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ATOMIC SPECTROSCOPY WITH THE SHOCK TUBE[*]

by

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ABSTRACT

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Transition probabilities for lines of light atoms and ions are
measured with a gas-driven shock tube in the temperature range 9000-
13000°K. A complete "case study" is given for a set of experiments
on one element, including recent developments in circumventing the
sensitive dependence of level populations on temperature. The shock
tube and observing instruments are described: Pressure transducers,
photoelectric and photographic spectrographs are the main instruments;
auxilliary equipment includes flash lamps and arcs for absorption data
and calibration. The many elements of interest are introduced in
gaseous additives to the carrier gas which is usually neon. Computer
programs provide two things: mainly the details of ionization-
excitation equilibria based on measured temperatures and pressures,
also comparison of these measurements with Rankine-Hugoniot theory.
Given a spectral line intensity, the associated transition probability
is determined from the measured thermal quantities, not from the theory
of shock heating. Redundant temperature measurements greatly reduce

the random and systematic errors which ordinarily attend this type of experiment. Preliminary results of such a program are given for visible lines of neutral carbon. Spectra of other light elements will also be presented and discussed.

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1. Introduction

Our title could apply to a wide variety of experiments. The
breadth of the field of shock tube spectroscopy is attested to by
the many other papers on this subject given at this Symposium.
Specifically I want to discuss the role of the shock tube in an
important spectroscopic program: the determination of relative and
absolute line strengths for atomic species, the term "strength"
standing for a number of common terms (oscillator strength, gf-value,
transition probability, Übergangswahrscheinlichkeit). As for molecules,
much of what will be said will also apply, though some assumptions
and observational problems are different. The temperature of the gas
will be singled out for special attention, since its value is crucial
in the interpretation of measured line intensities. To this extent
then, we are discussing the data from all light sources which derive
their atomic excitation from a hot gas.

By the term "shock tube" we will usually mean the classical, gas-
driven type yielding temperatures up to 15,000°K; tubes driven by
detonations or pulsed arcs will not need a separate treatment here,
since we will focus on thermal and radiative properties which are
independent of heating mechanisms. Let me begin with a few questions
about the kind of shock tube spectroscopy we are doing.

A. Why measure radiative transition probabilities between the various electronic states of atomic systems, particularly just for the optical levels? Our iterest is mainly in establishing reliable values for the purpose of plasma state measurements, particularly for element abundances in stellar atmospheres[1] and temperature measurements in hot gases generally. Calculated oscillator strengths are usually not adequate for observed transitions. Measured values, of known precision and accuracy, are greatly needed for abundances, for the elimination and identification of lines in closely spaced spectra, and for measuring plasma temperatures and electron densities from emission and absorption spectra.

B. What makes the shock tube of interest in such a program? The shock tube belongs to a family of light sources one might call "thermal"; i.e., sources in which the populations of atomic and molecular levels and the degrees of ionization and dissociation follow from the temperature, density and composition of the plasma _via_ thermodynamic relations. (Most thermal sources can be pushed into regimes where this is not strictly true, but tests are available for determining the extent of adherence to local thermal equilibrium.) Moreover the gas-driven shock tube, for example, opens up whole ranges of physical variables which are not so readily accessible with other thermal sources. The shock tubes with which we have been working establish plasma having a volume of about 1 liter, characteristic transverse dimension 10 cm, temperatures 9000° - 13000°K, and total particle densities 3 to 8 x 10^{18} per cc. Changes from one set of conditions to another are easily made by adjusting initial pressures

or gas compositions. Very rich emission and absorption spectra of
many elements are generated, under conditions of known abundance,
by inclusion of appropriate gases in the initial gas mixture[2].

C. What is the general method by which a thermal light source
is used for line strength measurements, and what other methods are
available? Most thermal light sources, shock tubes included, provide
emission or absorption lines of known intensity under presumably
known conditions of density and temperature. The Einstein coefficient
for spontaneous emission (or the absorption oscillator strength) for
any resolvable line is then found by dividing the line intensity (in
appropriate units) by the number of atoms in the appropriate level.
The "hook method" of displaying anomalous dispersion[3] is also used
with thermal sources, again making use of presumably known level
population.

A quite different sort of method is that of observing the
statistical radiative decay[4] of large numbers of excited atoms or
molecules, following a short period of excitation by photons or electrons.
This and related kinetic methods[5] are very powerful for some tran-
sitions, while level-cascading and collisional effects make for quite
imprecise results for many lines. A thermal light source by definition
does not suffer from this difficulty, but is sensitive to temperature
errors in ways we will further explore below. It now seems very likely
that the thermal and non-thermal light source methods will be required
to complement each other for some years to come, in order to find
acceptably accurate line strengths for use with laboratory and astro-
physical plasmas.

In sections to follow, we will first briefly describe our atomic spectroscopy experiments with the shock tube, which now concentrate largely on the lighter elements. Then we will bring up to date an older and persistent problem with the spectrum of neutral chromium, which seems now to have been resolved in one important respect while remaining open in another. The improved relative of gf-value scale for Cr I based on shock tube and arc measurements is discussed in terms of propagating temperature errors, partly in order to leave a large "caution" sign for certain types of temperature determination. Going then to the higher temperatures required for the lighter elements, whose excitation potentials are generally much higher than for the metals, we will observe the accumulation of large systematic errors due again to the Boltzmann factor in level population. Finally we will discuss a general method whereby the troublesome systematic errors in oscillator strength determinations can be reduced to the level of random errors.

2. Experimental Regime

Figure 1 is a schematic of our shock tube arrangement. Several optical instruments view the gas near the end wall of the 3 in. x 4 in. tube, where quartz pressure transducers are also located. Incident shock phenomena trigger photoelectric recording of events behind the reflected shock wave, and emission spectra are recorded on moving film in the f/6.3 spectrograph. Photomultipliers record twelve closely spaced wave-length bands in the monochromator and six separate bands in the B & L spectrograph; all wavebands are roughly 1 Å wide by virtue of

glass "cover slide" optical elements[6] used in the image planes.
Typically, absolute intensities for certain neon, carbon, and hydrogen
lines are recorded in the B & L with sideband detectors for subtraction
of background continuum. This instrument also observes line reversal
when the flash lamp[7] is triggered; a line of moderately high optical
depth, such as the Balmer line H_α , is used for this purpose. Stark
profiles of the H_β line are recorded in the 12-channel instrument, in
order to determine electron density ($\sim$ 2 to 6 x 10^{16}/cc) from half-
width ($\sim$ 25 - 40 Å). Absolute and relative line intensities over
1000 Å intervals are determined from spectrograph films which are
carefully calibrated with graduated intensities and a carbon arc
radiation standard.

