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Evaluation of Uranium Transitions for Isotopically-Selective
Laser Induced Fluorescence with Diode Lasers
(Technical Report for ST064)

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Summary

Isotopically-selective excitation of uranium atoms by diode lasers can be the basis for a portable instrument to perform uranium isotopic assays in the field. Such an instrument would improve the ability of on-site inspections to detect and deter nuclear proliferation. Published and unpublished spectroscopic data on atomic uranium were examined to identify candidate transitions for isotopically-selective laser excitation with diode lasers. Eleven candidate transitions were identified and evaluated for their potential usefulness for a portable uranium assay instrument. Eight of these transitions are suitable for laser induced fluorescence using different excitation and detection wavelengths, which will improve sensitivity and elemental selectivity. Data sheets on the 25 uranium transitions in the wavelength range 629 nm to 1000 nm that originate in the ground or first excited states of neutral atomic uranium are included. Each data sheet provides the wavelength, upper and lower energy levels, angular momentum quantum numbers, ^{235}U isotope shift (relative to ^{238}U), and high-resolution spectra of weapons-grade uranium (93% ^{235}U and 7% ^{238}U).

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Introduction

Uranium enrichment was central to Iraq's efforts to develop nuclear weapons, and enriched uranium is central to many of the most probable scenarios for nuclear proliferation. The $^{235}\text{U}/^{238}\text{U}$ ratio is a signature of both enriching uranium and handling stolen or diverted enriched uranium. Under the nuclear nonproliferation treaty (NPT), the International Atomic Energy Agency (IAEA) sends on-site inspection teams to signatory nations to monitor compliance with the NPT. However, at present no instrument exists that allows IAEA inspectors to measure the $^{235}\text{U}/^{238}\text{U}$ ratio of samples while still in the field. Current practice is for on-site inspectors to take samples and send them to laboratories in other countries for analysis. This leads to two sets of problems: 1) an extensive chain-of-custody must be maintained and 2) a long delay in obtaining results of sample analyses. A chain-of-custody must be maintained to ensure samples have not been tampered with, lost, or mislabeled and that the results will be accepted by the legal and diplomatic communities. The long delay in analyzing samples means that inspection teams will be out of the inspected country before the analyses are complete. The ability to rapidly measure $^{235}\text{U}/^{238}\text{U}$ isotope ratios in the field would reduce or eliminate these problems and strengthen the ability of IAEA inspections to detect and deter nuclear proliferation.

The U.S. Department of Energy's Office of Research and Development, IS-10, is funding two projects (ST064 at Pacific Northwest Laboratory^(a) and ST587 at Oak Ridge National Laboratory) that propose to meet this need for in-field uranium-isotope-ratio measurement by using isotopically selective diode laser excitation of neutral uranium atoms (U I). These diode lasers are the same ones used in compact disk players, bar code scanners, and laser printers. Diode lasers are intense, narrow bandwidth light sources that are small, mechanically rugged, and inexpensive, and that require little cooling or electrical power. They are ideal sources for this application because a number of uranium transitions can be excited with commercially available diode lasers. Many uranium transitions have isotope shifts much larger than the linewidths so diode laser excitation can be isotopically selective for these transitions. This report compiles, from open publications and unpublished spectra of weapons-grade uranium, spectroscopic information on U I transitions that could be used for isotopic analysis of uranium with diode lasers.

Uranium Spectroscopy

The spectroscopy of atomic uranium is very complicated and has received extensive study in conjunction with laser isotope separation and spectroscopic calibration. In 1976, 92,000 uranium lines and 5,500 isotope shifts were known between 200 nm and 4,200 nm with only 35,000 of the line classified

(a) Pacific Northwest Laboratory is Operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

(Blaise and Radziemski 1976). A further extensive high-precision study of U I isotope shifts in the visible and near infrared (Engleman and Palmer 1980) reported over 2,000 isotope shifts. The usefulness of the uranium lines for spectroscopic calibration between 200 nm and 900 nm was greatly enhanced when an atlas of uranium emission intensities from a hollow cathode discharge (Palmer et al. 1980) was published. Using reported line strengths and lifetimes (Corliss 1976), the relative emission intensities measured for the uranium atlas (Palmer et al. 1980) were put on an absolute scale.

