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Hyperfine interactions of excited nuclei in highly ionized atoms†

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Abstract. The hyperfine interaction of excited nuclear levels with deeply ionized atoms is discussed. A measurement is reported for $^{18}O[2^+]$ at 1·98 MeV interacting with 7^+ ions in the 1s state. Limits for the g factor of this level are reported as: $0{\cdot}2 < |g| < 0{\cdot}36$. The excitation pattern of highly stripped ions is considered and it is concluded that such ions are formed in two distinct patterns, one characterized by predominant ground state occupation and the other by prolific excitation. The feature which determines the pattern is the degree of isolation of the ground state of the ions.

1. The production of highly ionized atoms

Hyperfine interactions in highly ionized atoms have recently been observed in a number of cases (Ben-Zvi *et al* 1968, Berant *et al* 1971, Faessler *et al* 1971 and Goldring *et al* 1972), and experiments of this type are now likely to develop into potent tools for measuring magnetic moments of nuclear excited states, in particular for light nuclei.

The motivation for hyperfine interaction measurements is usually the study of nuclear parameters, but the physics involved in these measurements itself is always atomic physics. In this particular case the atomic scene is constituted by the beams of highly ionized, high velocity ions emerging from a foil.

It is well known that the charge distribution in such beams reaches, after a short initial thickness of foil, an equilibrium which is independent of the initial charge distribution and of the foil thickness. The equilibrium charge distribution depends essentially only on the nature of the ion and on its velocity. The various ions are evidently produced by repeated loss and capture of electrons in successive collisions of the moving ion with the atoms of the solid. A qualitative description of these processes is afforded by the theory of Dmitriev (1957) which is based on a number of broad and general assumptions:

(i) The various electronic states are characterized by one number: The mean orbital velocity v_1.

(ii) The probability for stripping off an electron is a universal function of v/v_1. The universal function $\phi_i(v/v_1)$ is shown in figure 1 as determined from measurements of the ionization of hydrogen in air.

(iii) The neutral atoms are considered to be in their ground state and the possible production of highly excited states is consistently ignored.

The theory of Dmitriev is fairly adequate for the description of the charge distribution of very deeply ionized atoms stripped in foils. The theory fails for atoms in a low degree of ionization.

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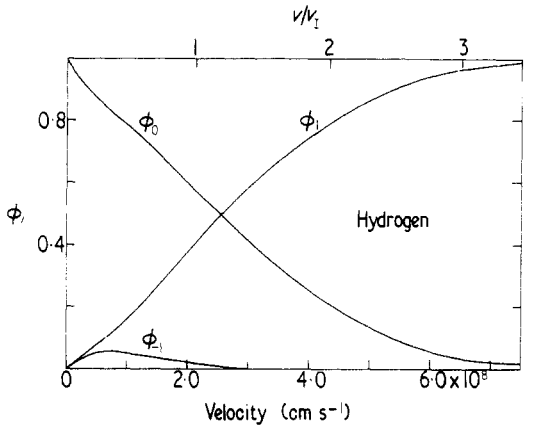

Figure 1. The probability $\phi_i(v)$ for ionization to the charge state i of hydrogen atoms travelling through air as a function of v. The upper scale shows v in terms of the characteristic velocity v_1. $\phi_1(v/v_1)$ is the universal probability function of the Dmitriev theory.

In gas stripping one consistently finds a lower average charge than in foil stripping. This is generally ascribed to the very large difference (a factor of about 10^6) in the collision time in the two cases. In a solid the electrons are presumed to be removed in the stripping process from the same states in which they were previously captured, whereas in the gas there is usually sufficient time for them to decay to lower levels where the subsequent stripping will be more difficult and less probable.

There is a remarkable difference in the process of gas stripping in light ions such as oxygen and heavy ions like iodine in the energy range generally encountered in the terminal of tandem accelerators: whereas for light ions the mean charge in gas stripping is only slightly less than in foil stripping, the corresponding difference for heavy ions is very large. For example, for 12 MeV iodine ions the mean charge in oxygen gas and carbon foil strippers is 6 and 11 respectively (Ryding *et al* 1971).