The shock tube is driven by H_2 at pressures of 1000 - 2000 pounds
per square inch. The low pressure of "test" gas is nearly always neon
(p_o $\sim$ 1 cm Hg) with about 1% spectroscopic additive (CH_4, CS_2, PH_3,
SiH_4, CCl_4, Xe, Kr, etc.). A typical film in the blue-green is reproduced
in Figure 2 with time running downward and wavelength increasing to the
left. The earliest segment of constant appearance is due to emission
from behind the first reflected shock, where the temperature is roughly
11,500°K (1 eV); later emission is due to multiple wave interactions
and erratic quenching by cold, expanded driver gas in the shock tube.
From this type of data film, the integrated intensities of neon, carbon,
hydrogen and sulphur lines are compared and the gf-values for many
lines calculated from knowledge of the gas conditions. Present work
with these lighter elements is discussed in Section 4, and past and

present work with metallic elements in the vapor phase in the shock
tube is discussed in Section 3. For the latter, for example, Cr $(CO)_6$
in neon even at levels of 1/10% leads to films like Figure 2 except
that they are dominated by strong lines of neutral and singly ionized
chromium[8].

3. Relative Line Strengths, Temperature Measurement and Propagation of Temperature Errors

Sets of relative line strengths for various elements are extremely
useful for the measurement of plasma temperature. Out of all the
spectral lines of a given element, one needs to know the gf-value only
for a subset of lines arising from a range of upper level energies.
The absolute gf-value scale is not needed for this kind of temperature
measurement; the wider the range of level energies and the more uniform
the precision of gf-values, the better. The integrated intensity of
an optically thin line[10] [11] [12] (upper level i, energy Ei; lower
level j) is given by

$$I = n_i A_{ij} h\nu\ell = \frac{2\pi e^2 \nu^2}{mc^3} \cdot \frac{n_i}{g_i} g_j f_{ji} h\nu\ell$$

$$= \frac{2\pi h e^2 \ell n}{m\mathcal{Z}} \cdot \frac{g_j f_{ji} e^{-Ei/kT}}{\lambda^3} , \tag{1}$$

where ν and λ are frequency and wavelength of the line, n_k is the number
density and g_k the degeneracy of atoms in the kth level, n is the total
species number density and $\mathcal{Z}$ the partition function, A_{ij} the Einstein
coefficient for spontaneous emission and $g_j f_{ji}$ the "absorption oscillator

strength" related to it, e is the electron charge, h Planck's constant and ℓ the extent of the light source along the line of sight.

It is a well known corollary of Equation (1) that the temperature T describing a given distribution of level populations can be measured by plotting log $(I_r \lambda^3/gf_r)$ <u>vs</u> E_i, where r denotes relative intensity or gf-value. In such a plot, T appears as the negative inverse slope of a straight line; i.e., for E in electron-volts,

$$T(°K) = 5041(E_i^n - Ei^m)/\log_{10} \left(\frac{I_r \lambda^3}{gf_r}\right)_m - \log_{10} \left(\frac{I_r \lambda^3}{gf_r}\right)_n \quad (2)$$

For aerodynamics experiments, trace amounts of salts or metallo-organic compounds added to the flow stream can give rise to optically thin lines of elements not usually present, and the experimenter has at his disposal a powerful thermometric tool. Considering what is now known just about the metals between titanium and nickel, the temperature range from 2000 to 10,000°K is certainly open to this technique, and it is from such measurements that much has been learned about the atmospheres of the sun and other stars.

It is less widely appreciated that the use of an erroneous temperature in the original gf-value determination leads first to an erroneous set of values gf' and then to serious temperature errors in subsequent determinations based on the set gf'. If experimenter A employs a temperature T_A' instead of the true value T_A in reducing line intensities to line strengths, then his results are

$$(gf)' = (gf)e^{-Ei/kT_A} \quad e^{+Ei/kT'_A} \quad . \tag{3}$$

Therefore experimenter B is later led to straight-line plots of the type mentioned above, but the temperature T'_B so derived and his actual temperature T_B differ according to

$$\frac{1}{T'_A} - \frac{1}{T_A} = \frac{1}{T'_B} - \frac{1}{T_B} \quad . \tag{4}$$

(e.g., 2000 vs 2500 → 5000 vs 10,000)

As an example of this type of difficulty, we illustrate in Figure 3 both an early attempt[13] at shock tube temperature measurement using Cr I lines and the later interpretation made possible by remeasurements[8] [14] of the Cr I gf-values. The old values for higher lying levels had to be reduced relative to the lower levels. With the correct relative scale, we indeed find an excitation temperature near 9200°K which is close to the expected shock tube temperature of 9300°K. With the older scale of Hill and King[15], one would be left to explain a strikingly lower excitation temperature of 5200°K. This is due, we believe, to a small temperature error in the furnace measurements having propagated, as explained above, into the large effect we see here.

That the previous relative scale for Cr I probably contained a strong temperature effect was pointed out by Goldberg, Müller, and Aller[16] and others from intensities in the sun's Fraunhofer spectrum. Our shock tube results[8] to this effect were buttressed by Charatis'

measurements of line reversal temperature[9], and were confirmed by
the arc results of Corliss and Bozman[14], and by the demonstration of
Müller and Mutschlecner that the newer scale for Cr I makes sense
for the solar atmosphere[17].

Because of continuing interest and discussion on chromium spectra,
we are reassessing our older work, in so far as this is possible, and
Charatis is preparing for new absolute measurements. An important
component of both programs is Koopman's development of computer methods[18]
for detailed calculations of ionization and level population. The first
conclusion has been that our prior hand calculations of neutral chromium
abundance in various excited states were accurately performed, as is
indicated in Figure 4 for various energy levels typical of Cr I. Since
the Hugoniot-calculated temperatures agree between the old and new methods,
and since these temperatures were experimentally checked in a few cases[9],
we have as yet unearthed no reason to doubt the gf-values[8] we measured
for Cr I and Cr II. These are shown in Figure 5 by comparison with the
results of Corliss and Bozman for the same lines. Our absolute results
for Cr I are within a factor of two of the sum rule for 4s - 4p transi-
tions[16]. We understand that ultraviolet shock tube work by Huber[19]
at Harvard tends also to support the relative scale of Corliss and
Bozman, but that Huber's absolute scale is different. To summarize, it
seems that the absolute gf-value scale for Cr I may indeed still be
unsettled, but the relative scale is now sufficiently more reliable than
it used to be that it suffices for 5% temperature measurements near
10,000°K.

4. Absolute Line Strengths, Effect of Temperature Errors, Avoidance by "Thermal Balancing"

We determine absolute line strengths in a variety of ways. Conceptually, the simplest is to calibrate photoelectric detectors and films absolutely over the necessary ranges of wavelength and intensity. This is now standard fare for shock tube spectroscopic work, which is not to say, however, that it is easy or foolproof. As an example of procedure let us assume that we measure the total energy I_c in an optically thin carbon line, such as the 3s - 4p transition C I λ 5052, by comparison with a standard radiation source such as the carbon arc. By the equation

$$I_c = N_c \, h\nu \, \ell \, A_c$$

we must determine A_c from knowledge of N_c, the upper level population.

Carbon abundance in the appropriate level follows from our knowledge of the gas composition plus state measurements; e.g., transducer measurements of total pressure and line-reversal measurements of temperature. We do not rely, as once was necessary, on the Hugoniot equations because of the greater sensitivity to temperature errors with the lighter elements. Again, computer codes have proven extremely useful for accurate calculations of many closely spaced thermodynamic states. In Figure 6, we show the calculated variations of upper state populations with temperature for a number or observed lines. (Note that this is for a particular pressure and gas composition.)

