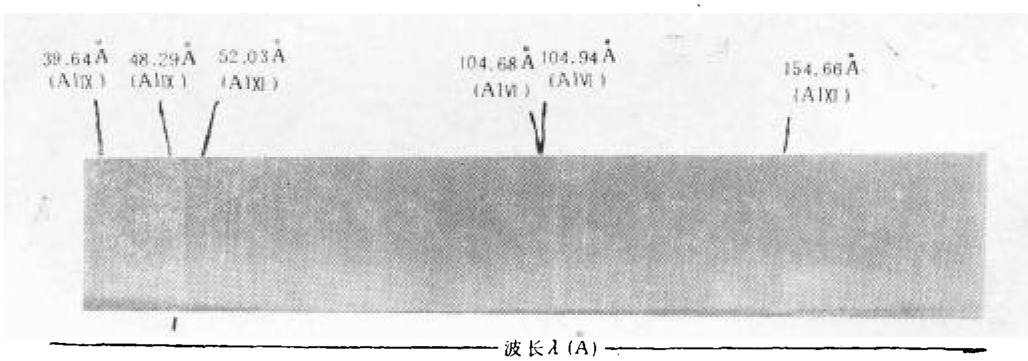

图2 Al 的 XUV 谱线

三、结论与讨论

辨认出的 140 条谱线列于表 1 中，其中有 82 条谱线是文献[2]中所没有的，这些谱线来自 AlV—AlXI 离子的发射. 140 条谱线中，离子丰度最大的为 AlVIII 和 AlIX. 此外，在本次实验中，还观测到类 Li—Al 3d—5f（波长为 105.78 Å）和 3d—4f（波长为 154.66 Å）跃迁的激光线，测得增益系数 G[3]. 由于采用线聚焦激光打靶，谱线宽度比点聚焦激光打靶时变窄 0.03 Å，这是 Doppler 展宽变窄的原因. 所测得的新谱线与线聚焦激光打靶所形成的柱状等离子体密切相关，光性薄的谱线沿柱状等离子体轴向得到放大，其强度比点聚焦时要强得多. 对这些谱线的辨认是在电偶极近似下完成，还有 25 条谱线没能识别，有待于在电四极和磁多极近似中研究.