Selected Transitions

To use laser excitation for measuring uranium isotope ratios, only those transitions originating from the ground or first excited state (at 620.323 cm^{-1}) of U I are of interest. These two states will have the largest population, and only transitions originating from them are included in this report. The second and higher excited states of U I are above 3800 cm^{-1} and will have significantly smaller populations. Only transitions in the wavelength range 629 nm to 1000 nm are included in this report. This wavelength range is primarily determined by the lasing wavelengths of commercially available diode lasers, though not all wavelengths in this range can be accessed. Two long wavelength transitions that originate in the lowest two states of U I (at 1560 nm and 1060 nm) are not considered here because spectroscopic data are lacking, even though commercial diode lasers that could excite them are available.

For the 25 transitions that meet these criteria, Table I lists the air wavelengths (Palmer et al. 1980), the energies of the upper and lower levels (Blaise and Radziemski 1976), the gA value for the line (Palmer et al. 1980), and the separation between the maxima of the ^{238}U and ^{235}U peak. The gA value is the upper level degeneracy, $g=2J+1$, times the spontaneous radiative rate, A . The peak separations were determined from unpublished spectra, supplied by Rolf Engleman, Jr., of a hollow cathode lamp containing weapons grade uranium (93% ^{235}U and 7% ^{238}U). These spectra were taken on the Fourier transform spectrometer at Kitt Peak National Observatory, which was used to measure spectra (Engleman and Palmer 1980; Palmer et al. 1980). The instrumental resolution of these spectra (full width at half maximum of the $\sin(x)/x$ function) is 0.027 cm^{-1} except for the 918.67 nm and 909.37 nm lines where the resolution was 0.014 cm^{-1} . The positions of the ^{238}U lines and the ^{235}U isotope shifts (relative to ^{238}U) in these unpublished spectra are in excellent agreement with published positions (Palmer et al. 1980) and isotope shifts (Blaise and Radziemski 1976; Engleman and Palmer 1980). The entries in Table I shown in bold are for transitions whose wavelengths are likely to match commercial diode laser wavelengths. Three additional lines are included in Table I that originate in the ground state of U I and share an upper level with a line in the table originating with the 620 cm^{-1} state.

Table I. Spectral Lines of Neutral Uranium Between 629 nm and 1000 nm Whose Lower Levels are Either the Ground or First Excited State. Three lines (with wavelengths shorter than 629 nm) that have a common upper level with another line in this table are also included. Those transitions whose wavelengths are likely to match that of a commercial diode laser are in **bold**. Wavelengths are in dry air at 1 atmosphere.

Wavelength (nm)	Upper-Level Energy (cm ⁻¹)	Lower-Level Energy (cm ⁻¹)	gA (10 ⁸ s ⁻¹)	²³⁸ U - ²³⁵ U Peak Separation (cm ⁻¹)
994.6218	10051.314	0.000		-0.327
918.6712	11502.624	620.323		0.461
909.3661	11613.977	620.323	0.022	0.179
875.7761	12035.632	620.323	0.041	0.300
869.1282	11502.624	0.000	0.033	0.442
860.7950	11613.977	0.000	0.113	0.164
790.7103	12643.378	0.000	0.001	-0.304
778.4159	13463.392	620.323	0.101	0.112
763.7312	13710.331	620.323	0.0002	-0.180
757.0761	13825.400	620.323	0.003	-0.124
742.5503	13463.392	0.000	0.034	0.075
712.8900	14643.867	620.323	0.066	-0.355
703.0700	14839.736	620.323	0.009	-0.321
682.6913	14643.867	0.000	0.223	-0.370
673.6805	14839.736	0.000	0.010	-0.428
672.8167	14858.786	0.000	0.001	-0.313
665.6819	15638.367	620.323	0.010	0.170
662.0531	15720.682	620.323	0.031	-0.208
644.9161	16121.933	620.323	0.234	-0.178
641.8756	16195.360	620.323	<0.0003	-0.301
639.5426	15631.855	0.000	0.131	0.297
639.2763	15638.367	0.000	0.039	0.168
637.8354	16294.017	620.323	0.006	0.344
635.9289	15720.682	0.000	0.036	-0.243
629.3329	16505.773	620.323	0.038	0.184
617.2900	16195.360	0.000	0.011	-0.324
613.5524	16294.017	0.000	<0.0002	0.221
605.6810	16505.773	0.000	0.025	0.179

