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Ca^{17+} 和 Mn^{22+} 的辐射跃迁几率

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提要：上海光机所徐至展等的研究[1]预言，采用类锂复合机制，有可能在他们现有的激光驱动装置上将软 X 射线激光推进到“水窗”(4.376～2.332 nm) 波段。本文的计算表明，Ca^{17+} 和 Mn^{22+} 的 $5f$-$3d$ 和 $5d$-$3p$ 跃迁波长处于水窗两端。进而，详尽地计算了这两个元素类锂离子的精细能级 ($n\leqslant12$, $l\leqslant5$) 及它们间的辐射跃迁几率。

关键词：类锂离子，水窗 X 射线激光，精细能级，辐射跃迁几率

Radiative transition probabilities for Ca^{17+} and Mn^{22+}

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Abstract: The investigation by Zhizhan Xu *et al.* of SIOM predicted[1] that it is possible that the lasing in the water window (4.376～2.332 nm) will be realized with the Li-like recombination scheme using their high power laser facility.

Our calculations show that the wavelengths of the transitions $5f$-$3d$ and $5d$-$3p$ in Ca^{17+} and Mn^{22+} lie at both ends of the water window. The fine levels ($n\leqslant12$, $l\leqslant5$) for these two Li-like ions and the radiative transition probabilities between them are calculated.

Key words: water window lasers of Li-like ions, fine levels, radiative transition probabilities

以简单的类锂复合方案实现“水窗”(4.376～2.332 nm) 激光的前景[1]令人鼓舞。本文首次详尽地计算了其 $5f$-$3d$ 和 $5d$-$3p$ 跃迁波长居于水窗两端的 Ca^{17+} 和 Mn^{22+} 的精细能级($n\leqslant12$, $l\leqslant5$)和它们间的辐射跃迁几率。人们可以由这些数据以及它们表现出的确定规律获得从理论上求解动力学方程组所需的全部辐射过程的信息。

一、计算方法

本文对于辐射过程的计算，是运行 MCDF 程序包[2]，连同其横向 Breit 修正和量子电动力学修正程序[3]，以及我们自编的计算相对论辐射跃迁几率的后续程序[4]完成的。对于每对能级，均分别在 Coulomb 规范和长度规范下求得两个跃迁几率值，它们的相对偏差非常灵敏地反映了所得波函数的准确度。对于本文所涉及的大部分跃迁，这种偏差均在 1% 之内；对于

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Table 1 Fine levels(eV) of Ca^{17+} and Mn^{22+}. The upper data are for Ca^{17+} and the lower ones for Ma^{22+} in every level

Level	Energy	Level	Energy	Level	Energy	Level	Energy
$2s$	0 0	$6p_{3/2}$	1034.248 1678.535	$8f_{5/2}$	1088.386 1766.876	$10g_{9/2}$	1113.209 1807.431
$2p_{1/2}$	35.961 46.449	$6d_{3/2}$	1034.689 1679.111	$8f_{7/2}$	1088.399 1766.909	$10h_{9/2}$	1113.209 1807.431
$2p_{3/2}$	41.014 59.886	$6d_{5/2}$	1034.748 1679.268	$8g_{7/2}$	1088.399 1766.910	$10h_{11/2}$	1113.212 1807.438
$3s$	651.475 1055.928	$6f_{5/2}$	1034.776 1679.306	$8g_{9/2}$	1088.407 1766.929	$11s$	1120.545 1819.451
$3p_{1/2}$	661.445 1068.830	$6f_{7/2}$	1034.806 1679.385	$8h_{9/2}$	1088.407 1766.929	$11p_{1/2}$	1120.747 1819.712
