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Study on Energy-Level Radiation Parameters of Tin Atom, Molybdenum Atom and Molybdenum Monovalention

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This paper aims at analyzing energy level radiation parameters of tin atom, molybdenum atom and molybdenum monovalent ion. With this research purpose, it measures tin atom branching ratio and the energy level radiation parameters of tin atom, molybdenum atom and molybdenum monovalent ion with TR-LIF technology. The research result shows that the life spans of the two energy levels 31654.79 and 40488.28 cm−1of molybdenum atom are respectively 21.4and 15.9 ns, which is closed to those measured by Whaling et al., therefore, the result is reliable.

1. Introduction

With the rapid development of laser technology and plasma technology, the measurement and analysis of the elemental natural radiation parameter have also made great progress. Photon ion beam technology, ion source time-resolved laser-induced fluorescence spectroscopy and other technologies have been widely used in the measurement of atomic and ion life span.

This experiment mainly measures tin atom branching ratio and the energy level radiation parameters of tin atom, molybdenum atom and molybdenum monovalent ion with TR-LIF technology, and compares the research result with that measured by Whaling et al.

2. Literature review

Astrophysics is a discipline that applies physics techniques and theories to study the surface physical state, internal structure and chemical composition of celestial bodies, the relationship between celestial bodies, and the origin and evolution of the universe. Astrophysical research requires a large number of accurate and sufficient atomic and molecular spectral data as basic support conditions. As of now, the main way for humans to obtain astronomical knowledge such as the origin of the universe, the formation of galaxies, and the physical state of stars or nebulae is spectroscopic observations (Brown et al., 2014). Through ground-based or space astronomical telescopes, the celestial body's electromagnetic radiation and its interaction with atoms and ions are observed. Then, the obtained celestial body spectral information is compared with the existing atomic ion spectrum data to determine the chemical composition and abundance contained in the celestial body. A detailed study of elemental abundance will yield astronomical parameters such as the formation mechanism of stars, surface conditions, atmospheric models, and age and astrophysics. Therefore, the accuracy and adequacy of the atomic and molecular spectral data will directly influence the accuracy of the astronomical state determined by the celestial spectrum analysis (Jiang et al., 2015).

In these spectral data, the radiation parameters such as natural radiation lifetime, branching ratio, transition probability, and oscillator strength of atoms and ions are particularly important for the analysis of celestial bodies. In astrophysics, only the spectral line intensity determined by the combined lifetime lifetime and branch ratio can be directly used for quantitative analysis of element abundance. The relative physical state of the medium in the celestial body is determined by studying the intensity of radiation transitions of the higher abundance elements. To study spectral line intensity, photoionization cross-section, collisional excitation, ionization rate, and precise atomic ion natural radiation parameters are required (Uppuluri et al., 2018). In addition, elemental abundance, kinematic parameters of celestial bodies, and age information are the most

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powerful probes for the study of galaxy evolution. Thus, the study of the abundance and evolution of chemical elements in celestial bodies is closely related to the resolution of many major problems in astrophysics. Therefore, researchers in related fields have always attached great importance to this research.

The nucleosynthsis is often used to describe the formation of various chemical elements during the evolution of celestial bodies. It refers to the process of nuclear formation of various nuclide, including the capture process of slow neutrons, fast neutrons and protons. They are represented as s, r, and p processes, respectively. Different synthesis processes will form chemical elements of different abundances, so the mechanism of nuclear synthesis can be determined by studying element abundance. In recent years, it has been found that the abundance and nucleosynthesis of heavier elements in extremely poor metal stars in galactichalo contribute to the accurate determination of the age of celestial bodies (Jung et al., 2018). In addition, the research on the formation of heavy elements in the galaxy is whether the r process or the s process is related to the accuracy of the galactic age calculation. This has also become an important issue in stellar nucleosynthesis studies (Fu et al., 2016). Recent studies have shown that the formation of lead elements in low-metal stars is dominated by the s process. However, the validation of the nucleosynthesis mechanism of many elements of the sixth cycle of stars is still unresolved. This requires a large number of precise atomic ion radiance transitions for these elements to ensure accurate element abundance values in astronomical spectral analysis. The study of the radiation parameters of the fifth cycle element ($38<Z<53$) is also of great significance for studying the chemical composition and evolution of celestial bodies such as hot stars and chemically specific stars (CP stars). However, the experimental radiation characteristics of atomic ions such as YIII, MoII, SnII, and SbI of some elements are basically left blank. In addition, iron peak elements ($21<Z<28$) have always been valued by people because of their high cosmic abundance. Therefore, neutral and once ionized iron peak elemental ions in recent years have been studied in depth through the well-known IRON and FERRUM international cooperation projects. However, their radiation characteristics are still very scarce, and some of the existing data are less reliable (He et al., 2016).

