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* PARTICLE BEAMS

* FOILS (MATERIALS)

* SPECTROSCOPY

KINETIC ENERGY

DOPPLER EFFECT

ULTRAVIOLET RADIATION

SPECTRAL LINES

IONIZING RADIATION

VAN DE GRAEFF GENERATORS

ENERGY LEVELS

METASTABLE STATE

QUANTUM ELECTRODYNAMICS

ELECTRONS

No abstract

	Elite	Pico
1	Summary as of 1970. The method underlying beam-foil spectro-	
2	scopy (BFS) and the main features of the beam-foil source were	
3	described in the 1970 Yearbook, pp. 117, 118. As of that time,	
4	the highest particle energy used was 20 MeV, the Doppler effect	
5	caused seriously degraded shapes of the spectral lines, few ob-	
6	servations had been made in the extreme ultraviolet wavelength	
7	range, many spectral lines of unknown origin appeared, and the	
8	experiments were restricted to the emission of light from the ex-	
9	cited particles. Advances have since been made in all the fore-	
10	going.	
11	Particle energies. The higher the particle energy, the greater	
12	the number of electrons which are removed by the beam-foil inter-	
13	action. Ions with but few bound electrons characterize hot	
14	plasmas, such as the solar corona or controlled thermonuclear	
15	reactors (CTR's) so the study of such ions gives basic information	
16	about plasma behavior. Moreover, the electrons in ions of high	
17	net charge move with relativistic speeds; the determination of the	
18	electron orbits and their decay rates in such ions offers a sensi-	
19	tive test of quantum electrodynamics (QED).	
20	The highest energy achieved so far in a standard beam-foil ex-	
21	periment is now 110 MeV, used in an experiment on iron at Brook-	
22	haven National Laboratory's tandem Van de Graaff facility. Iron	
23	ions were detected with as many as 17 electrons removed; some of	
24	those ions have been seen in the solar corona and in CTR's. A new	
25	experiment on iron is planned to be done at 500 MeV, with the	
26	Super Hilac at Berkeley. A net charge of +23 will be produced in	
27	that work.	
28		

1 Marrus and collaborators have studied relativistic effects by
2 producing ions from Si (+13) to Fe (+23). They are investigating
3 the Lamb Shift, and have measured the decay rates for "forbidden"
4 transitions, including the double electric-dipole decay mode. The
5 measured decay rates are generally in good agreement with the pre-
6 dictions of QED, but there appears to be an anomaly in the re-
7 sults on Cl^{+15} and Ar^{+16} . Marrus' work differs from "standard"
8 BFS experiments in that he detects soft x-rays with solid-state,
9 non-dispersive systems, whereas "standard" experiments employ
10 diffraction-grating spectrometers.

11 Doppler Effect. The spectroscopic quality of an experiment may
12 be described in terms of the width of the spectral lines; broad
13 lines may conceal blends of contributions from several sources.
14 Because of the high speed (several percent of the speed of light)
15 of the particle beams, the Doppler effect often produces line
16 widths of 10 \AA or more. That is unacceptable for precision mea-
17 surements. Stoner and Leavitt showed that a spectrometer could
18 be "refocused", i.e., have its slits or grating moved so that the
19 Doppler-broadened lines are brought to a reasonably good focus.
20 The Doppler width is roughly proportional to wavelength and, with
21 refocusing, can be reduced to about 1 \AA at 4000 \AA . Further re-
22 duction in line width is presently limited by foil-scattering,
23 but laser techniques (see below) might lead to further improvement.

24 Extreme Ultra-Violet. The more highly ionized a system, the
25 greater the energy separation of the main electronic orbits, and
26 the shorter the wavelengths of the transitions between orbits.
27 Also, the rates of decay rise rapidly with increasing degree of
28

1 ionization so that the largest part of the decay power in ions of
2 high net charge is associated with radiations of short wavelength.
3 To examine those radiations, grazing-incidence spectrometers have
4 been used with increasing frequency in BFS. Those instruments al-
5 low one to detect spectral lines as short as 40 \AA ; below 100 \AA ,
6 curved-crystal, x-ray spectrometers have also been introduced into
7 BFS.

8 Identification of Spectral Lines. Many of the "new" spectral
9 lines of BFS have been identified as "Rydberg" lines. Such lines
10 occur when an electron makes a transition out of a level of large
11 principal quantum number, the orbiting electron being far from the
12 nucleus and inner electrons which form the field which causes the
13 transition to occur. One consequence of this arrangement is that
14 the detailed structure of the inner electron cloud is relatively
15 unimportant in dictating the nature of the transition, the single
16 most significant factor being the net charge of the ion. There-
17 fore all Rydberg transitions are much the same, independent of
18 the element and the stage of ionization. The energies of Rydberg
19 levels can be roughly calculated using theory originally created
20 by N. Bohr to account for the atomic structure of hydrogen. New
21 experiments are underway in which the Rydberg levels are created
22 within a microwave region. By adjusting the microwave frequency
23 until the microwaves are absorbed by one of the Rydberg levels,
24 the energy separation of two neighboring Rydberg levels can be
25 measured and compared with the predictions of sophisticated atomic
26 theory.