$3p_{3/2}$	662.938 1072.805	$6g_{7/2}$	1034.806 1679.386	$8h_{11/2}$	1088.412 1766.943	$11p_{3/2}$	1120.777 1819.792
$3d_{3/2}$	666.649 1077.641	$6g_{9/2}$	1034.824 1679.432	$9s$	1102.287 1789.071	$11d_{3/2}$	1120.839 1819.874
$3d_{5/2}$	667.118 1078.896	$6h_{9/2}$	1034.824 1679.433	$9p_{1/2}$	1102.648 1790.138	$11d_{5/2}$	1120.848 1819.899
$4s$	875.058 1419.493	$6h_{11/2}$	1034.836 1679.464	$9p_{3/2}$	1102.703 1790.284	$11f_{5/2}$	1120.854 1819.907
$4p_{1/2}$	879.163 1424.808	$7s$	1066.082 1730.636	$9d_{3/2}$	1102.825 1790.444	$11f_{7/2}$	1120.859 1819.920
$4p_{3/2}$	879.792 1426.482	$7p_{1/2}$	1066.841 1731.618	$9d_{5/2}$	1102.843 1790.491	$11g_{7/2}$	1120.859 1819.920
$4d_{3/2}$	881.335 1428.402	$7p_{3/2}$	1066.958 1731.930	$9f_{5/2}$	1102.852 1790.504	$11g_{9/2}$	1120.862 1819.928
$4d_{5/2}$	881.533 1429.022	$7d_{3/2}$	1067.231 1732.286	$9f_{7/2}$	1102.861 1790.527	$11h_{9/2}$	1120.862 1819.928
$4f_{5/2}$	881.613 1429.129	$7d_{5/2}$	1067.268 1732.385	$9g_{7/2}$	1102.861 1790.528	$11h_{11/2}$	1120.864 1819.933
$4f_{7/2}$	881.712 1429.394	$7f_{5/2}$	1067.287 1732.410	$9g_{9/2}$	1102.866 1790.542	$12s$	1126.438 1829.065
$5s$	977.531 1586.337	$7f_{7/2}$	1067.305 1732.460	$9h_{9/2}$	1102.866 1790.542	$12p_{1/2}$	1126.596 1829.268
$5p_{1/2}$	979.608 1589.027	$7g_{7/2}$	1067.305 1732.461	$9h_{11/2}$	1102.870 1790.551	$12p_{3/2}$	1126.619 1829.330
$5p_{3/2}$	979.929 1589.883	$7g_{9/2}$	1067.317 1732.490	$10s$	1112.787 1806.797	$12d_{3/2}$	1126.664 1829.390
$5d_{3/2}$	980.713 1590.904	$7h_{9/2}$	1067.317 1732.490	$10p_{1/2}$	1113.053 1807.140	$12d_{5/2}$	1126.671 1829.410
$5d_{5/2}$	980.815 1591.175	$7h_{11/2}$	1067.324 1732.510	$10p_{3/2}$	1113.093 1807.246	$12f_{5/2}$	1126.676 1829.416
$5f_{5/2}$	980.860 1591.236	$8s$	1087.581 1765.689	$10d_{3/2}$	1113.179 1807.360	$12f_{7/2}$	1126.680 1829.426
$5f_{7/2}$	980.911 1591.371	$8p_{1/2}$	1088.092 1766.349	$10d_{5/2}$	1113.192 1807.394	$12g_{7/2}$	1126.680 1829.426
$5g_{7/2}$	980.911 1591.373	$8p_{3/2}$	1088.170 1766.558	$10f_{5/2}$	1113.199 1807.404	$12g_{9/2}$	1126.682 1829.432
$5g_{9/2}$	980.942 1591.454	$8d_{3/2}$	1088.349 1766.792	$10f_{7/2}$	1113.205 1807.421	$12h_{9/2}$	1126.682 1829.432
$6s$	1032.858 1676.482	$8d_{5/2}$	1088.374 1766.858	$10g_{7/2}$	1113.205 1807.421	$12h_{11/2}$	1126.684 1829.436
$6p_{1/2}$	1034.063 1678.041						