表 1　Al 离子的波长和分类

离子	跃迁	强度	λ_{exp}(Å)	λ_{cal}(Å)	gf	备注
	$2s^22p^6\ {}^1S_0$—$2s^22p^54d\ {}^3P$		117.22	117.370		[2]
AlIV	$2s^22p^6\ {}^1S_0$—$2s^22p^54s\ {}^3P$	1	124.56	124.550		[2]
	$2s^22p^6\ {}^1S_0$—$2s^22p^53d\ {}^1P_1$	1	129.63	129.730		[2]
	$2s^22p^5\ {}^2P_{3/2}$—$2s^22p^44d\ {}^2F_{5/2}$		94.23	94.208	0.046	
	$2s^22p^5\ {}^2P_{3/2}$—$2s^22p^44d\ {}^4P_{3/2}$		94.39	94.392	0.014	
	$2s^22p^5\ {}^2P_{3/2}$—$2s^22p^43d\ {}^2P_{3/2}$	2	104.00	104.001	1.224	*
	$2s^22p^5\ {}^2P_{1/2}$—$2s^22p^43d\ {}^2D_{3/2}$	2	104.05	104.062	0.798	
	$2s^22p^5\ {}^2P_{1/2}$—$2s^22p^43d\ {}^2P_{3/2}$	2	108.43	108.384	0.465	
	$2s^22p^5\ {}^2P_{1/2}$—$2s^22p^43d\ {}^2D_{3/2}$		108.71	108.691	0.448	*
AlV	$2s2p^6\ {}^2S_{1/2}$—$2s2p^53d\ {}^2D_{3/2}$		113.19	113.054	0.033	
	$2s^22p^5\ {}^2P_{1/2}$—$2s^22p^43s\ {}^2S_{1/2}$	2	120.18	119.995	0.039	*
	$2s^22p^5\ {}^2P_{3/2}$—$2s^22p^43s\ {}^2D_{5/2}$		125.97	125.895	0.315	*
	$2s^22p^5\ {}^2P_{3/2}$—$2s^22p^43s\ {}^2P_{1/2}$		131.29	131.097	0.102	*
	$2s2p^6\ {}^2S_{1/2}$—$2s^22p^44p\ {}^2P_{3/2}$		134.94	134.577	0.123	*
	$2s2p^6\ {}^2S_{1/2}$—$2s2p^53s\ {}^2P_{3/2}$		136.87	136.668		[2]
	$2s^22p^4\ {}^3P_2$—$2s^22p^33d\ {}^1D_2$		85.18	85.199	0.012	
	$2s^22p^4\ {}^3P_1$—$2s^22p^33d\ {}^3D_2$		85.79	85.766	0.820	
	$2s^22p^4\ {}^3P_1$—$2s^22p^33d\ {}^3P_1$		86.22	86.261	0.098	
	$2s^22p^4\ {}^3P_0$—$2s^22p^33d\ {}^3P_1$		86.34	86.350	0.094	
	$2s2p^5\ {}^1P_1$—$2s2p^44s\ {}^1D_2$		86.93	87.029	0.026	
	$2s^22p^4\ {}^3P_1$—$2s^22p^33d\ {}^3D_2$		88.19	88.197	0.889	
	$2s^22p^4\ {}^1D_2$—$2s^22p^33d\ {}^1D_2$	2.5	88.68	88.581	1.584	
	$2P^6\ {}^1S_0$—$2p^53d\ {}^1P_1$	1	91.63	91.909	2.066	*
AlVI	$2s2p^5\ {}^3p_2$—$2s2p^43d\ {}^3D_3$		96.33	96.203	2.516	*
	$2s2p^5\ {}^3P_0$—$2s^22p^34p\ {}^3D_1$		102.94	102.379	0.028	
	$2s^22p^4\ {}^3P_0$—$2s^22p^33s\ {}^3D_1$	5	104.68	104.466		[2]
	$2s^22p^4\ {}^1D_2$—$2s^22p^33s\ {}^3P_2$	6	104.95	104.960		[2]
	$2s^22p^4\ {}^1D_2$—$2s^22p^33s\ {}^1D_2$		107.55	107.620		[2]
	$2s2p^5\ {}^3P_2$—$2s2p^43s\ {}^3P_1$		113.72	113.882	0.148	
	$2s^22p^33d\ {}^1G_4$—$2s2p^44d\ {}^3F_3$	3	155.81	155.712	0.009	*
	$2s^22p^34d\ {}^3D_3$—$2s2p^44d\ {}^3P_2$		245.97	245.910	0.403	*
	$2s2p^43d\ {}^3G_4$—$2p^53d\ {}^3F_3$		264.87	264.800	1.041	*
	$2s2p^4\ {}^4P_{5/2}$—$2s2p^35d\ {}^4D_{7/2}$	2	56.71	56.781	0.166	*
	$2s^22p^3\ {}^2D_{5/2}$—$2s^22p^25d\ {}^2F_{7/2}$	3	58.38	58.358	0.276	
	$2s^22p^3\ {}^2D_{5/2}$—$2s^22p^25d\ {}^2F_{7/2}$	1	59.87	59.853	0.410	
	$2s^22p^3\ {}^2D_{5/2}$—$2s^22p^24d\ {}^2D_{5/2}$		64.48	64.454	0.175	
	$2s^22p^3\ {}^2D_{5/2}$—$2s^22p^24s\ {}^2D_{5/2}$	1	65.68	65.742	0.329	
	$2s^22p^3\ {}^2P_{3/2}$—$2s^22p^24d\ {}^2D_{5/2}$	2	65.79	65.813	0.425	*
	$2s2p^4\ {}^4P_{3/2}$—$2s2p^34d\ {}^4D_{5/2}$	2.5	68.95	68.987	0.418	*
	$2s2p^4\ {}^4P_{3/2}$—$2s2p^33d\ {}^4D_{5/2}$		69.31	69.367	0.101	*
	$2s2p^4\ {}^2D_{5/2}$—$2s2p^33d\ {}^2D_{5/2}$		73.08	73.008	0.193	*
AlVII	$2s2p^4\ {}^2D_{5/2}$—$2s2p^33d\ {}^2F_{7/2}$		74.68	74.733	1.861	*
	$2s2p^4\ {}^2D_{5/2}$—$2s2p^33d\ {}^2F_{5/2}$			74.723	1.316	
	$2s2p^4\ {}^4P_{5/2}$—$2s2p^33d\ {}^4S_{3/2}$		75.36	75.386	0.906	
	$2s^22p^3\ {}^2P_{3/2}$—$2s^22p^23d\ {}^2D_{5/2}$		75.63	75.645	1.208	