Taking a temperature range 400 degrees on either side of 10,400°K, the number density appropriate to C I λ 5052 swings over a factor of 2. This is a common amount of temperature uncertainty in this range and suggests at least a random error of order 40% in the final Einstein coefficient. Moreover, most experiments have proven to be difficult enough that one type of temperature measurement has had to suffice; i.e., the experimenter uses a complement of measurements just large enough to determine all unknowns. Over a given set of experiments, the particular method of thermometry employed will tend to err on one side or the other of the true value, while care in measurement may lead to good reproducibility and small scatter of results. Hence, the accumulated literature on atomic transition probabilities contains many precise values, and far fewer accurate ones to judge by discrepancies typically running between 3 and 10. In turn, the effects of such discrepancies on subsequent analysis of stellar or plasma spectra can be small, in some abundance determinations, or very large as we have illustrated in the foregoing discussion of temperature measurements by relative line intensities.

Figure 6 shows also the much more sensitive temperature dependence of the upper level population for the 5852 neon line, which is due to the greater excitation potential of the level. Generally this is easily shown to follow from the Boltzmann factor $e^{-E_i/kT}$ in the level population. By logarithmic differentiation,

$$\frac{dN_i}{N_i} = \frac{E_i}{kT} \cdot \frac{dT}{T} \quad ,$$

which tells us that a percentage temperature change (or uncertainty) is multiplied by a large factor (of order 10 in most of our cases) which makes a serious percentage effect on level population.

Now, how can this be overcome? One might propose several independent measurements of the conditions in the shock tube, arc, flame, furnace or whatever source is being used. We have done this by measuring absolute pressure, temperatures via spectral line reversal, absolute hydrogen line intensity, and absolute neon line intensity, plus electron density from hydrogen line profiles. The fruits of these extensive labors have been primarily a demonstration of agreement to 5% or better[24] in most of the quantities of interest - plus a confusion as to which method or methods was intrinsically more reliable, and what sort of averaged result for line strength was the most suitable and free of systematic error. We will go further into the question of averaging the results of independent measurements, after mentioning another approach which is sometimes useful.

The right hand side of Figure 6 shows ratios of upper level populations for various lines we are interested in. The uppermost curve, for example, illustrates the greater temperature sensitivity of the n = 4 level of hydrogen (E = 12.69eV) dominating the temperature effect in the upper level of this neutral sulphur line (E = 9.12eV). For a line of ionized sulphur however, we have nearly the same temperature dependence as for the line NeI λ 5852; presuming the strength of the latter to be known, clearly one could measure the absolute strength of S II λ 5453 with very little error introduced by temperature uncertainties.

Doherty took advantage of such trans-species similarities (O I vs H I) in his pioneering shock tube measurements ten years ago[20]. Unfortunately such Saha-Boltzmann pairings between interesting lines of unknown strength and available lines of known strength are rather rare, and some other method of temperature compensation must be sought.

It is in the equal-and-oppositeness of the curves for C I λ 5052 (left side of Figure 6) and $N_{5052\ C\ I}/N_{H\beta}$ (right side) that Mr. Miller saw a method of temperature compensation which now promises to be very general and useful. A full account of the "thermal balancing" technique is in preparation[21]; the method is being applied to many line strength measurements in our laboratory[22]. We will consider here only the case mentioned above and the resulting line strength for C I λ 5052.

In the upper part of Figure 7, we select the two thermal properties of interest for the remainder of our discussion, namely the reciprocal number density of carbon atoms in the upper level of C I λ 5052 and the inverse of the population ratio between this line and the H_β line of hydrogen. These are needed for two methods:

(1) If the absolute intensity I_c for the carbon line is measured, the transition probability $A_c^{(1)}$ follows directly from $1/N_c$ as indicated by the equation on the lower left of the figure.

(2) If the intensity ratio I_c/I_H (carbon to hydrogen) is measured, the carbon transition probability $A_c^{(2)}$ follows from the known value for hydrogen and the equation in the lower right side of Figure 7.

Of course these two independent measurements and methods would yield

the same result if all the intensities were accurate and the true

temperature, indicated by the ticks on the curves, were employed in

reducing the intensity data. Suppose instead that erroneous temperatures

might be used; the transition probability results by both methods are

shown as functions of assumed temperature in the lower part of Figure 7,

where T_o stands for the actual temperature of the light source. If

one assumes a temperature which is less (or greater) than T_o, then

the results of method (1) and method (2) are systematically too high

and too low, respectively (or the reverse). So far we simply confirm

that a very confusing pattern of agreement and disagreement between

the results of different experimenters can result from the use of

different methods and the occurence of different systematic temperature

errors.

For pairs of curves having the degree of symmetry indicated here,

an averaging procedure is not only reasonable but gives a striking

reduction in systematic gf-value error even though one's choice of

temperature may be quite imprecise. This is indicated in Figure 8,

where we have normalized to the true magnitude of the oscillator

strength. The average curve between these two methods depends only

slightly on the assumed temperature, and generally lies much closer

to the true transition probability than the result of either method

used alone. To put it another way, the experimenter can measure the

gf-value for the carbon line with very little systematic error simply

by performing both the absolute and hydrogen-relative methods, knowing

the temperature only roughly, and averaging the results of the two methods.

Another experimenter with his light source also operating near T_o can make a gross temperature error in the other direction, but get nearly the same reasonably accurate result by averaging the carbon line strengths deduced from the two independent methods described. No matter what temperature is chosen in the range illustrated in Figure 8, the average of the two methods is very close to the true A value, while each method by itself could give large errors.

Certain general features of thermal balancing should be remarked upon. For any given pair of line-to-be measured and comparison line, there is a best operating temperature T_o for which the average curve has a small slope over the widest range of assumed temperature. For clarity our illustrations above have been made in the vicinity of the optimum T_o, but the method can stand departures on either side of T_o by 1000°K and still give shallow average-A curves--which is to say one is still much better off by averaging than not. Neither is the thermal balance destroyed by different choices of number density. Lastly, the average-A curves share the convex-upward property of the parent curves; thus the average curve is below the true value only over a small temperature range. This has the effect of concentrating those A-value errors encountered in thermal balancing to the high side of the true value. (Distributions of A-value results using synthetic data and a variety of assumed temperature errors are characteristically near zero just below the true A-value and fall of quasiexponentially above

it.) So it is very hard to underestimate transition probabilities by this method.

Of course, no amount of juggling can correct a mis-measurement of line intensity, for example, so one is still left with errors of this type. They tend to be diluted by an averaging process such as we have described and, in any event, lead only to linear rather than exponential errors. Currently our probable errors in intensity are of order 10%, so that the idealized distributions of results from synthetic data are made somewhat fuzzy. In Figure 9 we show a recent set of results for C I λ 5052, where the two methods were first used separately with a reversal temperature that was 3% in error, and finally where the set of results united by the averaging described above lead to a value of A = (1.55 ±0.3) x 10^6 sec^{-1}. In the recent compendium of Wiese et al[23], this value was listed as 1.7 x 10^6 with a 50% probable error on the basis of various measurements. We had previously verified[24] the relative values listed by Wiese et al for the C I lines of multiplets 34-37, so we have therefore indirectly confirmed the listed absolute values for them as well.

