S. L. Mandel'shtam and É. Ya. Kononov. Spectroscopy of Highly Ionized Atoms. One of the highest-priority trends in modern atomic spectroscopy is the spectroscopy of highly ionized atoms—atoms that have been deprived of a significant part of their electron shell. This trend, which was brought into being basically by modern astrophysics, is also highly important for the physics of the hot plasma, and, as it has turned out, is also of purely spectroscopic interest.

Classical (optical) astrophysics, which used the "optical window" of the earth's atmosphere at 10000-3000 Å for its observations, was satisfied with the spectra of neutral, singly ionized, and only rarely doubly ionized atoms, whose principal information-bearing lines lie in this region of the spectrum.

Study of the shortwave parts of the spectra of celestial bodies, primarily of the sun, which had hitherto been inaccessible due to absorption by the earth's atmosphere, began as soon as it became possible to lift instruments beyond the atmosphere on space rockets.

It was established in the very first experiments that the spectrum of the corona of the quiet sun extends all the way down to a few angstroms and consists of a continuous background and a line spectrum in which lines of the hydrogen- and helium-like ions of C, N, and O and other highly ionized ions corresponding to temperatures of $(2\text{-}4) \times 10^{6\circ}$K are represented.

Lines of the hydrogen- and helium-like ions of Fe, which correspond to $T_e \approx 4 \times 10^{7\circ}$K, were observed in the spectra of solar x-ray flares on the sun[1].

Soviet, American, and British studies of this type established that about 30% of the lines in the sun's shortwave spectrum (including the ultraviolet) cannot be identified owing to the inadequacy of laboratory data on the spectra of highly ionized atoms.

The above examples indicate how important the spectra of highly ionized atoms are in modern astrophysics. The problem is not, of course, confined to the sun. Galactic and extragalactic x-ray astronomy is beginning to develop. About a hundred discrete x-ray sources of galactic and extragalactic nature with temperatures of $10^7\text{-}10^{8\circ}$K have been observed during the past few years. Their emission is very faint and their spectra have not yet been obtained, but it appears that this will be possible in the near future. Thus, the era of "hot" and "superhot" astrophysics has opened, and spectroscopists must be ready for it. Similar demands are made of spectroscopy by the physics of "hot" and "superhot" laboratory plasmas.

What do we know of the spectra of highly ionized atoms today? The heavier elements have been studied much less thoroughly than the spectra of elements that present astrophysical interest. As a rule, we have only the spectra of the ions II-IV in very incomplete form for the very heavy elements. The electron temperature needed for observation of the emission lines of ions whose ionization potentials lie in the ranges ≤ 500, ≤ 1000, and ≤ 6500 eV are $T_e \approx 1 \times 10^6$, $\approx 2.5 \times 10^6$, and $\approx 20 \times 10^{6\circ}$K, respectively (Fig. 1).

Thus, study of the spectra of highly ionized atoms requires sources with $T_e \approx 10^6\text{-}10^{7\circ}$K to excite the spectra. For the most part, we use two types of sources: the vacuum spark and the laser spark.

The vacuum spark is the "classical" excitation source in the spectroscopy of highly ionized atoms. We use the vacuum spark with a very low total circuit inductance[2]. The electron temperature of the spark apparently reaches 20 million to 40 million degrees, and its electron density $10^{18}\text{-}10^{20}$ cm^{-3}. Using this spark, we have succeeded in obtaining a laboratory spectrum that reproduces the spectrum of a solar flare in the region of the Fe XXV (Fig. 2) and Fe XXIV (Fig. 3) resonance lines.

The laser spark formed on a target in a vacuum must be regarded as one of the most successful

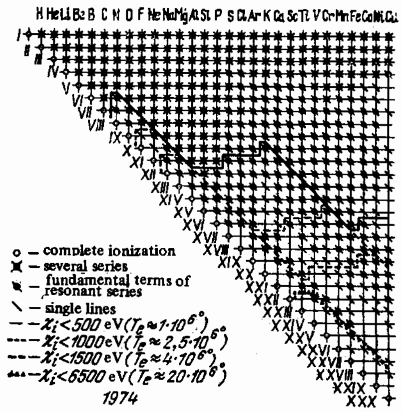

FIG. 1. State of study of the spectra of ions of elements that are of astrophysical importance. The vertical lines represent the elements and the horizontal lines the multiplicities of ionization.