续表 1

离子	跃 迁	强度	λ_{exp}(Å)	λ_{cal}(Å)	gf	备注
AlVII	$2s2p^4\ ^4P_{5/2}$—$2s2p^33d\ ^4P_{5/2}$	1.5	76.03	76.090	2.063	*
	$2s^22p^3\ ^2D_{5/2}$—$2s^22p^23d\ ^2F_{7/2}$		76.52	76.318	4.607	
	$2s^22p^3\ ^2D_{5/2}$—$2s^22p^23d\ ^2F_{7/2}$		79.19	79.120	0.839	
	$2s^22p^3\ ^4S_{3/2}$—$2s^22p^23s\ ^4P_{5/2}$	2.5	86.93	86.928	0.275	
	$2s2p^4\ ^2D_{5/2}$—$2s2p^33s\ ^2P_{3/2}$	1.5	91.32	91.327	0.203	
	$2s^22p^23s\ ^2D_{5/2}$—$2s^22p^25p\ ^2D_{5/2}$		177.38	177.454	0.088	*
	$2s^22p^25g\ ^2I_{11/2}$—$2s2p^35g\ ^2H_{9/2}$		242.72	242.735	1.717	*
	$2p^43p\ ^4P_{3/2}$—$2p^44d\ ^4P_{1/2}$		261.50	261.502	0.088	*
AlVIII	$2s^22p^2\ ^3P_2$—$2s^22p5d\ ^3P_2$		49.76	49.713	0.119	
	$2s2p^3\ ^5S_2$—$2s2p^24d\ ^5P_1$	2.5	53.70	53.683	0.333	
	$2s2p^3\ ^3P_2$—$2s2p^23d\ ^3D_3$	2.5	66.20	66.269	0.065	
	$2s^22p^2\ ^3P_2$—$2s^22p3d\ ^3P_2$	2	67.07	67.198	1.587	
	$2s2p^3\ ^3D_3$—$2s2p^23d\ ^3F_4$	1	67.80	67.704	4.148	
	$2s2p^3\ ^1P_1$—$2s2p^23d\ ^1D_2$	1	69.61	69.698	2.133	
	$2s2p^3\ ^1P_1$—$2s2p^23d\ ^1P_1$		71.93	72.101	0.966	
	$2s2p^3\ ^3D_2$—$2s2p^23d\ ^3F_3$		72.52	72.583	1.398	
	$2s2p^3\ ^1D_2$—$2s2p^23d\ ^1D_2$		73.40	73.227	1.478	
	$2s^22p^2\ ^3P_2$—$2s^22p3s\ ^3P_2$		75.74	75.723	0.267	
	$2s2p^3\ ^3P_2$—$2s2p^23s\ ^3D_3$	2	78.37	78.351	0.243	
	$2p^4\ ^3P_0$—$2p^33s\ ^3D_1$	1.5	80.14	79.980	0.089	
	$2s2p^3\ ^3D_2$—$2s2p^23s\ ^3P_1$	3	80.71	80.774	0.129	
	$2s2p^3\ ^1D_2$—$2s2p^23s\ ^1D_2$		82.54	82.845	0.214	
	$2p^4\ ^1S_0$—$2p^33s\ ^1P_1$		83.40	83.671	0.169	
	$2s2p^23s\ ^1P_1$—$2s2p^25p\ ^1P_1$		149.95	149.956	0.058	
	$2s^22p3s\ ^1P_1$—$2s^22p5p\ ^1P_1$		151.48	151.528	0.026	*
	$2p^33s\ ^3D_3$—$2p^35p\ ^3F_4$	3	153.19	153.187	0.229	*
	$2s2p^23s\ ^3P_2$—$2s2p^25p\ ^3P_1$	3	156.87	156.894	0.050	*
	$2s^22p3p\ ^1P_1$—$2s^22p5d\ ^1D_2$		158.19	158.329	0.055	*
	$2s2p^23p\ ^5S_2$—$2s2p^25d\ ^5P_2$	3	158.68	158.885	0.143	*
	$2s^22p3p^1p$—$2s^22p5d^3F_2$		159.68	159.795	0.113	*
	$2s^22p3p^3D_2$—$2s^22p5d^1D_2$		160.35	160.393	0.041	*
	$2s2p^23p^3D_2$—$2s2p^25d^3F_3$		162.09	162.094	0.367	*
	$2s2p^23p^3F_2$—$2s2p^25d^1F_3$		162.85	162.842	0.127	*
	$2p^33p\ ^3D_2$—$2p^35d\ ^3F_3$		164.46	164.482	0.242	*
	$2s2p^23p^3P_2$—$2s2p5d^3P_2$	2	164.78	164.742	0.157	*
	$2s2p^23p^1F_3$—$2s2p^25d^1G_4$		165.87	165.832	0.584	*
	$2p^33p^3F_2$—$2p^35d^3G_3$		166.47	166.493	0.397	*
	$2s2p^23p^3D_3$—$2s2p^25d^3D_3$		166.81	166.844	0.251	*
	$2p^33p^3P_2$—$2p^35d^3D_3$	3	168.51	168.595	0.425	*
	$2p^33p\ ^3F_3$—$2p^35s^3D_2$		174.26	174.186	0.072	*
	$2s2p^23d\ ^5F_5$—$2s2p5f^5G_6$		180.71	180.693	1.415	*
	$2p^33d\ ^5D_4$—$2p^35f^5F_5$		182.12	182.160	1.089	*
	$2s2p^23d^3G_5$—$2s2p^25f^3H_6$		183.63	183.601	1.375	*
	$3p^33d^1G_4$—$3p^35f^1H_5$		185.14	185.208	0.845	*
	$2s2p^23d^3D_3$—$2s2p^25f^3F_4$		187.28	187.267	0.618	*
	$\{2p^33d^3D_1$—$2p^35f^3F_2$		189.62	189.646	0.186	*
	$2s2p^23d^3P_0$—$2s2p^25f\ ^3D_1$			189.645	0.167	