Other methods for thermal balancing are also being explored in continuing studies of the lighter elements.

5. Conclusion

The gas-driven shock tube is an extremely useful spectroscopic source, since its conditions are readily varied over wider ranges than many other thermal light sources, and since means are available for discovering and circumventing the effects of temperature errors in

thermal sources. The shock tube has made possible a number of advances in the knowledge of radiative transition probabilities for neutral and singly ionized metals and lighter elements. This knowledge, in turn, improves our understanding of laboratory and astrophysical plasmas.

6. Acknowledgements

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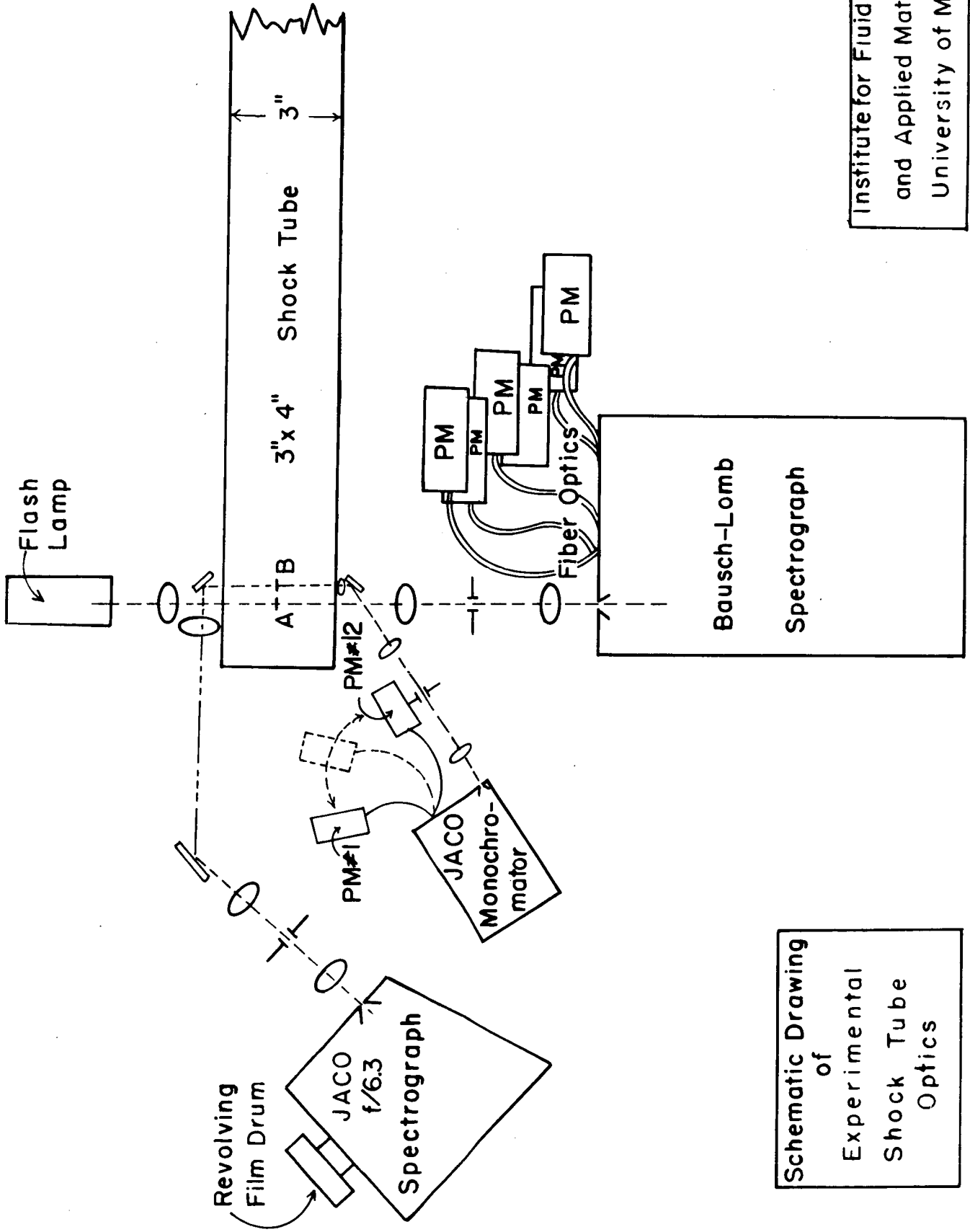
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FIGURE CAPTIONS

Figure 1. Methods of Observing Gas behind Reflected Shock Wave.

Figure 2. Time-resolved emission spectrum, showing carbon, hydrogen and sulphur lines behind first reflected shock (top) and subsequent waves.

Figure 3. Relation between temperature measurement and reliability of relative gf-values. Effect is shown for a particular shock tube experiment where relative intensities of spectral lines were measured.

Figure 4. Comparison of calculated level populations for various Cr I levels behind reflected shocks in neon plus $Cr(CO)_6$. Hand calculations and computer results agree with temperatures checked by line-reversal experiments.

Figure 5. Comparison of absolute gf-values for Cr I observed in shock tube (Charatis-Wilkerson) and arc (Corliss- Bozman).

Figure 6. Calculated thermal states for a particular gas mixture, showing strong temperature dependence of level populations, and a variety of temperature dependences of population ratios.

Figure 7. Dependence on assumed temperature of transition probability for C I λ 5052, for two methods of measurement.

Figure 8. Curves completing the implication of Figure 7, namely that the average of the two methods is very close to true transition probability for a wide range of assumed temperature.

Figure 9. Experimental transition probabilities for C I λ 5052, reduced by absolute emission and hydrogen-relative methods alone, and then by thermal balancing. Result chosen by comparison with distributions of results previously calculated from synthetic data.

Flash
Lamp

Shock Tube

3"

3" x 4"