Table 2 Transition probabilities $A(s^{-1})$ between fine levels in Ca^{17+} and Mn^{22+}. The upper date are for Ca^{17+} and the lower ones for Mn^{22+} in every transition. Here X(Y) means $X\times10^{Y}$.

Transition	Probability A	Transition	Probability A	Transition	Probability A	Transition	Probability A
$2s$–$3p_{1/2}$	2.321(12) 6.285(12)	$2p_{1/2}$–$9s$	9.950(9) 2.527(10)	$2p_{3/2}$–$5d_{3/2}$	1.702(11) 4.493(11)	$3s$–$12p_{1/2}$	1.241(10) 3.339(10)
$4p_{1/2}$	1.021(12) 2.747(12)	$10s$	7.222(9) 1.834(10)	$6d_{3/2}$	9.290(10) 2.451(11)	$3s$–$4p_{3/2}$	2.972(11) 7.993(11)
$5p_{1/2}$	5.257(11) 1.411(12)	$11s$	5.408(9) 1.375(10)	$7d_{3/2}$	5.653(10) 1.491(11)	$5p_{3/2}$	1.639(11) 4.395(11)
$6p_{1/2}$	3.045(11) 8.160(11)	$12s$	4.155(9) 1.056(10)	$8d_{3/2}$	3.706(10) 9.772(10)	$6p_{3/2}$	9.664(10) 2.590(11)
$7p_{1/2}$	1.917(11) 5.133(11)	$2p_{1/2}$–$3d_{3/2}$	5.887(12) 1.567(13)	$9d_{3/2}$	2.465(10) 6.761(10)	$7p_{3/2}$	6.130(10) 1.642(11)
$8p_{1/2}$	1.283(11) 3.434(11)	$4d_{3/2}$	1.892(12) 5.048(12)	$10d_{3/2}$	1.850(10) 4.877(10)	$8p_{3/2}$	4.121(10) 1.103(11)
$9p_{1/2}$	9.007(10) 2.410(11)	$5d_{3/2}$	8.669(11) 2.315(12)	$11d_{3/2}$	1.380(10) 3.636(10)	$9p_{3/2}$	2.900(10) 7.760(10)
$10p_{1/2}$	6.563(10) 1.756(11)	$6d_{3/2}$	4.739(11) 1.266(12)	$12d_{3/2}$	1.057(10) 2.785(10)	$10p_{3/2}$	2.116(10) 5.663(10)
$11p_{1/2}$	4.930(10) 1.319(11)	$7d_{3/2}$	2.886(11) 7.711(11)	$2p_{3/2}$–$3d_{5/2}$	7.006(12) 1.855(13)	$11p_{3/2}$	1.591(10) 4.257(10)
$12p_{1/2}$	3.796(10) 1.015(11)	$8d_{3/2}$	1.893(11) 5.057(11)	$4d_{5/2}$	2.242(12) 5.936(12)	$12p_{3/2}$	1.227(10) 3.281(10)
$2s$–$3p_{3/2}$	2.274(12) 6.086(12)	$9d_{3/2}$	1.310(11) 3.501(11)	$5d_{5/2}$	1.026(12) 2.718(12)	$3p_{1/2}$–$4s$	8.362(10) 2.133(11)
$4p_{3/2}$	1.007(12) 2.688(12)	$10d_{3/2}$	9.456(10) 2.526(11)	$6d_{5/2}$	5.602(11) 1.483(12)	$5s$	4.050(10) 1.036(11)
$5p_{3/2}$	5.198(11) 1.387(12)	$11d_{3/2}$	7.052(10) 1.884(11)	$7d_{5/2}$	3.411(11) 9.029(11)	$6s$	2.255(10) 5.775(10)
$6p_{3/2}$	3.015(11) 8.037(11)	$12d_{3/2}$	5.402(10) 1.443(11)	$8d_{5/2}$	2.236(11) 5.919(11)	$7s$	1.386(10) 3.550(10)
$7p_{3/2}$	1.899(11) 5.063(11)	$2p_{3/2}$–$3s$	6.349(11) 1.635(12)	$9d_{5/2}$	1.548(11) 4.097(11)	$8s$	9.131(9) 2.340(10)
$8p_{3/2}$	1.273(11) 3.391(11)	$4s$	2.530(11) 6.532(11)	$10d_{5/2}$	1.117(11) 2.956(11)	$9s$	6.340(9) 1.626(10)
$9p_{3/2}$	8.935(10) 2.381(11)	$5s$	1.252(11) 3.236(11)	$11d_{5/2}$	8.329(10) 2.204(11)	$10s$	4.584(9) 1.176(10)
$10p_{3/2}$	6.513(10) 1.736(11)	$6s$	7.102(10) 1.837(11)	$12d_{5/2}$	6.380(10) 1.688(11)	$11s$	3.423(9) 8.775(9)
$11p_{3/2}$	4.893(10) 1.304(11)	$7s$	4.415(10) 1.142(11)	$3s$–$4p_{1/2}$	3.044(11) 8.302(11)	$12s$	2.624(9) 6.728(9)
$12p_{3/2}$	3.769(10) 1.004(11)	$8s$	2.933(10) 7.587(10)	$5p_{1/2}$	1.669(11) 4.520(11)	$3p_{1/2}$–$4d_{3/2}$	6.249(11) 1.660(12)
$2p_{1/2}$–$3s$	3.077(11) 7.762(11)	$9s$	2.047(10) 5.296(10)	$6p_{1/2}$	9.813(10) 2.652(11)	$5d_{3/2}$	3.037(11) 8.090(11)
$4s$	1.229(11) 3.112(11)	$10s$	1.486(10) 3.844(10)	$7p_{1/2}$	6.216(10) 1.677(11)	$6d_{3/2}$	1.687(11) 4.500(11)
$5s$	6.085(10) 1.543(11)	$11s$	1.113(10) 2.879(10)	$8p_{1/2}$	4.175(10) 1.126(11)	$7d_{3/2}$	1.035(11) 2.761(11)
$6s$	3.452(10) 8.759(10)	$12s$	8.547(9) 2.212(10)	$9p_{1/2}$	2.936(10) 7.910(10)	$8d_{3/2}$	6.809(10) 1.818(11)
$7s$	2.146(10) 5.448(10)	$2p_{3/2}$–$3d_{3/2}$	1.167(12) 3.090(12)	$10p_{1/2}$	2.141(10) 5.768(10)	$9d_{3/2}$	4.724(10) 1.262(11)
$8s$	1.426(10) 3.620(10)	$4d_{3/2}$	3.724(11) 9.840(11)	$11p_{1/2}$	1.610(10) 4.284(10)	$10d_{3/2}$	3.414(10) 9.116(10)