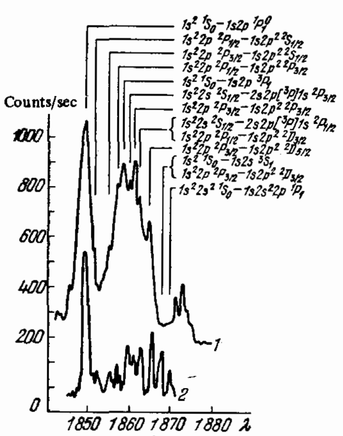

FIG. 2. Spectra of ion in the neighborhood of the FeXXV resonance line. 1—densitogram of laboratory spectrum; 2—x-ray flare on sun (16 November 1970, 01^h01^mUT; Interkosmos 4 satellite). The ordinate scale pertains to the curve (λ is in units of 10^{-3} Å).

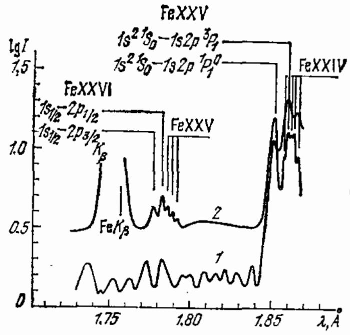

FIG. 3

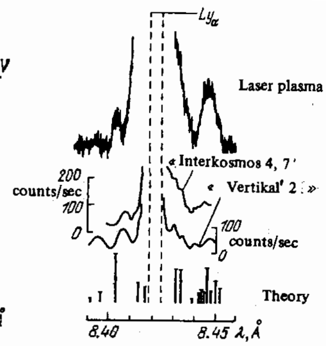

FIG. 4

FIG. 3. The spectral range from 1.73 to 1.87 Å. 1—solar flare (same conditions as in Fig. 2); 2—laboratory spectrum of iron (low-induction vacuum discharge).

FIG. 4. Comparison of spectra of solar flares with spectrum of laser plasma and with theory in the region of the MgXII resonance line.

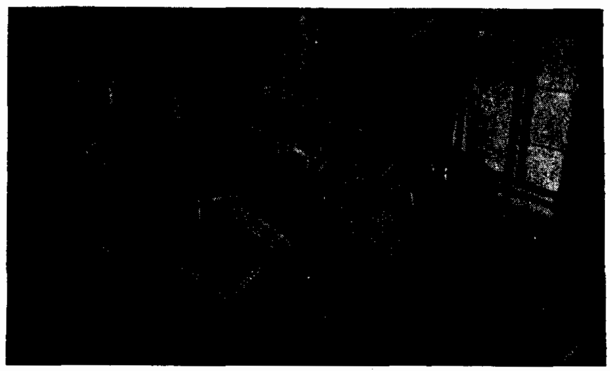

FIG. 5. High-resolution vacuum-ultraviolet spectrograph built at the USSR Academy of Sciences Institute of Spectroscopy (ISAN).

spectrum-exciting sources for our purposes. In our joint studies with the Academy of Sciences Physics Institute (FIAN), we use laser installations with radiated energies of 10 to 100 J and light-pulse durations from 15 to 1-2 nsec at half-height[3]. To give one example, Figure 4 shows the solar and laboratory spectra in the region of the resonance line of hydrogen-like magnesium, Mg XII. The temperature at the core of the laser spark has now been raised to about 10^7°K. Special instruments are required for observation of the spectra of the highly ionized atoms. First of all, spectral coverage has been broadened greatly. We now make observations down to 1 Å; it must be stressed that these are optical spectra governed by outer electrons and not the traditional, so-called characteristic x-ray spectra which correspond to inner electrons.

The instruments must also have large dispersions. If it is desired to hold the relative error of determination of the term energies $\Delta\nu/\nu$ at a sufficiently low level, it is necessary, in view of the relation $\Delta\nu/\nu = \Delta\lambda/\lambda$, to measure $\Delta\lambda$ with increasing accuracy as λ becomes smaller.

Figure 5 shows a one-of-a-kind vacuum spectrograph for the 400-2500 Å range with a focal length of about 7 m built at the ISAN.