A   B

PM#2

PM#1

JACO
Monochro-
mator

Revolving
Film Drum

JACO
f/6.3
Spectrograph

Fiber Optics

PM

PM

PM

PM

PM

Bausch–Lomb
Spectrograph

Schematic Drawing
of
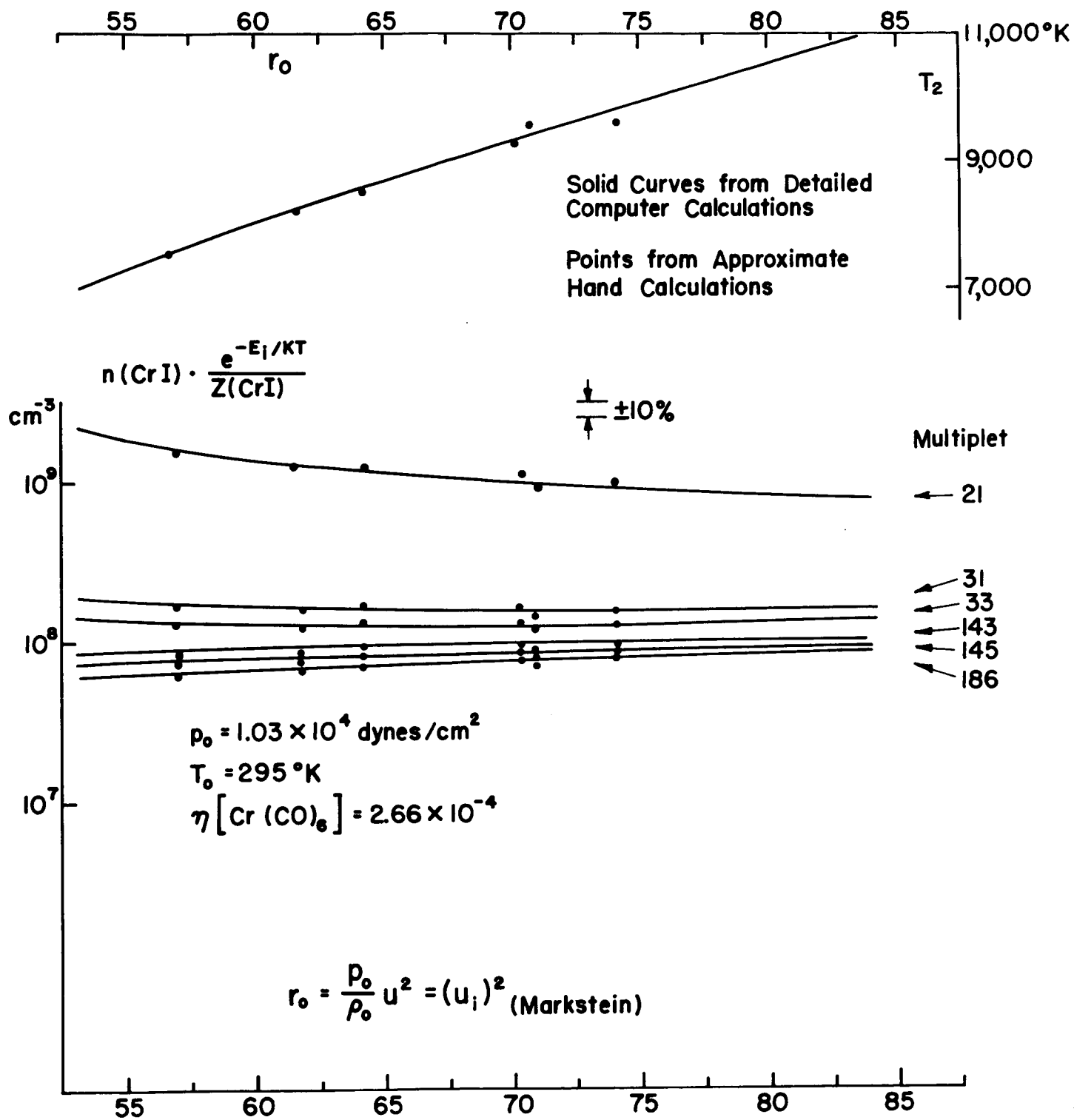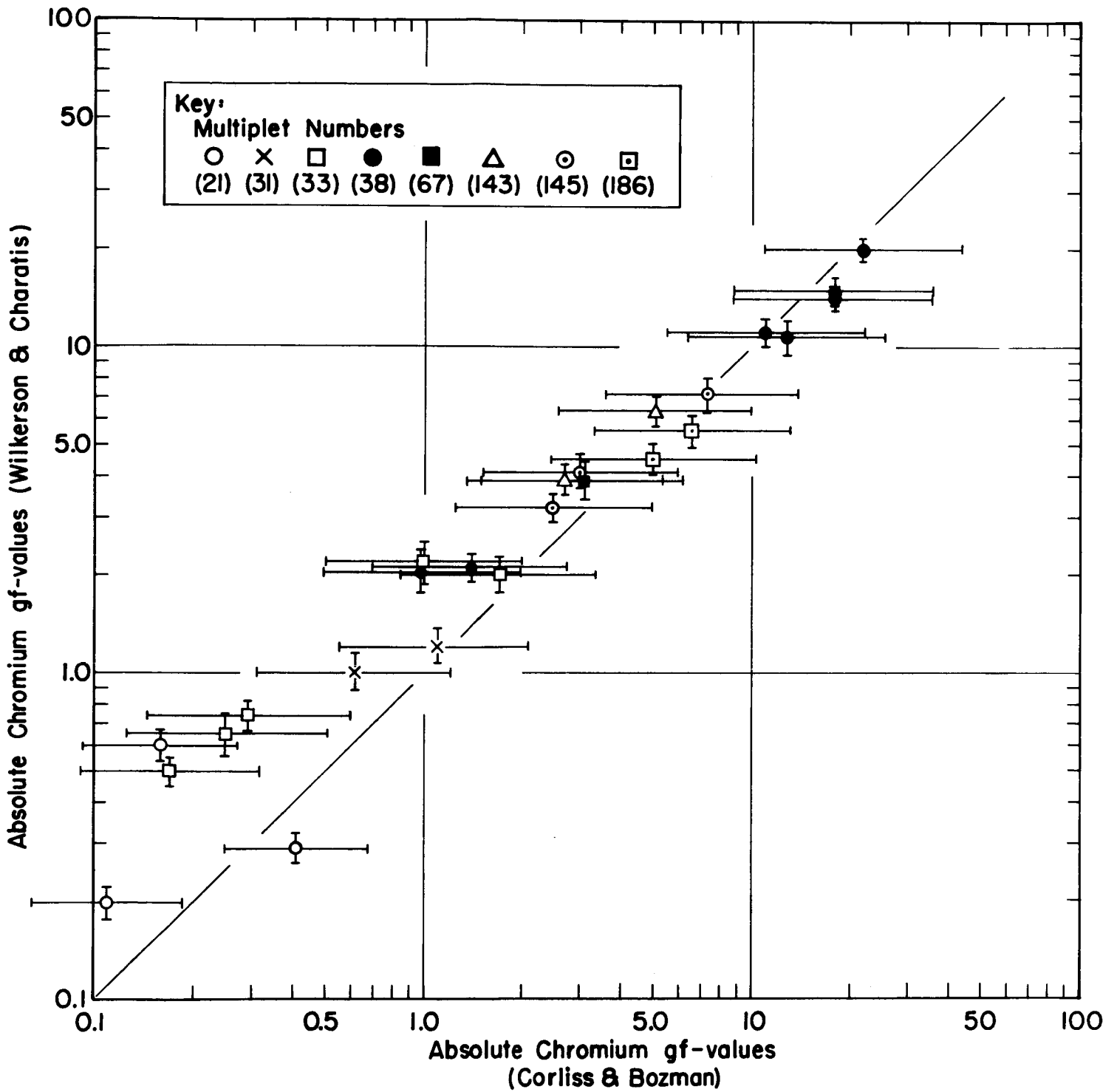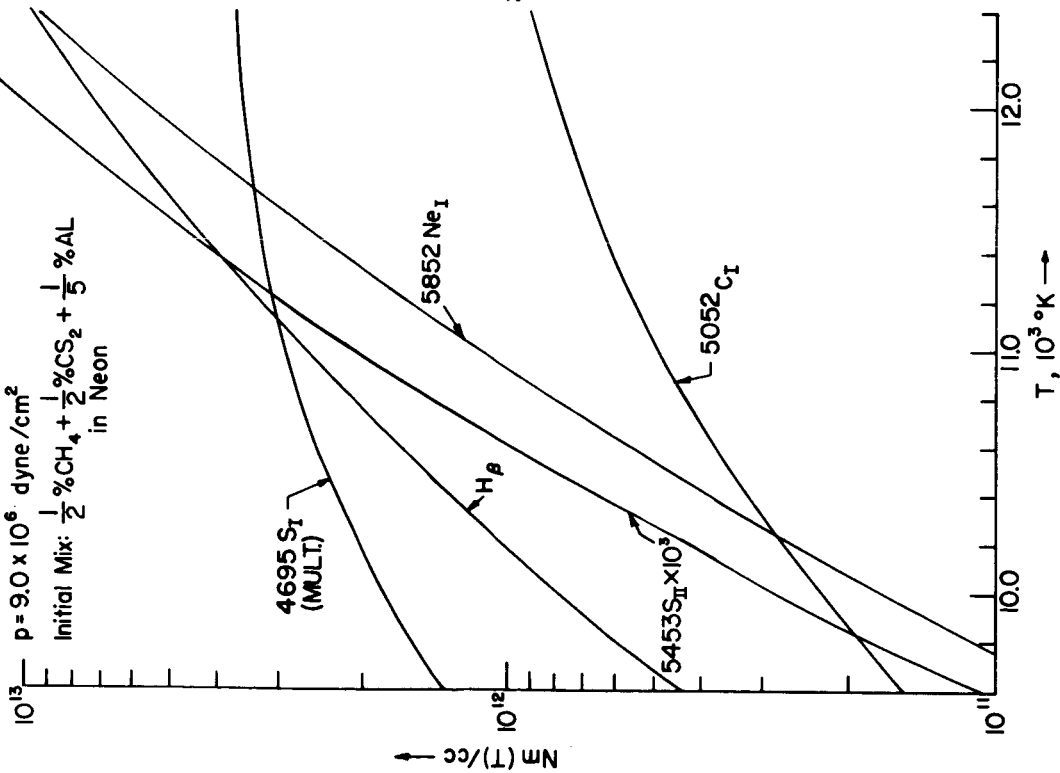Experimental
Shock Tube
Optics