2. Hyperfine interactions in isolated atoms

The hyperfine interaction in a given state in an isolated atom can be represented by the triangles shown in figure 2, where $\boldsymbol{I}$ and $\boldsymbol{J}$ are the angular momenta of the nucleus and the atom respectively and $\boldsymbol{F}$ is the total angular momentum which is a constant of the motion. If the nuclei are polarized in the initial excitation, the subsequent hyperfine interaction will tend to depolarize them because the atomic angular momenta $\boldsymbol{J}$ are randomly distributed, resulting in a spreading of the vectors $\boldsymbol{F}$ and a broadening of the pencil of the vectors $\boldsymbol{I}$ as each of them moves with respect to the $\boldsymbol{F}$ associated with it. The changes of the polarization are periodical but the mean polarization, averaged over the nuclear mean life, will always be equal to or less than the initial polarization. The polarization will however never be completely destroyed, even for arbitrarily large hyperfine interactions, because the vectors $\boldsymbol{F}$ and the extreme positions of vectors $\boldsymbol{I}$ are confined within cones that are determined by the relative magnitude of $\boldsymbol{I}$ and $\boldsymbol{J}$; the cones will be narrower and the limiting polarization larger, the larger the ratio of $\boldsymbol{I}$ to $\boldsymbol{J}$. This is referred to as hard core residual polarization.

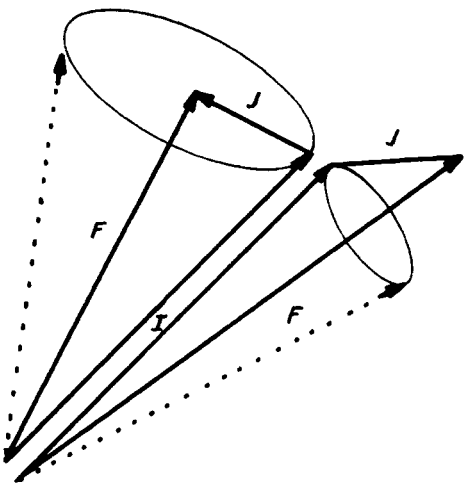

Figure 2. The coupling of the vectors I, J and F. The motion of I due to the interaction $I.J$ is indicated.

In the case of s electrons the motion induced by the hyperfine interaction can be described by a single Larmor frequency ω given by

$$\omega = \frac{\mu_N g H(0)}{\hbar}(2I+1)$$

where μ_N is the nuclear magneton, g is the gyromagnetic ratio of the nuclear level and $H(0)$ is given for hydrogen-like states with quantum numbers n, l, j, by

$$H(0) = \frac{Z^3}{n^3}\frac{1}{(l+\frac{1}{2})(j+1)}K \qquad K = \frac{hcR_\infty a^2}{\mu_B} = 0{\cdot}126\ \text{MG}.$$

In atoms with one electron outside of closed shells the fields are very similar to the one electron fields quoted above, provided the total number of electrons is small. Characteristic fields of some few-electron doublet configurations are listed in table 1.

It is evident that for any given atom the fields are ordered in a hierarchy of magnitude as the energy of excitation increases.

The effects of the hyperfine interactions are observed experimentally as a modification of the angular distribution of gamma rays emitted from the nuclear level in question. In the most general case the angular distribution will be given by

$$W(\theta, \phi) = \sum_{k,q} A_{kq} Y_{kq}(\theta, \phi). \tag{1}$$

Table 1.

	$H(0)$(MG)		
Atomic species	$(1s)^1 1\ ^2S_{1/2}$	$(1s)^2(2s)^1 2\ ^2S_{1/2}$	$(1s)^2(2s)^2(2p)^1 2\ ^2P_{1/2}$
Oxygen	85·5	7	1
Fluorine	122	10	2
Neon	167	15	3
Magnesium	289	30	6

This expression is considerably simplified if the experimental system has cylindrical symmetry, as for example in the system shown in figure 3, where scattered particles or reaction products are detected in a ring counter in the backward direction. This system has an added advantage for the type of experiment considered here in that it tends to produce high recoil velocities.