（续表）

Transition	Probability A	Transition	Probability A	Transition	Probability A	Transition	Probability A
$8p_{1/2}$–$11d_{3/2}$	2.549(10) 6.806(10)	$3p_{1/2}$–$11d_{5/2}$	3.034(10) 8.063(10)	$3d_{3/2}$–$11f_{5/2}$	2.580(10) 6.893(10)	$3d_{5/2}$–$11f_{7/2}$	2.751(10) 7.331(10)
$12d_{3/2}$	1.954(10) 5.217(10)	$12d_{5/2}$	2.325(10) 6.180(10)	$12f_{5/2}$	1.952(10) 5.216(10)	$12f_{7/2}$	2.082(10) 5.547(10)
$8p_{3/2}$–$4s$	1.722(11) 4.478(11)	$3d_{3/2}$–$4p_{1/2}$	4.081(10) 1.113(11)	$3d_{5/2}$–$4p_{3/2}$	3.538(10) 9.439(10)	$4s$–$5p_{1/2}$	7.151(10) 1.957(11)
$5s$	8.320(10) 2.167(11)	$5p_{1/2}$	1.761(10) 4.797(10)	$5p_{3/2}$	1.529(10) 4.074(10)	$6p_{1/2}$	4.440(10) 1.207(11)
$6s$	4.630(10) 1.206(11)	$6p_{1/2}$	9.229(9) 2.514(10)	$6p_{3/2}$	8.011(9) 2.135(10)	$7p_{1/2}$	2.845(10) 7.715(10)
$7s$	2.844(10) 7.413(10)	$7p_{1/2}$	5.474(9) 1.490(10)	$7p_{3/2}$	4.751(9) 1.266(10)	$8p_{1/2}$	1.919(10) 5.194(10)
$8s$	1.874(10) 4.885(10)	$8p_{1/2}$	3.527(9) 9.604(9)	$8p_{3/2}$	3.062(9) 8.159(9)	$9p_{1/2}$	1.351(10) 3.655(10)
$9s$	1.301(10) 3.392(10)	$9p_{1/2}$	2.412(9) 6.568(9)	$9d_{3/2}$	2.094(9) 5.581(9)	$10p_{1/2}$	9.863(9) 2.667(10)
$10s$	9.406(9) 2.453(10)	$10p_{1/2}$	1.726(9) 4.699(9)	$10p_{3/2}$	1.498(9) 3.992(9)	$11p_{1/2}$	7.416(9) 2.004(10)
$11s$	7.023(9) 1.832(10)	$11p_{1/2}$	1.179(9) 3.481(9)	$11p_{3/2}$	1.110(9) 2.958(9)	$12p_{1/2}$	5.715(9) 1.544(10)
$12s$	5.384(9) 1.404(10)	$12p_{1/2}$	9.747(8) 2.653(9)	$12p_{3/2}$	8.462(8) 2.255(9)	$4s$–$5p_{3/2}$	6.968(10) 1.879(11)
$8p_{3/2}$–$4d_{3/2}$	1.254(11) 3.337(11)	$3d_{3/2}$–$4p_{3/2}$	3.877(9) 1.025(10)	$3d_{5/2}$–$4f_{5/2}$	9.655(10) 2.572(11)	$6p_{3/2}$	4.352(10) 1.170(11)
$5d_{3/2}$	6.048(10) 1.608(11)	$5p_{3/2}$	1.675(9) 4.427(9)	$5f_{5/2}$	3.176(10) 8.453(10)	$7p_{3/2}$	2.796(10) 7.507(10)
$6d_{3/2}$	3.351(10) 8.904(10)	$6p_{3/2}$	8.779(8) 2.320(9)	$6f_{5/2}$	1.500(10) 3.989(10)	$8p_{3/2}$	1.888(10) 5.066(10)
$7d_{3/2}$	2.053(10) 5.451(10)	$7p_{3/2}$	5.207(8) 1.375(9)	$7f_{5/2}$	8.432(9) 2.242(10)	$9p_{3/2}$	1.331(10) 3.570(10)
$8d_{3/2}$	1.350(10) 3.584(10)	$8p_{3/2}$	3.355(8) 8.863(8)	$8f_{5/2}$	5.265(9) 1.400(10)	$10p_{3/2}$	9.720(9) 2.607(10)
$9d_{3/2}$	9.359(9) 2.485(10)	$9p_{3/2}$	2.295(8) 6.061(8)	$9f_{5/2}$	3.529(9) 9.378(9)	$11p_{3/2}$	7.312(9) 1.961(10)
$10d_{3/2}$	6.761(9) 1.795(10)	$10p_{3/2}$	1.642(8) 4.336(8)	$10f_{5/2}$	2.489(9) 6.615(9)	$12p_{3/2}$	5.637(9) 1.512(10)
$11d_{3/2}$	5.046(9) 1.339(10)	$11p_{3/2}$	1.216(8) 3.213(8)	$11f_{5/2}$	1.826(9) 4.852(9)	$4p_{1/2}$–$5s$	2.850(10) 7.302(10)
$12d_{3/2}$	3.867(9) 1.027(10)	$12p_{3/2}$	9.271(7) 2.449(8)	$12f_{5/2}$	1.381(9) 3.671(9)	$6s$	1.556(10) 3.999(10)
$8p_{3/2}$–$4d_{5/2}$	7.500(11) 1.993(12)	$3d_{3/2}$–$4f_{5/2}$	1.356(12) 3.618(12)	$3d_{5/2}$–$4f_{7/2}$	1.449(12) 3.862(12)	$7s$	9.383(9) 2.414(10)
$5d_{5/2}$	3.627(11) 9.642(11)	$5f_{5/2}$	4.473(11) 1.195(12)	$5f_{7/2}$	4.777(11) 1.273(12)	$8s$	6.107(9) 1.572(10)
$6d_{5/2}$	2.012(11) 5.348(11)	$6f_{5/2}$	2.115(11) 5.650(11)	$6f_{/2}$	2.257(11) 6.015(11)	$9s$	4.205(9) 1.083(10)
$7d_{5/2}$	1.233(11) 3.277(11)	$7f_{5/2}$	1.190(11) 3.179(11)	$7f_{7/2}$	1.269(11) 3.384(11)	$10s$	3.022(9) 7.781(9)
$8d_{5/2}$	8.111(10) 2.156(11)	$8f_{5/2}$	7.433(10) 1.986(11)	$8f_{7/2}$	7.930(10) 2.113(11)	$11s$	2.247(9) 5.786(9)
$9d_{5/2}$	5.626(10) 1.496(11)	$9f_{5/2}$	4.983(10) 1.331(11)	$9f_{7/2}$	5.315(10) 1.416(11)	$12s$	1.717(9) 4.421(9)
$10d_{5/2}$	4.065(10) 1.080(11)	$10f_{5/2}$	3.516(10) 9.395(10)	$10f_{7/2}$	3.750(10) 9.993(10)	$4p_{1/2}$–$5d_{3/2}$	1.301(11) 3.449(11)