TIME

CI
λ5052

Hβ
λλ4861

SI
λλ4695

FIRST
REFLECTED
SHOCK
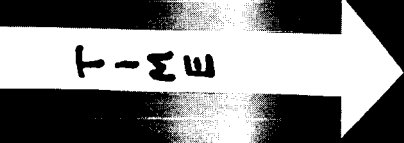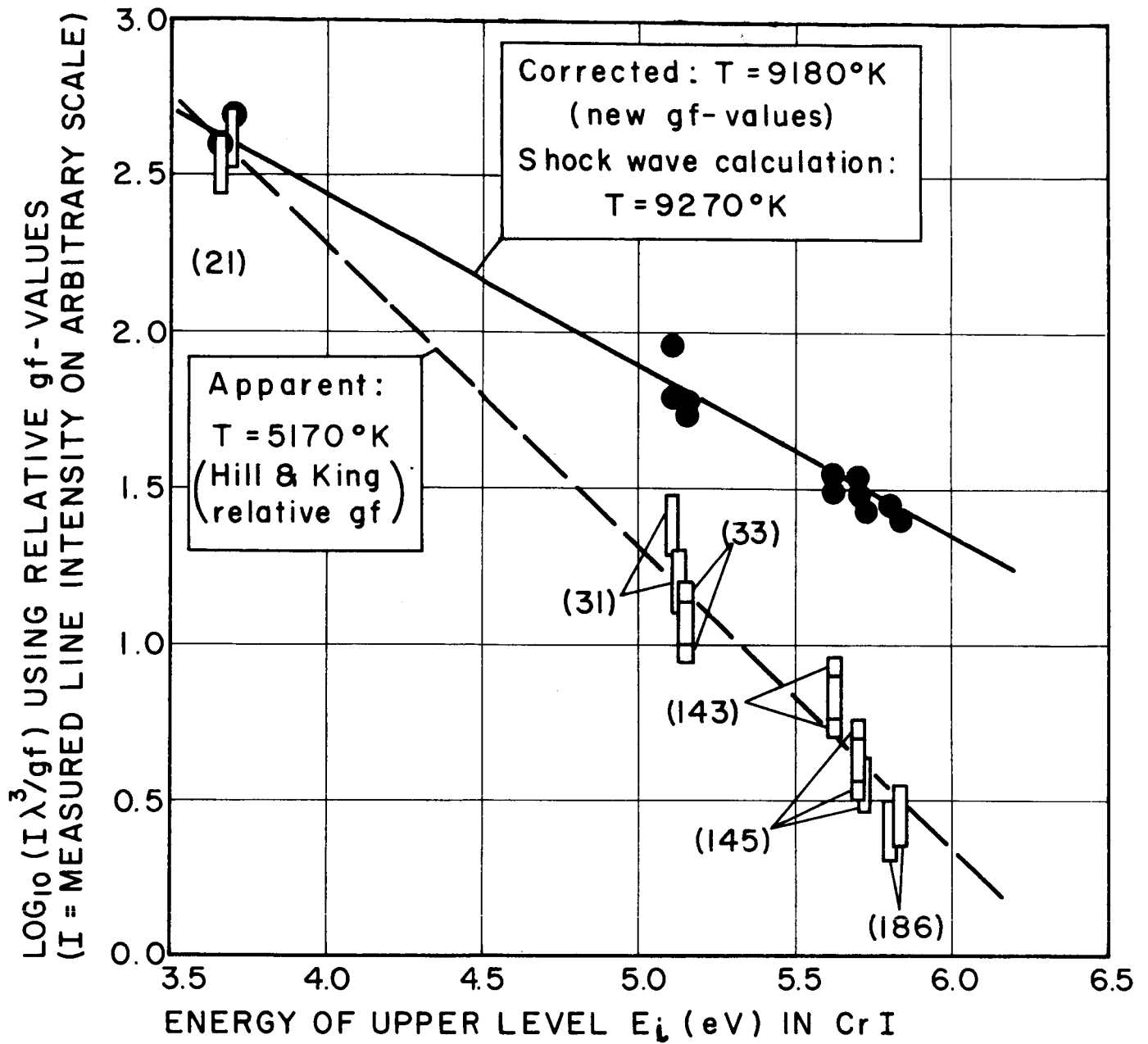
UPWARD ADJUSTMENTS OF $I\lambda^3/gf$ ARE DERIVED FROM SHIFTS IN LOG_{10} (gf) INDICATED BY CURVES OF GROWTH.