Evaluated For Laser Diode Excitation

Table II shows the same information as Table I, but only for pairs of transitions that share a common upper level. These pairs of transitions allow laser-induced fluorescence detection of U I with the fluorescence-detection wavelength well separated from the laser wavelength. Separate excitation and detection wavelengths increase sensitivity by reducing the scattered laser background and increase elemental selectivity by requiring both wavelengths to be matched. The pair of transitions sharing the 11503 cm^{-1} upper level has the two largest isotope shifts in Table I, but is marginal for diode laser excitation. Both transitions of the 11614 cm^{-1} pair are strong and have adequate isotope separations, but

Table II. Pairs of Lines from Table I That Share a Common Upper Level and are Attractive for Laser Induced Fluorescence with Different Excitation and Detection Wavelengths. Very weak transitions were excluded from this table. Those transitions whose wavelengths are likely to match that of a commercial diode laser are in **bold**.

Wavelength (nm)	Upper-Level Energy (cm^{-1})	Lower-Level Energy (cm^{-1})	gA (10^8 s^{-1})	$^{238}\text{U} - ^{235}\text{U}$ Peak Separation (cm^{-1})
918.6712	11502.624	620.323		0.461
869.1282	11502.624	0.000	0.033	0.442
909.3661	11613.977	620.323	0.022	0.179
860.7950	11613.977	0.000	0.113	0.164
778.4159	13463.392	620.323	0.101	0.112
742.5503	13463.392	0.000	0.034	0.075
712.8900	14643.867	620.323	0.066	-0.355
682.6913	14643.867	0.000	0.223	-0.370
703.0700	14839.736	620.323	0.009	-0.321
673.6805	14839.736	0.000	0.010	-0.428
665.6819	15638.367	620.323	0.010	0.170
639.2763	15638.367	0.000	0.039	0.168
662.0531	15720.682	620.323	0.031	-0.208
635.9289	15720.682	0.000	0.036	-0.243
629.3329	16505.773	620.323	0.038	0.184
605.6810	16505.773	0.000	0.025	0.179

860.8 nm is not a wavelength of interest to diode laser manufacturers. This means laser power, lifetime, and availability may be below average. For the 13464 cm^{-1} pair, isotope selectivity may be inadequate because of the relatively small isotope separations, though the separation for the 778.4 nm line is ten times the room temperature Doppler width. Both the 14644 cm^{-1} and 14840 cm^{-1} pairs are very attractive for isotopically selective laser induced fluorescence of U I. The three remaining pairs of transitions in Table II all require the newest class of commercially available visible diode lasers, 635 nm diode lasers. While rapid progress in laser power, lifetime, and availability is to be expected for these lasers, at present their low output power and newness make these three pairs of transitions less attractive than the 14644 cm^{-1} and 14840 cm^{-1} pairs. Three additional transitions in Table I (but not Table II) are likely matches to commercial diode lasers. Two of these transitions (at 672.8 nm and 637.8 nm) are poor choices for diode laser excitation because they are weak. The third transition (at 639.5 nm) is strong and ^{235}U is well separated from ^{238}U . The 639.5 nm transition would be a good candidate for measurements based on absorption or the optogalvanic effect. The sole disadvantage is that this transition requires the less developed 635 nm diode lasers.