Before the laser was developed, the celestial body spectral analysis mainly used the radiation parameters of the various atom and ion levels in the monograph published by Corliss and Bozman of the National Bureau of Standards (NBS). Later, it was found that the inaccuracy of the data in this monograph was one of the main reasons for the large error in the results of astronomical spectrum analysis.

With the rapid development of laser technology, plasma technology, and detection technology, the measuring technology of elemental natural radiation parameters has also been continuously improved. At present, several methods for accurately measuring the life of atoms and ions at the international level include laser ion beam technology, time-resolved laser-induced fluorescence spectroscopy for the excitation of free atoms and ion sources by hollow cathode discharge, and laser ablation to generate plasma time-resolved laser-induced fluorescence decay technology. The branching ratio is usually measured by measuring the emission spectrum of the element and analyzing it (Malcheva et al., 2015). Due to the precision of the calibration of the detection system and the accurate measurement of the spectral line strength, the available branching ratios are less. In the past, the spectral intensity of most elements was determined by using the Hook method to obtain relative values. Combined with the multi-channel delay at the time of the measurement, the life of the device was converted to an absolute scale and the accuracy was not high. Nowadays, the strength of the oscillator is mostly derived from the combination of the lifetime and the branch ratio (Marconi and Oliva, 2016). Because of the continuous development of measurement technology, the accuracy of the result is also improved.

In summary, large-scale astronomical optical telescopes, large-scale astronomical radio telescopes, and space astronomical exploration equipment have been put into use since the 1990s. Large astronomical optical telescopes include Keck of the United States, the Aungsa Cluster of Japan, and the Columbus Telescope of the US-Italy. The large-scale astronomical radio telescope includes the United States millimeter-wave array telescope MMA, the British microwave interferometer MERLIN, and the Indian giant Mipo radio telescope array GMRT. Space astronomical exploration equipment includes the Hubble Space Telescope HST, the Galileo Jupiter, the Cassini Saturn, the Space Infrared SIRTF, the Solar Peak Year Observation Satellite SMM, and the Far Ultraviolet Spectroscopy Satellite FUSE as well as China’s large-area area multi-objective fiber-optic spectroscopic telescope LAMOST and the solar space telescope SST. This shows that the human astronomical observation technology is constantly developing. The band range and resolution of celestial bodies are also constantly expanding and improving. It will become easier to obtain a large number of high-resolution astronomical spectral data. The research group of the National Astronomical Observatory of the Chinese Academy of Sciences on the abundance of celestial bodies and the chemical evolution of galaxies has conducted systematic and in-depth research work in the field of celestial chemical element abundance. Stellar spectral analysis and globular cluster study are the two key research topics of the research group. It can be foreseen that the research of many new fields such as the evolution and nuclear synthesis of newly discovered cosmic objects will inevitably increase the demand for basic atomic physics data.

3. The experimental method

The experimental method applied to measure the life span is the time-resolved laser spectroscopy. First of all, we used the laser pulse whose pulse width was shorter than the measured lifetime to excite the interested energy level and realized the population of particles in the excited state of energy level. Secondly, the fluorescence generated by spontaneous emission was separated by monochromator or optical filter, and the fluorescent signal was detected by a photomultiplier tube (PMT), then, the signal was transmitted to an oscilloscope for display and recording. Finally, the natural radiation life span of the energy level could be calculated by the fitting procedure.

The branching ratio of the line spectrum is usually measured by the hollow cathode discharge method which enables the atom transferring to the excited state. The existence of transition spectral line is confirmed, and the spectrum signal was collected through observing the transition path of the energy level to all possible lower energy levels. Then, the strength of spectral line to be measured was obtained by Gaussian fitting of transitional signal, and the spectral response curves of different wavelengths in the measurement system is used to correct the measured value. Finally, the branching ratio of all spectral lines could be figured out.

Experimental instruments are Nd: YAG laser, dye laser, digital retarder, mechanical pump, molecular pump, BBO frequency doubling crystal, phase retarder, stimulated Brillouin scattering pulse compression system, grating monochromator, photomultiplier tube, Cathode lamp, microchannel plate photomultiplier tube.

4. The result and analysis of the experiment

4.1 The energy-level radiation experiment of Tin atom

We used argon-filled tin hollow cathode lamp as light source (Figure 1). The lamp should be preheated for 30 minutes at standard operating currents to stabilize its operation. After the fluorescence radiated by cathode lamp was split by grating monochromator with the focal length of 0.5 m, the photomultiplier tube was employed to detect signals. The Grating Monochromator has three gratings at 2400, 1800 and 600 g / cm with operating ranges of 250-450nm, 350-850nm and 660-900nm, respectively. Spectra Sense software enables the selection of different gratings and the adjustment of the scanning wavelength range. NCL spectral data acquisition device was used to convert the electrical signal detected by photomultiplier tubes with the response range of 185-900 nm through A / D and then transmit it to the computer. At last, Spectra Sense software was applied to analyze the transition signals and record the data.