Solid Curves from Detailed
Computer Calculations

Points from Approximate
Hand Calculations

$n(Cr\,I) \cdot \dfrac{e^{-E_1/KT}}{Z(Cr\,I)}$

cm^{-3}

$\mp \pm 10\%$

Multiplet

21

31
33
143
145
186

$p_0 = 1.03 \times 10^4$ dynes/cm^2

$T_0 = 295\,°K$

$\eta\left[Cr\,(CO)_6\right] = 2.66 \times 10^{-4}$

$r_0 = \dfrac{p_0}{\rho_0}\,u^2 = (u_i)^2$ (Markstein)

r_0

T_2 11,000°K

9,000

7,000

Key:
Multiplet Numbers
○ (21)   × (31)   □ (33)   ● (38)   ■ (67)   △ (143)   ⊙ (145)   ⊡ (186)
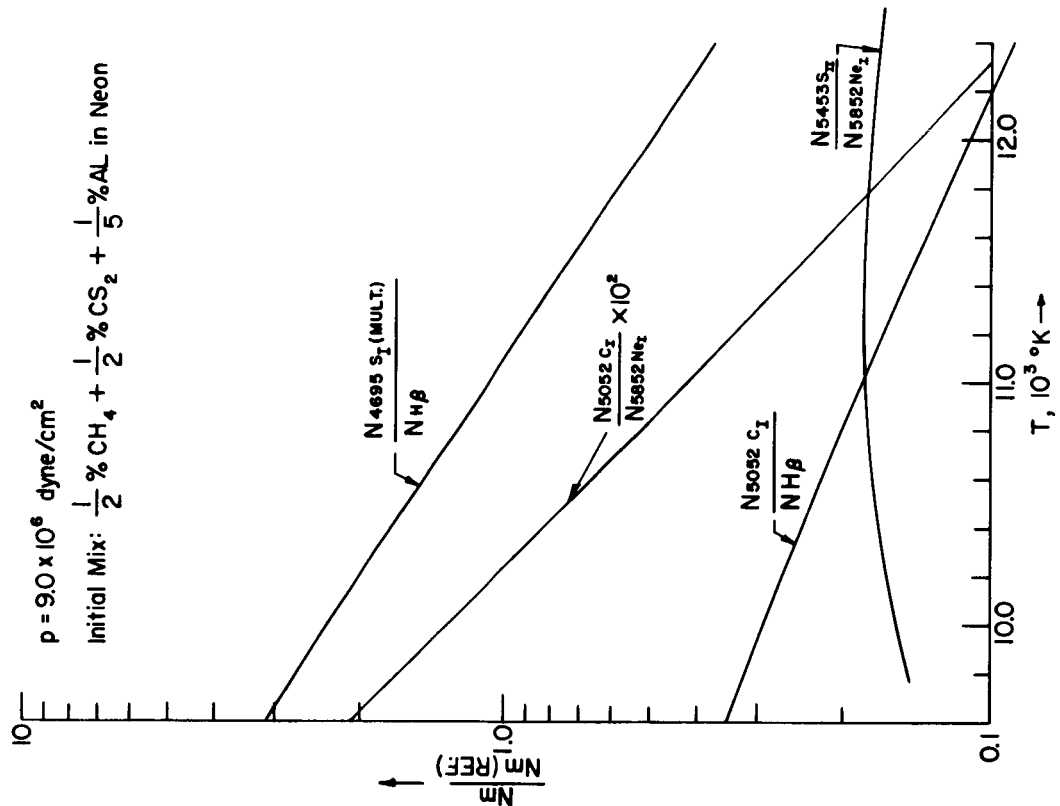
UPPER LEVEL POPULATION DENSITIES vs T

$p = 9.0 \times 10^6$ dyne/cm²

Initial Mix: $\frac{1}{2}$ %CH$_4$ + $\frac{1}{2}$ %CS$_2$ + $\frac{1}{5}$ %AL in Neon

4695 S$_I$ (MULT.)

H$_\beta$

5453 S$_{II}$ × 10³

5852 Ne$_I$

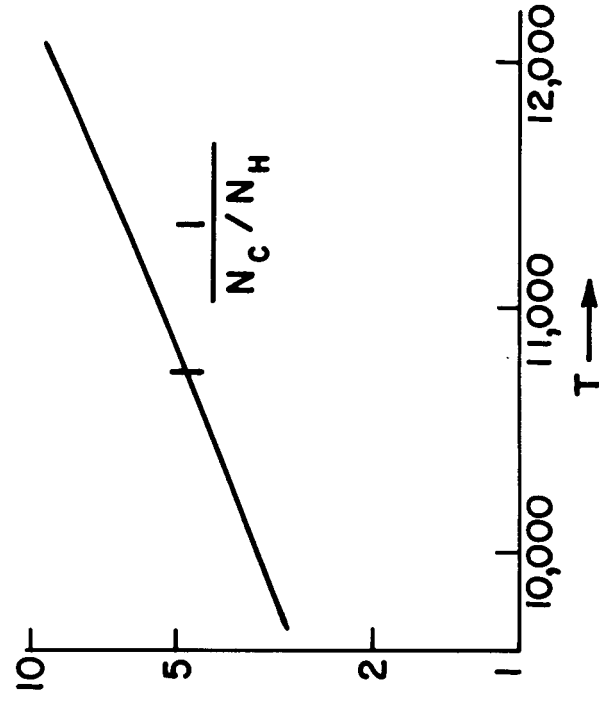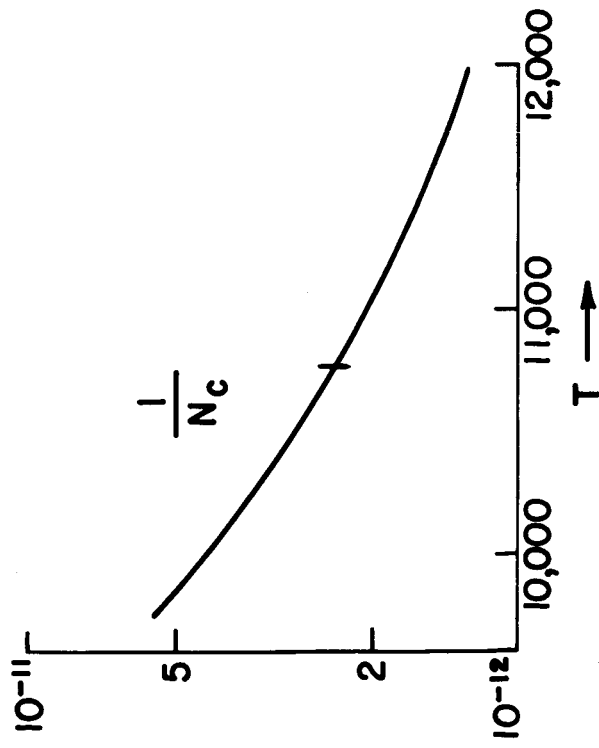5052 C$_I$

Nm(T)/cc

10^{13} 10^{12} 10^{11}

T, 10³ °K →

RATIOS OF UPPER LEVEL POPULATION DENSITIES vs T

$p = 9.0 \times 10^6$ dyne/cm²

Initial Mix: $\frac{1}{2}$ %CH$_4$ + $\frac{1}{2}$ %CS$_2$ + $\frac{1}{5}$ %AL in Neon