Description of Spectroscopic Data Sheets

Twenty-eight data sheets (see Appendix) for the transitions listed in Table I (given below) contain a table of spectroscopic data, high resolution spectra of weapons grade uranium, and comments about the U I transition. Transition wavelengths are from the uranium atlas (Palmer et al. 1980) and are for dry air at one atmosphere. For the four transitions in Table I that were not listed in the uranium atlas, the index of refraction was computed from the nearest line in that atlas. Transition energies, level energies, electronic angular momentum quantum numbers, J, and isotope shifts are from Blaise and Radziemski (1976). The gA value (the degeneracy of the upper level, g, times the spontaneous rate, A) in the first column is from the uranium atlas (Palmer et al. 1980) and that in the second column is from Corliss (1976). These results are not independent, as the results of Corliss (1976) were used in Palmer et al. (1980) to determine the electron temperature and establish an absolute scale. The relative values of gA from the uranium atlas (Palmer et al. 1980) have smaller estimated errors (8%) than those from Corliss (1976) (32%).

The "Isotope Peak Separations" were measured from the spectra of 93% ^{235}U and 7% ^{238}U shown on the data sheets. These spectra are a very small part of the unpublished spectral data on weapons grade uranium provided by Rolf Engleman, Jr. The frequency of the maximum for each ^{235}U line was determined by fitting a quadratic to the highest observed point and one point to either side. The frequency at which the resulting quadratic was a maximum was used as the frequency of the maximum of the ^{235}U peak. The "Isotope Peak Separation" is the difference between the transition frequency for ^{238}U found in Palmer et al. (1980) and the frequency of the maximum of the ^{235}U line.

Isotope shifts and isotope peak separations follow the normal convention: $^{238}\text{U} - ^{235}\text{U}$. Thus, a positive isotope shift means that the heavier isotope's transition is at higher frequency. All isotope shifts due to the normal mass shift are positive with this convention. For uranium, nuclear field shifts dominate the isotope shifts, and they can be of either sign. With the origins of the frequency axes set

to the ^{238}U transition, the position of the ^{235}U peak in these spectra is the negative of the isotope shift. The "Isotope Shift" and the "Isotope Peak Separation" are slightly different quantities. The isotope shift is the spacing between the center of gravity of the ^{238}U peak and the center of gravity of the set of ^{235}U hyperfine peaks. For a single peak or hyperfine splittings much smaller than the resolution, the center of gravity of a peak is the same as the peak maximum. For asymmetric peaks, such as ^{235}U peaks with partially resolved hyperfine structure, the center of gravity is different than the peak maximum.

Each data sheet shows a 1 cm^{-1} wide spectrum centered around the transition and also a wider spectrum (usually 10 cm^{-1} wide) centered on the ^{238}U peak. Because the transition frequencies of ^{238}U used for establishing the relative frequency scales come from the uranium atlas, (Palmer et al. 1980) the deviations in the positions of the ^{238}U peaks from 0.000 cm^{-1} are an indication of how well the absolute frequency measurements can be reproduced. The weapons-grade uranium spectra and those in the uranium atlas³ were both measured on the same instrument at the Kitt Peak National Observatory. The agreement is excellent, within the estimated error of $\pm 0.003\text{ cm}^{-1}$, except for one very weak transition.

Conclusion

In the wavelength region between 629 nm and 1036 nm, the two most promising transitions for isotopic uranium analysis are the 682.7 nm and the 673.7 nm transitions. The wavelengths are well matched to commercially available diode lasers, the isotope separations are good, and the transitions are strong. The 778.4 nm transition could be as good or perhaps better than the two most promising in those situations where the transition linewidths are near the room temperature Doppler width. Within two to five years, one of the four strong transitions in Table I between 629 nm and 640 nm may become the transition of choice, because 635 nm diode lasers continue to be the focus of a great development effort. For uranium isotopic analysis with diode lasers, the problem is choosing the best among several good choices.

Acknowledgement

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Appendix

Data Sheets for Transitions Listed in Table I

Spectroscopic Information on U I Transition

Data Sheet 1.