Figure 1 : A hollow cathode lamp brand

Before the experimental measurement, the wavelength of spectral line produced by energy level transition of tin atom and monovalent ions to a lower energy level that meets the transition selection criteria should be calculated to ensure that the measured spectral line wasn't overlapped with transition spectral line of other energy levels. During the experiment, the spectral resolution of the grating monochromator is 0.03 nm when its entrance and exit slit were adjusted to 10μm. Each transition line is measured at three different operating currents of 8, 9 and 10 mA to detect the possible self-priming effect of the light source. However, no obvious self-priming effect was observed, which meant the effect could be ignored. If the experimental measuring time is too long, photomultiplier tubes and other measuring instruments will have small changes in the working state, which would result in the changes in spectral line position and strength, thus leading to errors in the experimental result. Therefore, the presence of spectral lines should be firstly confirmed based on the line of argon atoms and their ions. If present, the wavelength range of the spectral scan could be figured out. After all the transition lines at this level have been validated, they should be scanned intensively. In this way, the strength measurement of each transition line at the same energy level could be completed in a shorter time, thereby reducing the measurement error. The transition spectral lines at each energy level measured four sets of spectral data, with the average value as the final branching ratio result.

To verify the reliability of experimental system, we firstly measured transition branching ratio of ArII4d4P5/2 energy levels. The data resulted from it were compared with those of Whaling et al. as shown in Table 1. By comparison, it was revealed that the system was reliable as the two results were identical.

Table 1: Transition branching ratio of ArII4d4P5/2 energy levels

Wavelength (nm)	Branching fractions This work	Previous
313.9035	0.2154(103)	0.2146
316.9686	0.1911(85)	0.1871
342.1639	0.0272(14)	0.0231
386.8548	0.5662(229)	0.5695

In the process of measuring branch ratio, the grating shift called for confirming the strong line of argon atom and its ions in the vicinity of the transition wavelength to be measured. In specific, the spectral line of two or more argon atoms or ions was applied to make sure the grating shift amount which was used to correct the wavelength of spectral line, thus obtaining wavelength value in the spectrum. In addition, the spectral line should be distinguished with care as the atomic and ion level of argon may be overlapped with the lines of tin atoms. As to the data of spectral line, we used Origin 7.5 software to perform the Gaussian fitting. The peak value of the fitting curve is taken as the strength value of this spectral line, and the typical spectral line and fitting curve were shown in Figure 2.

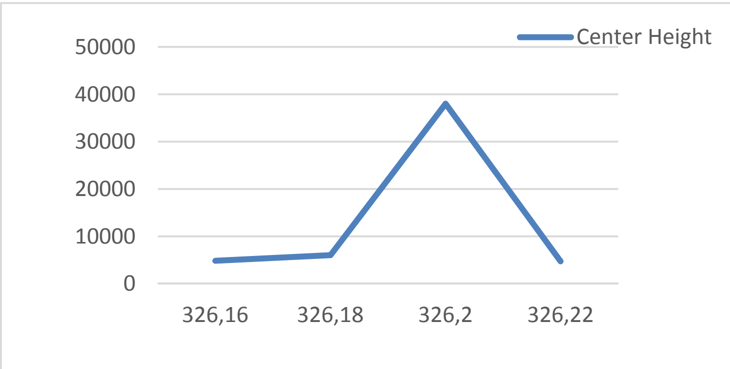

Figure 2: Gao Si fitting diagram of tin atomic level transition spectral line

4.2 The Experiment on the radiation parameters of molybdenum atoms and monovalent ions

Laser induced plasma was used to obtain free atoms of molybdenum. Since molybdenum is refractory metal, the energy ablating laser should be tuned to a higher strength and focused on the target with a lens until better plasma mass appears. The excitation light is provided by an Nd: YAG laser, a pumped dye laser with an output wavelength of 532 nm and, the dye is DCM. The pulse output by the dye laser was tripled by a system consisting of two BBO crystals and a phase retarder and is then incident horizontally to react with the molybdenum plasma at a distance of 5-8 mm above the molybdenum target in the vacuum system. Finally, the excitation of molybdenum atoms from the ground state to the energy level to be measured was realized by the selection of wavelength. To verify the reliability of experimental results, we measured branching ratio of ArII4d4P5/2 energy levels. The data resulted from it were compared with those of Whaling et al.. As shown in Table 2, it was revealed that the system was reliable as the two results were identical.