续表 1

离子	跃　迁	强度	λ_{exp}(Å)	λ_{cal}(Å)	gf	备注
AlIII	$2s2p^23d\ ^3F_4—2s2p^25f\ ^3G_5$		194.69	194.671	2.508	*
	$2s2p^23p\ ^1D_2—2s2p^24d\ ^1D_2$		218.60	218.602	0.262	*
	$2s^22p3p\ ^3D_3—2s^22p4d\ ^3F_4$		221.37	221.380	1.953	*
	$2s2p^23p\ ^3F_3—2s2p^24d\ ^3G_4$		225.10	225.375	1.367	*
	$2p^33d\ ^3F_2—2p^34f\ ^3G_3$		257.52	257.510	1.842	*
	$2s2p^23d\ ^3G_4—2s2p^24f\ ^3H_5$		259.19	259.230	5.428	*
	$2p^33d\ ^3F_4—2p^34f\ ^3G_5$		260.24	260.231	1.669	*
	$2s2p^24d\ ^3D_2—2s2p^25f\ ^3F_3$		264.02	263.962	1.610	*
AlIX	$2s2p^2\ ^2S_{1/2}—2p^25p\ ^2P_{3/2}$	3	39.64	39.673	0.032	
	$2s2p^2\ ^2D_{5/2}—2p^25p\ ^2P_{3/2}$	1	40.06	40.135	0.030	*
	$2s^22p\ ^2P_{1/2}—2s2p5p\ ^2D_{3/2}$		40.71	40.789	0.045	*
	$2s2p^2\ ^2P_{3/2}—2p^25p\ ^2D_{5/2}$		42.72	42.751	0.098	*
	$2s2p^2\ ^2D_{5/2}—2p^24p\ ^2P_{3/2}$	1	43.82	43.889	0.074	*
	$2s2p^2\ ^2P_{3/2}—2s2p5d\ ^2D_{5/2}$	1	44.45	44.454	0.177	*
	$2s2p^2\ ^2D_{3/2}—2s2p5d\ ^2F_{5/2}$		45.13	45.379	0.408	*
	$2s2p^2\ ^2P_{3/2}—2p^24p\ ^2P_{3/2}$		46.95	46.912	0.105	
	$2s2p^2\ ^4P_{3/2}—2s2p4d\ ^4F_{5/2}$	2	47.55	47.569	0.021	*
	$2p^3\ ^2P_{1/2}—2p^24d\ ^2D_{3/2}$	5	48.30	48.304	0.151	
	$2p^3\ ^2D_{5/2}—2p^24s\ ^2D_{5/2}$	1	50.59	50.500	0.069	*
	$2p^3\ ^2P_{3/2}—2p^24d\ ^2D_{5/2}$	1	51.02	51.002	0.199	
	$2s^22p\ ^2P_{3/2}—2s2p3p\ ^2D_{5/2}$		53.07	53.081	0.078	*
	$2s2p^2\ ^2S_{1/2}—2p^23p\ ^2P_{3/2}$	3	54.72	54.884	0.230	*
	$2s2p^2\ ^2D_{3/2}—2p^23p\ ^2P_{1/2}$		54.98	54.965	0.092	*
	$2s^22p\ ^2P_{3/2}—2s2p3p\ ^2S_{1/2}$	5	56.31	56.204	0.211	*
	$2s^22p\ ^2P_{3/2}—2s2p3p\ ^4D_{3/2}$	2	58.27	58.247	0.158	
	$2s2p^2\ ^2D_{5/2}—2s2p3d\ ^2D_{5/2}$	1.5	59.06	59.106	0.242	*
	{$2s2p^2\ ^2D_{5/2}—2s2p3d\ ^2F_{7/2}$	3	59.58	59.529	2.295	
	$2s2p^2\ ^2D_{3/2}—2s2p3d\ ^2F_{5/2}$			59.522	1.686	
	$2s2p^2\ ^4P_{1/2}—2s2p3d\ ^4P_{3/2}$	2	60.09	60.101	0.274	*
	$2p^3\ ^2P_{1/2}—2p^23d\ ^2D_{3/2}$	3	61.73	61.781	0.866	*
	$2p^3\ ^4S_{3/2}—2p^23d\ ^4P_{3/2}$	2.5	62.33	62.316	2.276	
	$2p^3\ ^4S_{3/2}—2p^23d\ ^4P_{5/2}$	2.5	62.39	62.366	3.386	
	$2p^3\ ^2D_{5/2}—2p^23d\ ^2D_{5/2}$		62.97	62.952	1.224	
	$2p^3\ ^4S_{3/2}—2p^23d\ ^4D_{5/2}$		63.10	63.070	0.034	
	$2p^23p\ ^4P_{5/2}—2p^24d\ ^4D_{7/2}$		195.05	195.042	1.442	*
	$2s2p3d\ ^4D_{7/2}—2s2p4f\ ^4D_{7/2}$		213.50	213.640	0.995	*
	$2p^23d\ ^2F_{5/2}—2p^24f\ ^2G_{7/2}$		217.14	217.221	2.433	*
	$2p^23d\ ^2F_{7/2}—2p^24f\ ^2G_{9/2}$		217.83	217.610	2.783	*
	$2s2p3d\ ^2F_{5/2}—2s2p4f\ ^2G_{7/2}$		209.74	209.438	3.876	*
AlX	{$2s3s\ ^3S_1—2s6p\ ^3P_1$		95.57	95.603	8.758	*
	$2s3s\ ^3S_1—2s6p\ ^3P_2$			95.590	14.687	
	$2s3d\ ^1D_2—2s7p\ ^1P_1$		100.89	100.625	263.041	
	$2s3p\ ^3P_1—2s6d\ ^3D_2$		101.81	101.977	0.117	*
	$2s3p\ ^3P_2—2s6d\ ^3D_3$		102.27	102.09	0.219	*
	$2s3s\ ^3S_1—2s5p\ ^3P_2$		110.42	110.341	1.444	*
	$2s3s\ ^1S_0—2s5p\ ^1P_1$	2	114.49	114.555	0.721	*