（续表）

Transition	Probability A	Transition	Probability A	Transition	Probability A	Transition	Probability A
$4p_{1/2}$-$6d_{3/2}$	7.607(10) 2.025(11)	$4p_{3/2}$-$9d_{5/2}$	2.603(10) 6.929(10)	$4d_{3/2}$-$12f_{5/2}$	1.200(10) 3.208(10)	$4f_{5/2}$-$7d_{3/2}$	1.209(9) 3.264(9)
$7d_{3/2}$	4.727(10) 1.260(11)	$10d_{5/2}$	1.883(10) 5.013(10)	$4d_{5/2}$-$5p_{3/2}$	1.900(10) 5.070(10)	$8d_{3/2}$	7.221(8) 1.949(9)
$8d_{3/2}$	3.218(10) 8.337(10)	$11d_{5/2}$	1.407(10) 3.744(10)	$6p_{3/2}$	9.521(9) 2.539(10)	$9d_{3/2}$	4.695(8) 1.267(9)
$9d_{3/2}$	2.176(10) 5.802(10)	$12d_{5/2}$	1.079(10) 2.872(10)	$7p_{3/2}$	5.459(9) 1.455(10)	$10d_{3/2}$	3.242(8) 8.754(8)
$10d_{3/2}$	1.575(10) 4.199(10)	$4d_{3/2}$-$5p_{1/2}$	2.182(10) 5.937(10)	$8p_{3/2}$	3.441(9) 9.171(9)	$11d_{3/2}$	2.342(8) 6.323(8)
$11d_{3/2}$	1.176(10) 3.138(10)	$6p_{1/2}$	1.092(10) 2.967(10)	$9p_{3/2}$	2.319(9) 6.181(9)	$12d_{3/2}$	1.751(8) 4.728(8)
$12d_{3/2}$	9.024(9) 2.408(10)	$7p_{1/2}$	6.259(9) 1.700(10)	$10p_{3/2}$	1.642(9) 4.377(9)	$4f_{5/2}$-$5d_{5/2}$	2.536(8) 6.765(8)
$4p_{3/2}$-$5s$	5.862(10) 1.530(11)	$8p_{1/2}$	3.94(59) 1.071(10)	$11p_{3/2}$	1.208(9) 3.219(9)	$6d_{5/2}$	1.079(8) 2.878(8)
$6s$	3.192(10) 8.342(10)	$9p_{1/2}$	2.659(9) 7.220(9)	$12p_{3/2}$	9.156(8) 2.440(9)	$7d_{5/2}$	5.656(7) 1.509(8)
$7s$	1.924(10) 5.030(10)	$10p_{1/2}$	1.883(9) 5.112(9)	$4d_{5/2}$-$5f_{5/2}$	1.812(10) 4.832(10)	$8d_{5/2}$	3.376(7) 9.010(7)
$8s$	1.252(10) 3.274(10)	$11p_{1/2}$	1.385(9) 3.760(9)	$6f_{5/2}$	9.020(9) 2.404(10)	$9d_{5/2}$	2.195(7) 5.858(7)
$9s$	8.615(9) 2.254(10)	$12p_{1/2}$	1.050(9) 2.849(9)	$7f_{5/2}$	5.142(9) 1.370(10)	$10d_{5/2}$	1.515(7) 4.045(7)
$10s$	6.191(9) 1.620(10)	$4d_{3/2}$-$5p_{3/2}$	2.085(9) 5.518(9)	$8f_{5/2}$	3.229(9) 8.601(9)	$11d_{5/2}$	1.094(7) 2.921(7)
$11s$	4.602(9) 1.204(10)	$6p_{3/2}$	1.045(9) 2.765(9)	$9f_{5/2}$	2.171(9) 5.780(9)	$12d_{5/2}$	8.184(6) 2.184(7)
$12s$	3.516(9) 9.202(9)	$7p_{3/2}$	5.992(8) 1.584(9)	$10f_{5/2}$	1.534(9) 4.084(9)	$4f_{5/2}$-$5g_{7/2}$	4.313(11) 1.150(12)
$4p_{3/2}$-$5d_{3/2}$	2.625(10) 7.000(10)	$8p_{3/2}$	3.777(8) 9.988(8)	$11f_{5/2}$	1.126(9) 2.999(9)	$6g_{7/2}$	1.393(11) 3.716(11)
$6d_{3/2}$	1.525(10) 4.065(10)	$9p_{3/2}$	2.546(8) 6.731(8)	$12f_{5/2}$	8.529(8) 2.270(9)	$7g_{7/2}$	6.553(10) 1.749(11)
$7d_{3/2}$	9.452(9) 2.518(10)	$10p_{3/2}$	1.802(8) 4.765(8)	$4d_{5/2}$-$5f_{7/2}$	2.717(11) 7.242(11)	$8g_{7/2}$	3.696(10) 9.865(10)
$8d_{3/2}$	6.245(9) 1.663(10)	$11p_{3/2}$	1.326(8) 3.505(8)	$6f_{7/2}$	1.354(11) 3.610(11)	$9g_{7/2}$	2.323(10) 6.198(10)
$9d_{3/2}$	4.340(9) 1.156(10)	$12p_{3/2}$	1.005(8) 2.656(8)	$7f_{7/2}$	7.724(10) 2.060(11)	$10g_{7/2}$	1.568(10) 4.185(10)
$10d_{3/2}$	3.139(9) 8.355(9)	$4d_{3/2}$-$5f_{5/2}$	2.538(11) 6.768(11)	$8f_{7/2}$	4.853(10) 1.294(11)	$11g_{7/2}$	1.115(10) 2.975(10)
$11d_{3/2}$	2.344(9) 6.239(9)	$6f_{5/2}$	1.266(11) 3.380(11)	$9f_{7/2}$	3.262(10) 8.700(10)	$12g_{7/2}$	8.242(9) 2.199(10)
$12d_{3/2}$	1.798(9) 4.783(9)	$7f_{5/2}$	7.226(10) 1.930(11)	$10f_{7/2}$	2.306(10) 6.149(10)	$4f_{7/2}$-$5d_{5/2}$	5.112(9) 1.370(10)
$4p_{3/2}$-$5d_{5/2}$	1.568(11) 4.170(11)	$8f_{5/2}$	4.541(10) 1.213(11)	$11f_{7/2}$	1.694(10) 4.516(10)	$6d_{5/2}$	2.175(9) 5.832(9)
$6d_{5/2}$	9.132(10) 2.431(11)	$9f_{5/2}$	3.054(10) 8.157(10)	$12f_{7/2}$	1.282(10) 3.420(10)	$7d_{5/2}$	1.141(9) 3.059(9)
$7d_{5/2}$	5.664(10) 1.508(11)	$10f_{5/2}$	2.159(10) 5.766(10)	$4f_{5/2}$-$5d_{3/2}$	5.419(9) 1.461(10)	$8d_{5/2}$	6.810(8) 1.827(9)
$8d_{5/2}$	3.744(10) 9.967(10)	$11f_{5/2}$	1.585(10) 4.236(10)	$6d_{3/2}$	2.305(9) 6.220(9)	$9d_{5/2}$	4.427(8) 1.188(9)