Transition Wavelength in air (nm)	994.6218
Transition Energy (cm ⁻¹)	10051.314
Upper Level Energy (cm ⁻¹)	10051.314
Lower Level Energy (cm ⁻¹)	0.000
Upper Level J	5
Lower Level J	6
gA (10 ⁸ s ⁻¹)	
Isotope Shift (cm ⁻¹)	-0.295
Isotope Peak Separation (cm ⁻¹)	-0.327

Comments: The ²³⁵U hyperfine structure appears to overlap the ²³⁸U line, though it is possible that the two peaks at -0.1 cm⁻¹ and +0.07 cm⁻¹ are due to a different transition.

Spectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 2.

Transition Wavelength in air (nm)	918.6712
Transition Energy (cm ⁻¹)	10882.301
Upper Level Energy (cm ⁻¹)	11502.624
Lower Level Energy (cm ⁻¹)	620.323
Upper Level J	6
Lower Level J	5
gA (10 ⁸ s ⁻¹)	
Isotope Shift (cm ⁻¹)	0.450
Isotope Peak Separation (cm ⁻¹)	0.461

Comments: The partially resolved ²³⁵U hyperfine structure can be seen between -0.35 cm⁻¹ and -0.50 cm⁻¹.

Spectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 3.

Transition Wavelength in air (nm)	909.3661
Transition Energy (cm ⁻¹)	10993.654
Upper Level Energy (cm ⁻¹)	11613.977
Lower Level Energy (cm ⁻¹)	620.323
Upper Level J	5
Lower Level J	5
gA (10 ⁸ s ⁻¹)	0.022
Isotope Shift (cm ⁻¹)	0.170
Isotope Peak Separation (cm ⁻¹)	0.179

Comments:

Spectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 4.

Transition Wavelength in air (nm)	875.7760	
Transition Energy (cm ⁻¹)	11415.309	
Upper Level Energy (cm ⁻¹)	12035.632	
Lower Level Energy (cm ⁻¹)	620.323	
Upper Level J	4	
Lower Level J	5	
gA (10 ⁸ s ⁻¹)	0.041	0.059
Isotope Shift (cm ⁻¹)	0.300	
Isotope Peak Separation (cm ⁻¹)	0.300	

Comments:

Spectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 5.

Transition Wavelength in air (nm)	869.1282	
Transition Energy (cm ⁻¹)	11502.624	
Upper Level Energy (cm ⁻¹)	11502.624	
Lower Level Energy (cm ⁻¹)	0.000	
Upper Level J	6	
Lower Level J	6	
gA (10 ⁸ s ⁻¹)	0.033	0.037
Isotope Shift (cm ⁻¹)	0.450	
Isotope Peak Separation (cm ⁻¹)	0.442	

Comments: Very attractive for isotopically selective excitation because the transition is strong, the ²³⁵U hyperfine structure is largely compressed into a single narrow peak, and the isotopic splitting is large.

Spectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 6.

Transition Wavelength in air (nm)	860.7950	
Transition Energy (cm ⁻¹)	11613.977	
Upper Level Energy (cm ⁻¹)	11613.977	
Lower Level Energy (cm ⁻¹)	0.000	
Upper Level J	5	
Lower Level J	6	
gA (10 ⁸ s ⁻¹)	0.113	0.130
Isotope Shift (cm ⁻¹)	0.170	
Isotope Peak Separation (cm ⁻¹)	0.164	

Comments: Strong transition, fairly good separation between isotopes

Spectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 7.

Transition Wavelength in air (nm)	790.7103
Transition Energy (cm ⁻¹)	12643.378
Upper Level Energy (cm ⁻¹)	12643.378
Lower Level Energy (cm ⁻¹)	0.000
Upper Level J	6
Lower Level J	6
gA (10 ⁸ s ⁻¹)	0.001
Isotope Shift (cm ⁻¹)	-0.265
Isotope Peak Separation (cm ⁻¹)	-0.304

Comments: Partially resolved ²³⁵U hyperfine structureSpectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 8.