27 Some Rydberg levels are shifted in energy from their Bohr values
28

1 because the orbiting electron polarizes the inner cloud of elec-
2 trons. The dipole and quadrupole polarizabilities have been mea-
3 sured for a number of Rydberg levels in several elements excited
4 in the beam-foil source.

5 Rydberg levels are quasi-degenerate in the orbital angular
6 momentum, the quantum number for which is symbolized by " l ". The
7 mean life of a level is a strong function of l , generally becoming
8 longer as l becomes larger. The application of an electric field
9 causes the several l -states to "mix", one effect being to reduce
10 the mean life of the excited system. The use of such a field with
11 the beam-foil source has proved to be a convenient way of corrobo-
12 rating the Rydberg character of the excited states, for a reduc-
13 tion of a Rydberg level's mean life shows up directly as a marked
14 change in the intensity of the emitted light.

15 A second source of the new spectral lines is "doubly-excited"
16 levels, in which two electrons are simultaneously lifted out of
17 their normal orbits but still stay bound to their parent nucleus.
18 It frequently happens that the total excitation energy is then
19 greater than the ionization energy needed to detach a single
20 electron completely from its parent nucleus. However, selection
21 rules may prevent that ionization from taking place. The result
22 is that optical transitions occur between a doubly-excited level
23 and another level of lower energy. Doubly-excited levels are
24 generated prolifically in the beam-foil source, particularly for
25 light elements in the He I and Li I isoelectronic sequences. Some
26 such states have also been identified in Na I, Mg II, and Ca II.
27
28

1 New Developments. While the great majority of BFS experiments
2 treat light, groups of electrons with well-defined energies also
3 arise from the foil-excited particles. These Auger electrons give
4 information about the electronic structures of complicated systems.
5 Pegg and Sellin have shown that metastable configurations, involv-
6 ing core excitation, are not uncommon in three-electron ions from
7 oxygen (5+) to argon (15+). These experiments, which include life-
8 time measurements, deal largely with forbidden transitions in
9 which relativistic effects are important. As an example, consider
10 the doubly-excited state $(1s2s2p) 4p_{5/2}^o$. Comparison of experiment
11 and theory for the decay rate indicates a disparity which in-
12 creases fairly rapidly with nuclear charge. It is interesting
13 that the difference reflects measured decay rates which exceed
14 the calculated ones. In optical BFS lifetime work, the dis-
15 crepancies between measurement and theory are usually in the
16 opposite sense.

17 Some of the metastable levels seen in this Auger-electron work
18 have also been detected in BFS experiments on x-rays.

19 An electronic level can be characterized by several numbers,
20 among them, the total angular momentum quantum number, J. Each
21 level contains $(2J + 1)$ states. In ordinary light sources, those
22 states are equally populated, but in the beam-foil source they
23 are distributed non-uniformly. This "alignment" causes the emit-
24 ted light to be linearly polarized; the polarization can be affect-
25 ed by an external magnetic field. Measurements of the polariza-
26 tion as a function of magnetic field give information on the Landé
27 g-factor, and can also be used to determine lifetimes independent
28

1 of the line-blending and cascade-repopulation problems which enter
2 into standard lifetime experiments. Furthermore, hyperfine ef-
3 fects can also be studied because of the imbalance mentioned above.
4 Usually the excited foil is perpendicular to the particle beam.
5 However, tilting the foil introduces a new feature into the emit-
6 ted light, which is now circularly polarized. This circular po-
7 larization reflects the "orientation" of the excited state, i.e.,
8 the total angular momenta of a large fraction of the particles all
9 point in the same direction. Orientations of 50% or more have
10 been reached by reflecting a beam of ions from the polished sur-
11 face of a solid, the effects being enhanced at grazing-incidence.
12 Some recent work has involved sending a laser beam across the
13 beam of excited particles. The laser wavelength can be Doppler-
14 shifted so as to coincide with the wavelength of a transition be-
15 tween some foil-excited level and a higher one. The decay of the
16 upper state can then be monitored by means of different transi-
17 tions. This technique promises to produce spectral lines with
18 much smaller widths than can now be obtained. In addition, life-
19 times determined for the upper states should be free from both
20 line-blending and cascade-repopulation effects.
21 Numerous lifetime measurements have now been reported for a wide
22 variety of levels, stages of ionization, and elements. Two major
23 applications of these results have been made to astrophysics and
24 to theory. In astrophysics, the intensity of a spectral line as
25 seen by astronomers is proportional to the number of source atoms
26 (or ions) and to the lifetime of the relevant excited level.
27 Whaling and collaborators have measured the lifetimes of a number
28

1 of levels in Fe I and Fe II. From their data, they showed that
2 the iron content of the sun is some ten times higher than earlier
3 data had suggested. This finding, which has been corroborated by
4 related work on non-beam-foil light sources, has major conse-
5 quences for the theory of the evolution of the chemical elements.
6 Beam-foil lifetime data are now sufficiently numerous that they
7 can guide theorists along the correct calculational lines; con-
8 versely, the calculations serve as indicators of which experiments
9 should be carried out or redone.
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