（续表）

Transition	Probability A	Transition	Probability A	Transition	Probability A	Transition	Probability A
$4f_{7/2}-10d_{5/2}$	3.057(8) 8.204(8)	$5s-7p_{3/2}$	1.529(10) 4.116(10)	$5p_{3/2}-6d_{3/2}$	7.895(9) 2.108(10)	$5d_{3/2}-12p_{3/2}$	9.072(7) 2.400(8)
$11d_{5/2}$	2.208(8) 5.925(8)	$8p_{3/2}$	1.043(10) 2.803(10)	$7d_{3/2}$	5.107(9) 1.363(10)	$5d_{3/2}-6f_{5/2}$	7.092(10) 1.890(11)
$12d_{5/2}$	1.651(8) 4.430(8)	$9p_{3/2}$	7.370(9) 1.981(10)	$8d_{3/2}$	3.406(9) 9.083(9)	$7f_{5/2}$	4.255(10) 1.135(11)
$4f_{7/2}-5g_{7/2}$	1.595(10) 4.249(10)	$10p_{3/2}$	5.388(9) 1.447(10)	$9d_{3/2}$	2.374(9) 6.330(9)	$8f_{5/2}$	2.707(10) 7.227(10)
$6g_{7/2}$	5.141(9) 1.369(10)	$11p_{3/2}$	4.054(9) 1.089(10)	$10d_{3/2}$	1.719(9) 4.583(9)	$9f_{5/2}$	1.829(10) 4.884(10)
$7g_{7/2}$	2.417(9) 6.433(9)	$12p_{3/2}$	3.125(9) 8.388(9)	$11d_{3/2}$	1.285(9) 3.424(9)	$10f_{5/2}$	1.296(10) 3.461(10)
$8g_{7/2}$	1.363(9) 3.626(9)	$5p_{1/2}-6s$	1.164(10) 2.989(10)	$12d_{3/2}$	9.853(8) 2.626(9)	$11f_{5/2}$	9.534(9) 2.546(10)
$9g_{7/2}$	8.560(8) 2.277(9)	$7s$	6.898(9) 1.777(10)	$5p_{3/2}-6d_{5/2}$	4.713(10) 1.255(11)	$12f_{5/2}$	7.225(9) 1.929(10)
$10g_{7/2}$	5.779(8) 1.537(9)	$8s$	4.410(9) 1.137(10)	$7d_{5/2}$	3.054(10) 8.134(10)	$5d_{5/2}-6p_{3/2}$	9.609(9) 2.565(10)
$11g_{7/2}$	4.108(8) 1.093(9)	$9s$	2.998(9) 7.739(9)	$8d_{5/2}$	2.039(10) 5.430(10)	$7p_{3/2}$	5.330(9) 1.421(10)
$12g_{7/2}$	3.036(8) 8.075(8)	$10s$	2.136(9) 5.516(9)	$9d_{5/2}$	1.422(10) 3.788(10)	$8p_{3/2}$	3.264(9) 8.700(9)
$4f_{7/2}-5g_{9/2}$	4.468(11) 1.191(12)	$11s$	1.578(9) 4.076(9)	$10d_{5/2}$	1.030(10) 2.743(10)	$9p_{3/2}$	2.157(9) 5.749(9)
$6g_{9/2}$	1.442(11) 3.844(11)	$12s$	1.201(9) 3.101(9)	$11d_{5/2}$	7.698(9) 2.051(10)	$10p_{3/2}$	1.507(9) 4.015(9)
$7g_{9/2}$	6.784(10) 1.808(11)	$5p_{1/2}-6d_{3/2}$	3.898(10) 1.033(11)	$12d_{5/2}$	5.906(9) 1.573(10)	$11p_{3/2}$	1.097(9) 2.924(9)
$8g_{9/2}$	3.826(10) 1.020(11)	$7d_{3/2}$	2.537(10) 6.743(10)	$5d_{3/2}-6p_{1/2}$	1.101(10) 2.991(10)	$12p_{3/2}$	8.259(8) 2.201(9)
$9g_{9/2}$	2.404(10) 6.048(10)	$8d_{3/2}$	1.697(10) 4.514(10)	$7p_{1/2}$	6.095(9) 1.653(10)	$5d_{5/2}-6f_{5/2}$	5.073(9) 1.353(10)
$10g_{9/2}$	1.623(10) 4.326(10)	$9d_{3/2}$	1.184(10) 3.153(10)	$8p_{1/2}$	3.731(9) 1.011(10)	$7f_{5/2}$	3.037(9) 8.098(9)
$11g_{9/2}$	1.154(10) 3.075(10)	$10d_{3/2}$	8.584(9) 2.287(10)	$9p_{1/2}$	2.465(9) 6.683(9)	$8f_{5/2}$	1.930(9) 5.147(9)
$12g_{9/2}$	8.530(9) 2.273(10)	$11d_{3/2}$	6.419(9) 1.710(10)	$10p_{1/2}$	1.722(9) 4.667(9)	$9f_{5/2}$	1.304(9) 3.475(9)
$5s-6p_{1/2}$	2.321(10) 6.365(10)	$12d_{3/2}$	4.925(9) 1.312(10)	$11p_{1/2}$	1.254(9) 3.399(9)	$10f_{5/2}$	9.233(8) 2.461(9)
$7p_{1/2}$	1.562(10) 4.256(10)	$5p_{3/2}-6s$	2.391(10) 6.254(10)	$12p_{1/2}$	9.440(8) 2.558(9)	$11f_{5/2}$	6.789(8) 1.809(9)
$8p_{1/2}$	1.063(10) 2.888(10)	$7s$	1.414(10) 3.702(10)	$5d_{3/2}-6p_{3/2}$	1.055(9) 2.796(9)	$12f_{5/2}$	5.144(8) 1.371(9)
$9p_{1/2}$	7.500(9) 2.036(10)	$8s$	9.029(9) 2.366(10)	$7p_{3/2}$	5.857(8) 1.550(9)	$5d_{5/2}-6f_{7/2}$	7.600(10) 2.025(11)
$10p_{1/2}$	5.478(9) 1.485(10)	$9s$	6.138(9) 1.609(10)	$8p_{3/2}$	3.586(8) 9.491(8)	$7f_{7/2}$	4.555(10) 1.215(11)
$11p_{1/2}$	4.119(9) 1.116(10)	$10s$	4.372(9) 1.146(10)	$9p_{3/2}$	2.370(8) 6.271(8)	$8f_{7/2}$	2.897(10) 7.725(10)
$12p_{1/2}$	3.173(9) 8.594(9)	$11s$	3.230(9) 8.468(9)	$10p_{3/2}$	1.655(8) 4.380(8)	$9f_{7/2}$	1.956(10) 5.218(10)
$5s-6p_{3/2}$	2.259(10) 6.098(10)	$12s$	2.457(9) 6.441(9)	$11p_{3/2}$	1.205(8) 3.189(8)	$10f_{7/2}$	1.386(10) 3.697(10)