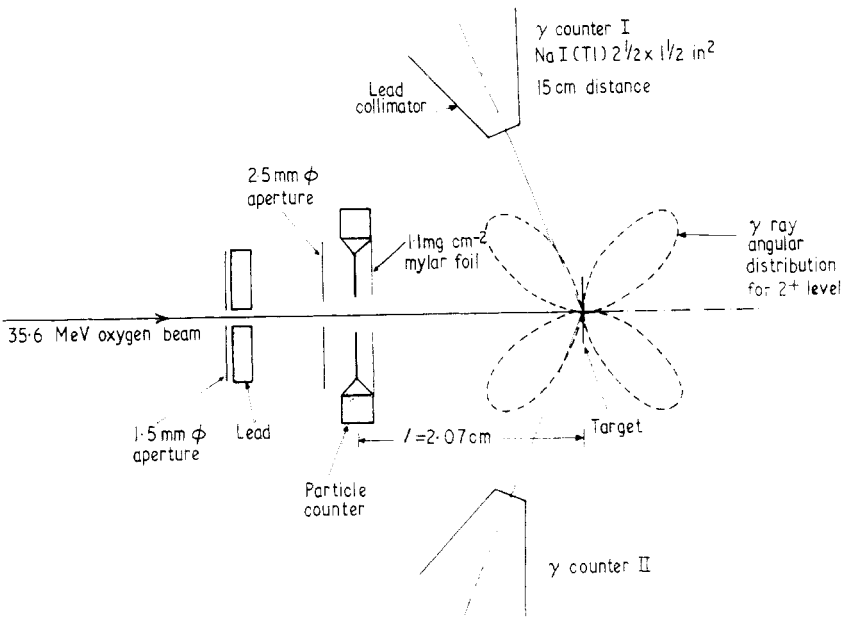

Figure 3. A frequently used experimental arrangement with cylindrical symmetry around the beam, yielding high recoil velocities.

In such cases the angular distribution of the gamma rays is given by

$$W(\theta) = \sum_k A_k P_k(\cos\theta) \qquad k \text{ even} \tag{2}$$

relative to the symmetry axis. Any modification caused by an ensemble of no lesser symmetry can be expressed by

$$\tilde{W}(\theta) = \sum_k A_k G_k P_k(\cos\theta) \qquad k \text{ even} \tag{3}$$

where the G_k are the attenuation coefficients, and $|G_k| \leqslant 1$. In integral measurements, where the attenuation is averaged over the nuclear lifetime, $G_k \geqslant 0$.

In the general case represented by (1), the perturbation by a spherically symmetric ensemble leads to a distribution

$$\tilde{W}(\theta, \phi) = \sum_{k,q} A_{kq} G_k Y_{kq}(\theta, \phi). \tag{4}$$

For hyperfine interactions in s levels the time integrated attenuation coefficients are given by

$$G_k = 1 - \frac{k(k+1)}{(2I+1)^2} \frac{(\omega\tau)^2}{1+(\omega\tau)^2} \tag{5}$$

or, introducing the attenuation parameter η

$$G_k = 1 - k(k+1)\eta$$
$$\eta = \frac{1}{(2I+1)^2} \frac{(\omega\tau)^2}{1+(\omega\tau)^2}. \tag{6}$$

The quantity $(\omega\tau)^2/\{1+(\omega\tau)^2\}$ is shown in figure 4 for the lowest doublet configurations. When this quantity is zero there is no perturbation, and the saturation value of unity corresponds to hard core perturbation. The hyperfine perturbations can also be computed for more complex configurations but the calculations are considerably more involved.

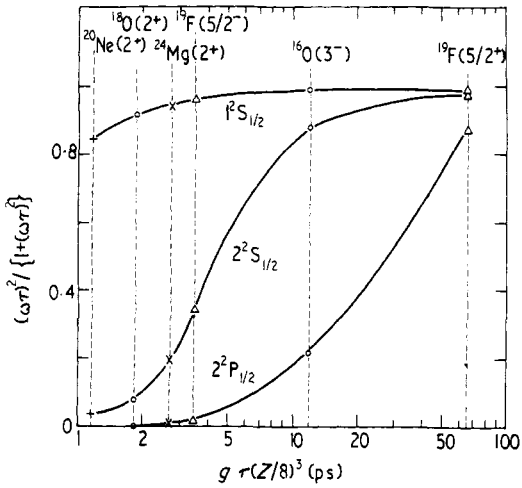

Figure 4. The quantity $(\omega\tau)^2/\{1+(\omega\tau)^2\}$ as function of the nuclear parameter $g\tau(Z/8)^3$.

If the atoms are distributed among a variety of configurations i with probabilities $p(i)$ then the overall attenuation coefficients will be given by

$$G_k = \sum_i p(i)G_k(i)$$

or

$$\eta = \sum_i p(i)\eta(i).$$

Evidently in any given case there is only a limited number of configurations that are 'turned on'.

The basic atomic problem in such measurements is the knowledge or evaluation of the coefficients p_i. In general there is very little *a priori* information on these parameters and one can estimate them only in cases where there is reason to believe that most of the ions are in their ground states and where therefore the distribution of atomic levels is linked to the rather well known charge distribution of the ions.