$\dfrac{N4695\ S_I(MULT.)}{NH\beta}$

$\dfrac{N5052\ C_I}{N5852Ne_z} \times 10^2$

$\dfrac{N5052\ C_I}{NH\beta}$

$\dfrac{N5453S_{II}}{N5852Ne_z}$

$\dfrac{Nm}{Nm(REF)}$ →

10   1.0   0.1

T, 10³ °K →

General results for a given mixture and pressure

$$\frac{1}{N_c}$$

$$\frac{1}{N_c/N_H}$$

T

T

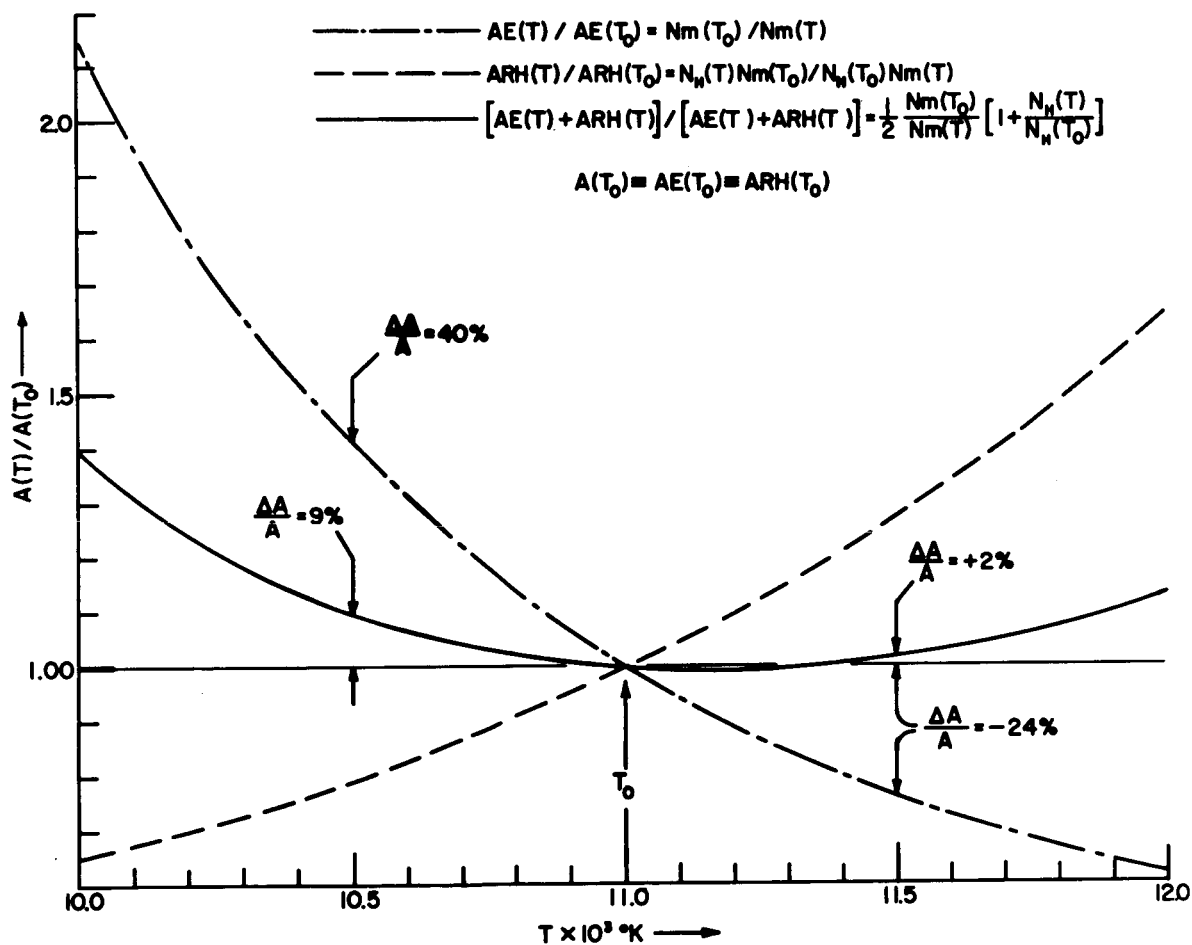**Particular Experiment (Temperature T_0)**

$$A_c^{(1)} = \frac{I_c}{h L \nu_c} \cdot \frac{1}{N_c}$$

Observation 1
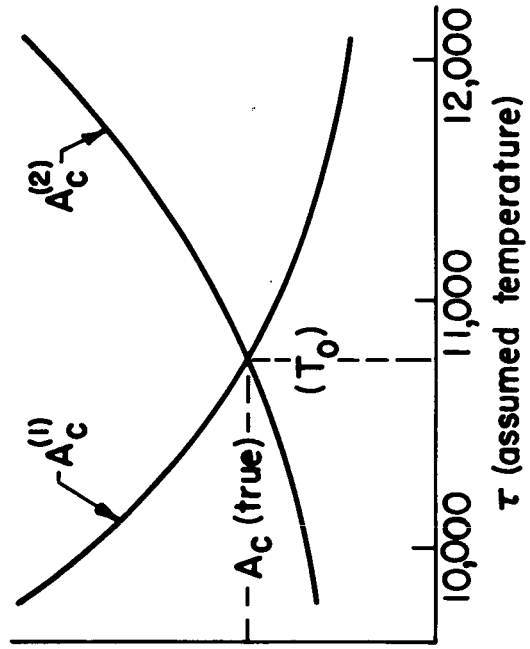
$$A_c^{(2)} = \frac{A_H}{\nu_c/\nu_H} \cdot \frac{I_c}{I_H} \cdot \frac{1}{N_c/N_H}$$

Observation 2

$A_c^{(2)}$

$A_c^{(1)}$

A_c (true)

(T_0)

τ (assumed temperature)

THERMAL ERROR PROPAGATION IN AE, ARH, $\frac{1}{2}$(AE+ARH) OF CIλ5052,
PLASMA OF INITIAL COMPOSITION $\frac{1}{2}$%CH$_4$ +$\frac{1}{2}$%CS$_2$ +$\frac{1}{5}$%AL IN NEON,
AT p=9.0×10^6 dyne/cm^2, TRUE TEMPERATURE (T$_0$)= 11,000 °K

RESULTS FOR A_{mn} OF $5052 c_{I}$

KEY: ● = $1\% CH_4 + \frac{1}{5} \% AL$ in NEON

▢ = $\frac{1}{2}\% CH_4 + \frac{1}{2} \% CS_2 + \frac{1}{5} \% AL$ in NEON

WITH: $\Delta \tilde{T} \cong \pm 3\%$
$\Delta p \cong \pm 7\%$
$\Delta R \cong \pm 10\%$
$\Delta \frac{a}{a_H} \cong \pm 15\%$

$AE \times 10^6 / SEC. = C_1 R / N_m (p,T) \int_{-\omega/2}^{\omega/2} L(\nu, p, T)\, d\nu$

$ARH \times 10^6 / SEC. = C_2 \dfrac{N_H}{N_m} (p,T) \dfrac{a}{a_H}$

$A \times 10^6 / SEC. \equiv \frac{1}{2} (AE + ARH)$

NBS COMPILATION
WIESE et. al. (1966): 1.70 , "D" ACCURACY

TENTATIVE
RESULT: 1.55 ± 10%

1.0   1.5   2.0   2.5   3.0