（续表）

Transition	Probability A	Transition	Probability A	Transition	Probability A	Transition	Probability A
$5d_{5/2}-11f_{7/2}$	1.019(10) 2.719(10)	$5f_{7/2}-12g_{7/2}$	7.173(9) 1.914(10)	$5g_{7/2}-6f_{5/2}$	1.206(9) 3.237(9)	$5g_{9/2}-6f_{7/2}$	1.168(9) 3.127(9)
$12f_{7/2}$	7.726(9) 2.060(10)	$5f_{5/2}-6d_{5/2}$	3.952(9) 1.059(10)	$7f_{5/2}$	4.939(8) 1.325(9)	$7f_{7/2}$	4.782(8) 1.280(9)
$5f_{5/2}-6d_{3/2}$	4.186(9) 1.127(10)	$7d_{5/2}$	1.936(9) 5.186(9)	$8f_{5/2}$	2.538(8) 6.815(8)	$8f_{7/2}$	2.457(8) 6.580(8)
$7d_{3/2}$	2.050(9) 5.520(9)	$8d_{5/2}$	1.103(9) 2.955(9)	$9f_{5/2}$	1.500(8) 4.028(8)	$9f_{7/2}$	1.452(8) 3.888(8)
$8d_{3/2}$	1.168(9) 3.146(9)	$9d_{5/2}$	6.957(8) 1.864(9)	$10f_{5/2}$	9.705(7) 2.607(8)	$10f_{7/2}$	9.395(7) 2.517(8)
$9d_{3/2}$	7.367(8) 1.985(9)	$10d_{5/2}$	4.707(8) 1.262(9)	$11f_{5/2}$	6.693(7) 1.798(8)	$11f_{7/2}$	6.477(7) 1.735(8)
$10d_{3/2}$	4.985(8) 1.343(9)	$11d_{5/2}$	3.351(8) 8.982(8)	$12f_{5/2}$	4.835(7) 1.299(8)	$12f_{7/2}$	4.680(7) 1.254(8)
$11d_{3/2}$	3.549(8) 9.565(8)	$12d_{5/2}$	2.479(8) 6.645(8)	$5g_{7/2}-6f_{7/2}$	3.322(7) 8.861(7)	$5g_{9/2}-6h_{9/2}$	3.837(9) 1.023(10)
$12d_{3/2}$	2.626(8) 7.077(8)	$5f_{7/2}-6g_{7/2}$	4.148(9) 1.106(10)	$7f_{7/2}$	1.359(7) 3.627(7)	$7h_{9/2}$	1.186(9) 3.158(9)
$5f_{5/2}-6d_{5/2}$	1.963(8) 5.234(8)	$7g_{7/2}$	2.055(9) 5.477(9)	$8f_{7/2}$	6.983(6) 1.863(7)	$8h_{9/2}$	5.448(8) 1.451(9)
$7d_{5/2}$	9.610(7) 2.563(8)	$8g_{7/2}$	1.175(9) 3.131(9)	$9f_{7/2}$	4.124(6) 1.101(7)	$9h_{9/2}$	3.033(8) 8.074(8)
$8d_{5/2}$	5.474(7) 1.460(8)	$9g_{7/2}$	7.422(8) 1.977(9)	$10f_{7/2}$	2.668(6) 7.122(6)	$10h_{9/2}$	1.893(8) 5.037(8)
$9d_{5/2}$	3.452(7) 9.210(7)	$10g_{7/2}$	5.025(8) 1.338(9)	$11f_{7/2}$	1.839(6) 4.910(6)	$11h_{9/2}$	1.274(8) 3.390(8)
$10d_{5/2}$	2.335(7) 6.231(7)	$11g_{7/2}$	3.578(8) 9.528(8)	$12f_{7/2}$	1.329(6) 3.547(6)	$12h_{9/2}$	9.049(7) 2.048(8)
$11d_{5/2}$	1.662(7) 4.435(7)	$12g_{7/2}$	2.647(8) 7.049(8)	$5g_{7/2}-6h_{9/2}$	1.690(11) 4.506(11)	$5g_{9/2}-6h_{11/2}$	1.728(11) 4.605(11)
$12d_{5/2}$	1.230(7) 3.281(7)	$5f_{7/2}-6g_{9/2}$	1.161(11) 3.096(11)	$7h_{9/2}$	5.229(10) 1.395(11)	$7h_{11/2}$	5.343(10) 1.424(11)
$5f_{5/2}-6g_{7/2}$	1.120(11) 2.988(11)	$7g_{9/2}$	5.760(10) 1.536(11)	$8h_{9/2}$	2.403(10) 6.411(10)	$8h_{11/2}$	2.456(10) 6.547(10)
$7g_{7/2}$	5.560(10) 1.483(11)	$8g_{9/2}$	3.294(10) 8.784(10)	$9h_{9/2}$	1.339(10) 3.570(10)	$9h_{11/2}$	1.368(10) 3.646(10)
$8g_{7/2}$	3.180(10) 8.487(10)	$9g_{9/2}$	2.081(10) 5.550(10)	$10h_{9/2}$	8.355(9) 2.228(10)	$10h_{11/2}$	8.536(9) 2.275(10)
$9g_{7/2}$	2.010(10) 5.364(10)	$10g_{9/2}$	1.409(10) 3.758(10)	$11h_{9/2}$	5.624(9) 1.500(10)	$11h_{11/2}$	5.746(9) 1.531(10)
$10g_{7/2}$	1.361(10) 3.632(10)	$11g_{9/2}$	1.004(10) 2.676(10)	$12h_{9/2}$	3.996(9) 1.066(10)	$12h_{11/2}$	4.082(9) 1.088(10)
$11g_{7/2}$	9.693(9) 2.587(10)	$12g_{9/2}$	7.427(9) 1.980(10)				