Transition Wavelength in air (nm)	778.4159	
Transition Energy (cm ⁻¹)	12843.069	
Upper Level Energy (cm ⁻¹)	13463.392	
Lower Level Energy (cm ⁻¹)	620.323	
Upper Level J	5	
Lower Level J	5	
gA (10 ⁸ s ⁻¹)	0.101	0.031
Isotope Shift (cm ⁻¹)	0.100	
Isotope Peak Separation (cm ⁻¹)	0.112	

Comments: Part of ²³⁵U hyperfine structure overlaps the ²³⁸U line.

Spectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 9.

Transition Wavelength in air (nm)	763.7312
Transition Energy (cm ⁻¹)	13090.008
Upper Level Energy (cm ⁻¹)	13710.331
Lower Level Energy (cm ⁻¹)	620.323
Upper Level J	4
Lower Level J	5
gA (10 ⁸ s ⁻¹)	0.0002
Isotope Shift (cm ⁻¹)	-0.310
Isotope Peak Separation (cm ⁻¹)	-0.180

Comments: A very weak line

Spectra of 93% ²³⁵U and 7% ²³⁸U

Transition Wavelength in air (nm)	757.0761
Transition Energy (cm ⁻¹)	13205.077
Upper Level Energy (cm ⁻¹)	13825.400
Lower Level Energy (cm ⁻¹)	620.323
Upper Level J	4
Lower Level J	5
gA (10 ⁸ s ⁻¹)	0.003
Isotope Shift (cm ⁻¹)	-0.11*
Isotope Peak Separation (cm ⁻¹)	-0.124

Comments: * Estimated by scaling the ²³⁴U-²³⁸U isotope shift reported in Ref. 4.

Spectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 11.

Transition Wavelength in air (nm)	742.5503	
Transition Energy (cm ⁻¹)	13463.392	
Upper Level Energy (cm ⁻¹)	13463.392	
Lower Level Energy (cm ⁻¹)	0.000	
Upper Level J	5	
Lower Level J	6	
gA (10 ⁸ s ⁻¹)	0.034	0.050
Isotope Shift (cm ⁻¹)	0.100	
Isotope Peak Separation (cm ⁻¹)	0.075	

Comments: ²³⁸U is barely resolved from ²³⁵U

Spectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 12.

Transition Wavelength in air (nm)	712.8900	
Transition Energy (cm ⁻¹)	14023.544	
Upper Level Energy (cm ⁻¹)	14643.867	
Lower Level Energy (cm ⁻¹)	620.323	
Upper Level J	6	
Lower Level J	5	
gA (10 ⁸ s ⁻¹)	0.066	0.088
Isotope Shift (cm ⁻¹)	-0.380	
Isotope Peak Separation (cm ⁻¹)	-0.355	

Comments: The peak at 0.48 cm⁻¹ is part of the ²³⁵U hyperfine that is resolved to the baseline.

Spectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 13.

Transition Wavelength in air (nm)	703.0700	
Transition Energy (cm ⁻¹)	14219.413	
Upper Level Energy (cm ⁻¹)	14839.736	
Lower Level Energy (cm ⁻¹)	620.323	
Upper Level J	5	
Lower Level J	5	
gA (10 ⁸ s ⁻¹)	0.009	0.016
Isotope Shift (cm ⁻¹)	-0.380	
Isotope Peak Separation (cm ⁻¹)	-0.321	

Comments: The peak at 0.9 cm⁻¹ is probably an interfering line and not part of the ²³⁵U hyperfine structure.

Spectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 14.

Transition Wavelength in air (nm)	682.6913	
Transition Energy (cm ⁻¹)	14643.867	
Upper Level Energy (cm ⁻¹)	14643.867	
Lower Level Energy (cm ⁻¹)	0.000	
Upper Level J	6	
Lower Level J	6	
gA (10 ⁸ s ⁻¹)	0.223	0.170
Isotope Shift (cm ⁻¹)	-0.380	
Isotope Peak Separation (cm ⁻¹)	-0.370	

Comments: Very strong transition with good separation between the ²³⁸U and ²³⁵U.

Spectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 15.

Transition Wavelength in air (nm)	673.6805	
Transition Energy (cm ⁻¹)	14839.736	
Upper Level Energy (cm ⁻¹)	14839.736	
Lower Level Energy (cm ⁻¹)	0.000	
Upper Level J	5	
Lower Level J	6	
gA (10 ⁸ s ⁻¹)	0.010	0.017
Isotope Shift (cm ⁻¹)	-0.380	
Isotope Peak Separation (cm ⁻¹)	-0.428	

Comments:

Spectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 16.

Transition Wavelength in air (nm)	672.8167
Transition Energy (cm ⁻¹)	14858.786
Upper Level Energy (cm ⁻¹)	14858.786
Lower Level Energy (cm ⁻¹)	0.000
Upper Level J	7
Lower Level J	6
gA (10 ⁸ s ⁻¹)	0.001
Isotope Shift (cm ⁻¹)	
Isotope Peak Separation (cm ⁻¹)	-0.313

Comments: Peak at 0.6 cm⁻¹ is identified in the U Atlas as the 20621-5762 line.

Spectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 17.

Transition Wavelength in air (nm)	665.6819	
Transition Energy (cm ⁻¹)	15018.044	
Upper Level Energy (cm ⁻¹)	15638.367	
Lower Level Energy (cm ⁻¹)	620.323	
Upper Level J	6	
Lower Level J	5	
gA (10 ⁸ s ⁻¹)	0.010	0.012
Isotope Shift (cm ⁻¹)	0.190	
Isotope Peak Separation (cm ⁻¹)	0.170	

Comments: The peak at +0.12 cm⁻¹ is probably an interference and not due to ²³⁵U for this transition.

Spectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 18.

Transition Wavelength in air (nm)	662.0531	
Transition Energy (cm ⁻¹)	15100.359	
Upper Level Energy (cm ⁻¹)	15720.682	
Lower Level Energy (cm ⁻¹)	620.323	
Upper Level J	5	
Lower Level J	5	
gA (10 ⁸ s ⁻¹)	0.031	0.037
Isotope Shift (cm ⁻¹)	-0.210	
Isotope Peak Separation (cm ⁻¹)	-0.208	

Comments:

Spectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 19.

Transition Wavelength in air (nm)	644.9161	
Transition Energy (cm ⁻¹)	15501.610	
Upper Level Energy (cm ⁻¹)	16121.933	
Lower Level Energy (cm ⁻¹)	620.323	
Upper Level J	4	
Lower Level J	5	
gA (10 ⁸ s ⁻¹)	0.234	0.160
Isotope Shift (cm ⁻¹)	-0.155	
Isotope Peak Separation (cm ⁻¹)	-0.178	

Comments: ²³⁸U is not resolved from low frequency tail of the ²³⁵U hyperfine structure.

Spectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 20.

Transition Wavelength in air (nm)	641.8756
Transition Energy (cm ⁻¹)	15575.037
Upper Level Energy (cm ⁻¹)	16195.360
Lower Level Energy (cm ⁻¹)	620.323
Upper Level J	6
Lower Level J	5
gA (10 ⁸ s ⁻¹)	< 0.0003
Isotope Shift (cm ⁻¹)	-0.325
Isotope Peak Separation (cm ⁻¹)	-0.301

Comments: Very weak line with many interferences

Spectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 21.

Transition Wavelength in air (nm)	639.5426	
Transition Energy (cm ⁻¹)	15631.855	
Upper Level Energy (cm ⁻¹)	15631.855	
Lower Level Energy (cm ⁻¹)	0.000	
Upper Level J	7	
Lower Level J	6	
gA (10 ⁸ s ⁻¹)	0.131	0.110
Isotope Shift (cm ⁻¹)	0.300	
Isotope Peak Separation (cm ⁻¹)	0.297	

Comments: Strong transition that would be good for isotopically selective excitation

Spectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 22.