Let us discuss certain spectroscopie features in the spectra of highly ionized atoms. Figure 2 presents the region of the ordinary lines of the helium-like spectrum of iron, showing the $^1S_0$-$^1P_1$ resonance line and the $^1S_0$-$^3P_1$ intercombination line. The $^1S_0$-$^3P_2$ line is also observed on the sun (it does not appear in the laboratory spectrum). It is a magnetic-dipole line; this is apparently the first such observation. Together with these lines, we see many others that have come to be known as satellite lines. They are also seen near the resonance lines of hydrogen-like ions. These lines appear due to the presence of two excited electrons on the preceding ion. The satellites in the spectra of helium-like ions are governed by transitions from the 1s2s2p, $1s2p^2$, and $1s2l3l'$ levels in the lithium-like ions, and the satellites in the spectra of the hydrogen-like ions result from transitions from the 2s2p, $2p^2$, 2p3d, etc., levels in the helium-like ions. Thus, a transition corresponding to satellite lines, e.g., 2s2p → 1s2s, in a helium-like ion in the presence of an additional excited 2s electron, etc. Why are these satellite lines not observed in the spectra of neutral atoms and first ions? The upper levels of the satellite lines lie above the ionization limit of the corresponding ions and are autoionization levels. Here the probability of autoionization-type, nonradiative decays is very high and depends weakly on the charge Z of the nucleus: $\Gamma_a = \Gamma_0 + (a/Z)$. . . The probability of radiative transitions producing satellite lines is very low, but it increases rapidly with Z: $A_p = A_0 Z^4[1 + (b/Z) + \ldots]$ and $A_p \approx \Gamma_a$ at $Z \approx 10$. As Z increases, therefore, the probability of radiative decays of levels quickly exceeds the probability of autoionization-type, nonradiative decays.

An important feature of a number of satellite lines is the mechanism by which their upper levels are populated. Here the basic factor is dielectronic recombination—capture of an electron with simultaneous excitation of a second electron, for example $1s^2 + e \rightarrow 1s2pnl \rightarrow 1s^2 2p + h\nu$. This mechanism, which was predicted theoretically for the solar corona, also plays a major role in the laboratory plasma. It explains, for example, the excitation of the strongest satellite line of Fe XXIV at $\lambda = 1.866$ Å.

The possibility of observing satellite lines simultaneously with resonance lines is explained as follows: a plasma of highly ionized atoms with $Z \gtrsim 10$ is described even at very large N_e ($\leq 10^{22}$ cm^{-3}) by the so-called corona model—excitation of the resonance level is determined by electron impact, but its decay is governed not by the reverse process (second-order impact with electrons), but by radiative decay ($\langle \sigma v \rangle \sim 1/Z^3$, $A \approx Z^4$, i.e., at large Z, $\langle \sigma v \rangle N_e \ll A$). Hence the population of the resonance level is significantly lower than the Boltzmann population. The population of the autoionization levels, on the other hand, is determined by the rate of autoionization and by the reverse process—electron capture—and is therefore Boltzmannian. In the corona model of the plasma, therefore, the intensity ratio J_{sat}/J_{res} is considerably larger than in the case of the thermal model. The intensities of certain satellite lines, in both the solar and laboratory-plasma spectra, become comparable with the intensities of the resonance lines. On the other hand, there are very many satellite lines: thus, for example, calculations indicate about 500 satellite lines in the region of the helium-like iron line from approximately 1.85 to 1.95 Å, i.e., on $\Delta\lambda \approx 0.1$ Å. Needless to say, we cannot resolve them because of the Doppler broadening. This is an essentially new type of spectrum—a quasicontinuous spectrum. Similar satellites are observed in the spectrum of Mg XII (see Fig. 4) and in other spectra.

We offer a brief concluding remark on theoretical calculations of the spectra of highly ionized atoms.

Theoretical assistance is needed acutely in analysis of such spectra: without a reliable method of calculating the wavelengths of the lines, it is impossible to identify the lines correctly. This trend is being developed broadly at the ISAN. A feature of these calculations is their use of a series expansion of the energy in powers of Z[4]:

$$E = -E_0 Z^2 + E_1 Z^1 + E_2 Z^0 + E_3 \frac{1}{Z} + \ldots$$

The Feynman diagram technique is used in calculating the terms of these series. For $Z \leq 30$, the relativistic energy of the electrons is a small correction to the total energy and can be treated as a perturbation. It will evidently be more advantageous to use Dirac functions as basis functions for ions with $Z > 30$.

The accuracy of the perturbation-theory calculation with expansion in powers of Z can be improved by extrapolating the experimental data for lower terms of the isoelectronic series. The error of values calculated in this way is ≈0.1%, and can be reduced to 0.01% by using a large number of experimental data or by extrapolating fewer terms ahead[5].

Very good results have recently been obtained in theoretical calculations of line intensities.

Finally, we note that the highest degrees of "stripping" attained thus far are for W^{55+} in Z (Z = 74) (FIAN)[6] and for Fe^{25+} (χ_i = 9 keV) in the ionization energy (ISAN).

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