少数由于径向相消效应[5]所造成的弱跃迁，其相对偏差亦在 5% 之内。我们取它们的算术平均值作为该对能级间跃迁几率的理论值。

表 1 一并列出了 Ca^{17+} 和 Mn^{22+} 的 $n\leqslant 12$, $l\leqslant 5$ 的全部精细能级值。对于 n, l 都很大的能级，由于它们应有很好的非相对论的类氢行为，可由表列的数据方便地推出。

表 2 一并列出了 Ca^{17+} 和 Mn^{22+} 的辐射跃迁几率值。注意到，对于 $\Delta n=0$ 的跃迁，由于其跃迁能甚小，在每一里德伯系之内，其跃迁几率均明显小于其它成员，故而未列。另外，为省篇

幅计，表中未列跃迁波长，读者可由表1数据依下式方便求得：

$$\lambda=\frac{12398.52}{\Delta E(\mathrm{eV})}\,\mathring{\mathrm{A}}, \tag{1}$$

式中 ΔE 为相应两能级的能量差(eV 单位)，λ 即为该跃迁波长(Å 单位)。

另外，由表2所列数据，依下式可得 $n\leqslant 6$ 所有精细能级的辐射衰变速率 Γ_k：

$$\Gamma_k=\sum_i A_{(nlj)_k-(nlj)_i} \tag{2}$$

二、结果与讨论

正如我们在 Si^{11+} 的计算[6]中已经发现的那样，由表2仍可看到，对于所有里德伯系，当跃迁上能级的主量数 n_k 足够大之后，其跃迁几率仅与 n_k^3 成反比。

另外，由表2可以看到，对于每组跃迁，上下两层数据几乎均保持着一个共同的比值：0.375。这是高电离类锂离子的类氢行为的又一生动反映：对于 Ca^{17+}，其光学电子所感受到的有效核电荷 $z_{eff}\cong 20-2=18$；对于 Mn^{22+}，$z_{eff}\cong 25-2=23$。所以，其跃迁几率比应为它们有效核电荷比的4次方。

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用半导体激光泵浦的 YAG 激光器获得绿光输出

中国科学院上海光机所激光技术开放研究实验室在外腔型“半导体激光泵浦 YAG 激光器”获得运转的基础上，于1991年8月22日实现了腔内倍频，获得了绿光输出。

半外腔的 Nd:YAG 激光腔，腔镜由两个凹面镜组成，5 mm 长的 YAG 棒的一个端面为腔镜之一，涂双色膜，对1064 nm 全反射，对808 nm 透过90%，另一个腔镜也是双色膜，对1064 nm 全反射，对532 nm 透过90%。激光腔的设计使得腔模与泵浦光束匹配，同时有利于增加倍频光的输出。

激光器采用端面纵向泵浦，由半导体温度控制器把泵浦激光波长稳定在 YAG 的吸收峰上，实现光谱匹配。

半导体激光器是本所研制的一维10单元锁相列阵的 GaAlAs/GaAs 双异质结激光器，连续波工作时，空间积分功率为50 mW，脉冲工作时，空间积分峰值功率为100 mW，重复频率1 kHz，脉冲宽度0.1 ms。

腔内倍频用 II 类相位匹配的 KTP 晶体，在连续和脉冲两种工作方式下都获得了532 nm 的绿光输出。除了能获得稳定的 TEM_{00} 模外，也可以得到 TEM_{mn} 模的绿光，m、n 可以从0到7之间变化。

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