续表 1

离子	跃 迁	强度	λ_{exp}(Å)	λ_{cal}(Å)	gf	备注
AlX	2s3p $^3P_0$—2s5d $^3D_1$		118.37	118.431	0.129	*
	2s3p $^3P_0$—2s5s$^3s_1$		121.41	121.465	0.011	*
AlXI	2p $^2P_{1/2}$—3d $^2D_{3/2}$	5	52.03	52.219	1.300	
	{3d $^2D_{5/2}$—5f $^2F_{1/2}$	4	105.78	105.616	0.905	*
	{3d $^2D_{3/2}$—5f $^2F_{5/2}$			105.562	0.634	
	3P $^2P_{3/2}$ — 4*d* $^2D_{5/2}$		150.52	150.592	1.866	*
	3d $^2D_{5/2}$—4f $^2F_{7/2}$	3	154.66	154.326	5.694	
	4f $^2F_{5/2}$—7g $^2G_{7/2}$		178.78	178.809	0.356	*

注: λ_{exp} 为实验波长,$\Delta\lambda = \pm 0.04$ Å,强度为微密度计的相对值;λ_{cal} 和 gf 值为用 Cowan[1] 程序计算的结果; "{"符号表示混和谱线;"*"代表新谱线;"[2]"表示文献[2]的波长值.

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ALUMINIUM XUV SPECTRA EXCITED IN A LINE FOCUS LASER ——PRODUCED PLASMA

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Abstract

Aluminium targets were irradiated by line focus laser. We observed spectra of high ionization states in the range of VUV. By means of Cowan program for atomic energy level, we caleulated the wavelength and gf value of different ionization state and identified 140 spectra lines.82 new spectra lines were found.

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