An example of an angular distribution perturbed by such hyperfine fields is shown in figure 5 (Berant *et al* 1971) relating to the reaction $^{19}F(p, \alpha)^{16}O[3^-]$. When the excited nuclei recoil into an aluminium backing one observes the full correlation whereas recoiling into vacuum the correlation exhibits an attenuation caused by hyperfine fields.

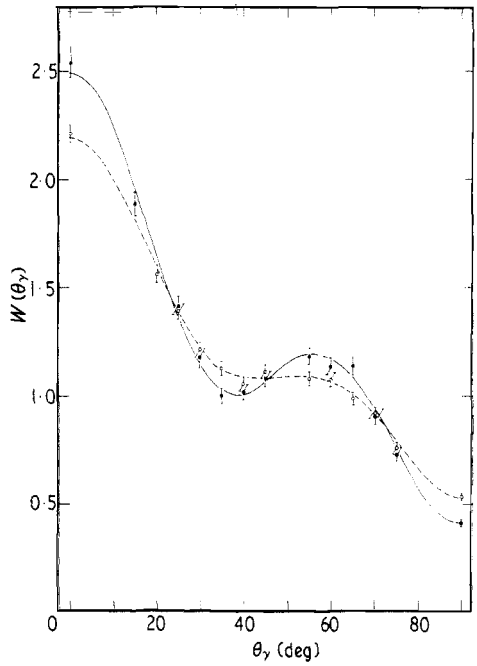

Figure 5. The gamma ray angular distribution in the same geometry as that of figure 3, for the reaction $^{19}F(p, \alpha\gamma)^{16}O$ at the 873 keV resonance, following recoil into aluminium (full curve and full circles) and vacuum (broken curve and open circles).

3. A survey of experiments

The important case of one electron systems was first examined by Faessler *et al* (1971) in an attenuation measurement, carried out in the geometry of figure 3, on the first excited 2^+ state of ^{20}Ne with a mean life τ of 1·2 ps, following the reaction $^{12}C(^{12}C, \alpha)^{20}Ne[2^+]$. Only the 1s state is expected to be turned on for this level (see figure 4).

The observed attenuation coefficients G_4 are shown in figure 6 as a function of the ion velocity. The following conclusions can be drawn from this measurement:

(i) The measured points follow rather closely the probability ϕ_9 for 9^+ ionization, as a function of the neon velocity (curve A in figure 6) signifying that the perturbation is associated with 9^+ ions.

(ii) If one compares the measured perturbation with the calculated value of figure 4, (with a reasonable estimate of the value of the g factor) one obtains a coefficient $(p_9(1s))$ which is close to unity. In other words, the majority of the 9^+ ions are in their ground state.

More detailed information on hydrogen-like configurations was obtained in a recent measurement relating to the first excited 2^+ state in ^{18}O (Berant *et al* 1971) with a mean life τ of $3{\cdot}25 \pm 0{\cdot}20$ ps (Lawson 1968). The 2^+ state is excited by inelastic scattering of ^{18}O on ^{12}C, and the angular distribution of the subsequent gamma rays is observed. The geometry of the experiment is shown in figure 7.

The predominant charge states of the emerging oxygen ions are 8^+, 7^+ and 6^+. Here again only the 1s hyperfine interaction is expected to be turned on (see figure 4). The observed gamma distribution (figure 7) is a superposition of the unperturbed

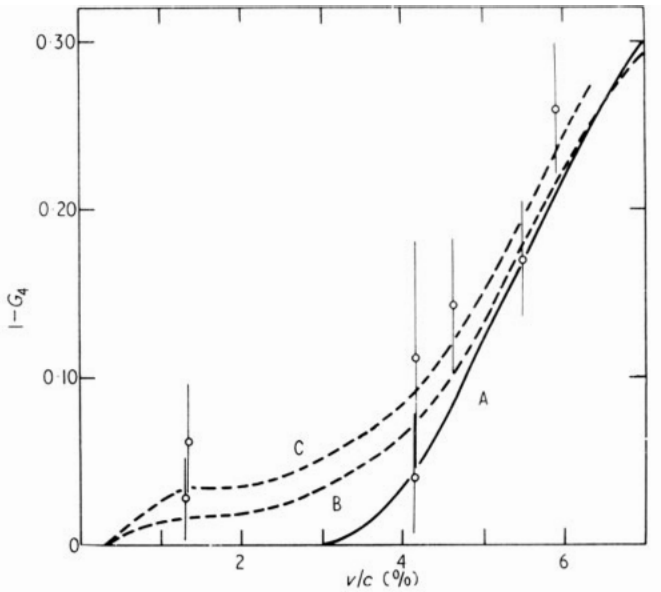

Figure 6. The coefficient G_4, measured in the same geometry as in figure 3, for the gamma rays emitted from the first excited 2^+ state in ^{20}Ne following recoil into vacuum (Faessler *et al* 1971). Curve A follows the probability ϕ_9 for the 9^+ ionization state.