Transition Wavelength in air (nm)	639.2762	
Transition Energy (cm ⁻¹)	15638.367	
Upper Level Energy (cm ⁻¹)	15638.367	
Lower Level Energy (cm ⁻¹)	0.000	
Upper Level J	6	
Lower Level J	6	
gA (10 ⁸ s ⁻¹)	0.039	0.035
Isotope Shift (cm ⁻¹)	0.190	
Isotope Peak Separation (cm ⁻¹)	0.168	

Comments:

Spectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 23.

Transition Wavelength in air (nm)	637.8354
Transition Energy (cm ⁻¹)	15673.694
Upper Level Energy (cm ⁻¹)	16294.017
Lower Level Energy (cm ⁻¹)	620.323
Upper Level J	5
Lower Level J	5
gA (10 ⁸ s ⁻¹)	0.006
Isotope Shift (cm ⁻¹)	0.360
Isotope Peak Separation (cm ⁻¹)	0.344

Comments:

Spectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 24.

Transition Wavelength in air (nm)	635.9289	
Transition Energy (cm ⁻¹)	15720.682	
Upper Level Energy (cm ⁻¹)	15720.682	
Lower Level Energy (cm ⁻¹)	0.000	
Upper Level J	5	
Lower Level J	6	
gA (10 ⁸ s ⁻¹)	0.036	0.036
Isotope Shift (cm ⁻¹)	-0.210	
Isotope Peak Separation (cm ⁻¹)	-0.243	

Comments:

Spectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 25.

Transition Wavelength in air (nm)	629.3329	
Transition Energy (cm ⁻¹)	15885.450	
Upper Level Energy (cm ⁻¹)	16505.773	
Lower Level Energy (cm ⁻¹)	620.323	
Upper Level J	6	
Lower Level J	5	
gA (10 ⁸ s ⁻¹)	0.038	0.030
Isotope Shift (cm ⁻¹)	0.190	
Isotope Peak Separation (cm ⁻¹)	0.184	

Comments:

Spectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 26.

Transition Wavelength in air (nm)	617.2900
Transition Energy (cm ⁻¹)	16195.360
Upper Level Energy (cm ⁻¹)	16195.360
Lower Level Energy (cm ⁻¹)	0.000
Upper Level J	6
Lower Level J	6
gA (10 ⁸ s ⁻¹)	0.011
Isotope Shift (cm ⁻¹)	-0.325
Isotope Peak Separation (cm ⁻¹)	-0.324

Comments:

Spectra of 93% ²³⁵U and 7% ²³⁸U

Transition Wavelength in air (nm)	613.5524
Transition Energy (cm ⁻¹)	16294.017
Upper Level Energy (cm ⁻¹)	16294.017
Lower Level Energy (cm ⁻¹)	0.000
Upper Level J	5
Lower Level J	6
gA (10 ⁸ s ⁻¹)	<0.0002
Isotope Shift (cm ⁻¹)	0.360
Isotope Peak Separation (cm ⁻¹)	0.221

Comments: The disagreement between predicted and observed ²³⁸U frequencies (+0.03 cm⁻¹) is ten times the estimated frequency error. This very weak transition is the only one in Table I for which the disagreement exceeds the estimated errors.

Spectra of 93% ²³⁵U and 7% ²³⁸U

Spectroscopic Information on U I Transition

Data Sheet 28.

Transition Wavelength in air (nm)	605.6810	
Transition Energy (cm ⁻¹)	16505.773	
Upper Level Energy (cm ⁻¹)	16505.773	
Lower Level Energy (cm ⁻¹)	0.000	
Upper Level J	6	
Lower Level J	6	
gA (10 ⁸ s ⁻¹)	0.025	0.023
Isotope Shift (cm ⁻¹)	0.190	
Isotope Peak Separation (cm ⁻¹)	0.179	

Comments:

Spectra of 93% ²³⁵U and 7% ²³⁸U

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