Table 2: The branching ratio of ArII4d4P5/2 level and its comparison with the results of others

Wavelength (nm)	Branching fractions This work	Previous
313.9035	0.210(9)	0.215(6)
316.9686	0.173(7)	0.187(4)
342.1629	0.024(1)	0.029(2)
386.8548	0.593(24)	0.570

From Table 1 and 2, we can see that the life span of the two energy levels of molybdenum atoms 31654.79 and 40488.28 cm^{-1} were respectively 21.4 and 15.9 ns while those of Whaling et al. were 21.5 and 15.0 ns. The difference is only 0.5% and 6% with the latter as the basis, which showed the two sets of results are in consensus.

4.3 The measurement of the life span and radiation parameters of Molybdenum monovalent ion energy level

(1) The experimental principle

The source of molybdenum ion was obtained by laser ablation of a 2-3 mm thick molybdenum target. The pulse width of the laser used in the life span measurement was about 8 ns. Yet, the lifetimes of the measured MoII energy levels are all less than 8 ns, so the width of excited pulse was compressed by SBS pulse compression system with water as its liquid medium. The specific compression device had been introduced earlier. The width would become 1.5−2 ns after being compressed, thus meeting the measuring requirements. The compressed pulse is used to pump the dye laser with DCM as the dye's output light in the wavelength range of 605-658 nm. The output pulse of the dye laser passes through the triplet frequency of the system consisting of two BBO crystals and a phase retarder (see Fig. 3), and is incident to the plasma at 5-8 mm above the molybdenum target in the vacuum system horizontally. The choice of wavelength enabled the excitation of molybdenum ions from the ground state to the energy level to be measured.

Figure 3: Dye laser

(2) The measurement of life span and its result

When measuring the life span, the monochromator was used to change the observed wavelength to confirm whether the signal belonged to the energy level to be measured. Then the fluorescence attenuation signal was detected by selecting the channel with strong fluorescence signal and less interference from scattering. The impact of possible effects such as saturation, impact and field-of-view cancellation on the measurement results are eliminated by changing the monochromator slit width, the strength of the excitation and etching light, and the delay between the excitation pulse and the etching pulse.

A pair of Helmholtz coils are applied in both sides of the vacuum system to produce a magnetic field to eliminate the effect of quantum beat and composite backlight.

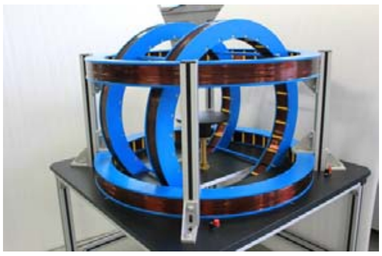

Figure 4: Helmholtz coil

When collecting the signal, the average value of fluorescence excited over 1000 times was taken as experimental signal to gain attenuation curve with a higher Signal to Noise Ratio (SNR). As the measured life span is all less than 8 ns, deconvolution fitting was adapted to measure it.

Migdalek et al. proposed the concept of real polarization potential and mentioned that the calculating equation of spectral line strength from γJ state to $\gamma' J'$ state is as follows:

$$S = \left| \gamma J \right\| r \left[1 - \frac{\alpha_d}{\left(r^2 + r_c^2 \right)^{\frac{3}{2}}} \right] \left\| \gamma' J' \right|^2$$

where αd is ion dipole polarization and rc is cutoff radius. With the HFR method, the energy level and the wave function can be obtained by iterative calculation. According to the above equation, the line strength S can be obtained. Cowan proposed transition probability A and oscillator strength f and line strength have the following relationship:

$$gA = 2.0261 * 10^{-6} \sigma^3 S$$
$$gf = 3.0376 * 10^{-6} \sigma S$$

Therefore, the branching ratio can be gained through A:

$$BR_{ji} = \frac{A_{ji}}{\left[\sum_i A_{ji} \right]}$$

The MoII life span calculated from this method had consensus in that of the experiment, indicating the result calculated by the theoretical calculation model is relatively reliable.

5. Conclusion

This experiment measures the life span of the energy level of tin atom, molybdenum atom and molybdenum monovalent ion.

The life span of the two energy levels 31654.79 and 40488.28 cm−1 of tin atom and molybdenum atom are respectively 21.4 and 15.9 ns. The experimental result is almost identical with that of Whaling et al., which discloses the result is relatively reliable. The result enables a further understanding of the celestial evolution law and nucleosynthesis.

At present, China still doesn't possess a theory to independently measure radiation parameter of tin atom and molybdenum atom, and the analysis as well as calculation of atomic structure and radiation parameters still have a long process to be developed.

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