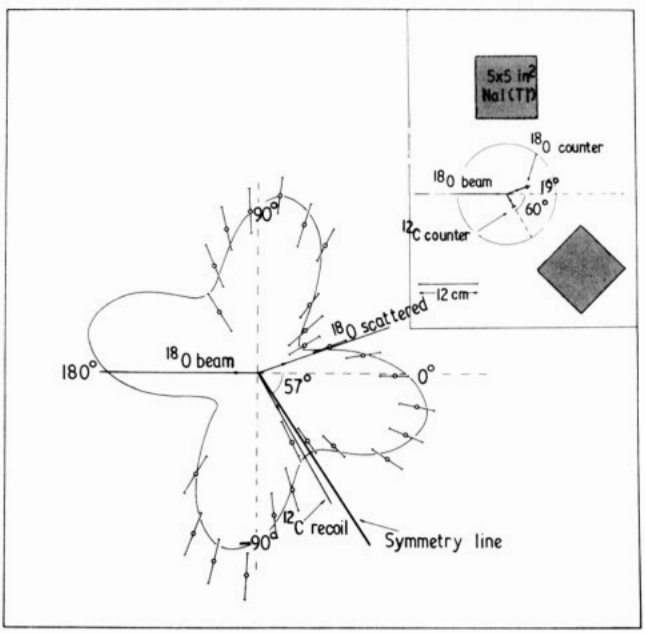

Figure 7. Angular correlation of the 1·98 MeV γ transition in ^{18}O following projectile excitation (^{12}C(^{18}O, ^{18}O*)^{12}C, $E_{^{18}O}$ = 33 MeV). Coincidence with both scattered ^{18}O and recoiling ^{12}C nuclei was required. The reaction plane geometry is shown schematically in the inset.

distribution in the 8^+ state and distributions perturbed by 1s electrons in 7^+ ions and by unpaired 1s electrons in 6^+ ions.

This particular experimental arrangement does not have cylindrical symmetry. There are however restrictions imposed by the symmetry of reflection with respect to the reaction plane (Bohr 1959 and Cramer and Eidson 1964). The most general unperturbed distribution can in this case be represented by

$$W(\theta, \phi) \propto \sin^2\theta\{(a_2^2+1)(1+\cos^2\theta)+6a_0^2\cos^2\theta - 2\sqrt{6}a_0\cos^2\theta(a_2\cos[2\{\phi-\tfrac{1}{2}(\delta_2-\delta_0)\}]+\cos\{2(\phi-\tfrac{1}{2}\delta_0)\}) - 2a_2\sin^2\theta\cos\{4(\phi-\tfrac{1}{4}\delta_2)\}\} \quad (7)$$

where θ, ϕ refer to a coordinate system with the z axis perpendicular to the reaction plane and the x axis along the beam. The unperturbed distribution in the reaction plane is given by

$$W(\tfrac{1}{2}\pi, \phi) \propto (a_2^2+1)-2a_2\cos\{4(\phi-\tfrac{1}{4}\delta_2)\}. \quad (8)$$

The perturbed distribution will in general depend also on the other coefficients a_0 and δ_0.

The analysis of the perturbed distribution will be discussed in detail later on. At this point we only refer to the perturbation as a guide in the determination of the angle $\frac{1}{4}\delta_2$ between the beam direction and the symmetry axis in the reaction plane. The function $W(\frac{1}{2}\pi, \phi)$ in (8) determines $\frac{1}{4}\delta_2$ only to within $\frac{1}{2}\pi$ because of the $\frac{1}{2}\pi$ periodicity of this expression. For the perturbed distribution there is however a marked difference between these two possible solutions, because a magnetic perturbation (equations (5) and (6)) of a cylindrically symmetric distribution $1-\cos(4\phi)$ yields a ratio

$$\frac{W(0)}{W(\frac{1}{2}\pi)} = 2.$$

We expect this relation to carry over, at least qualitatively, into the distribution of figure 7, and we therefore determine the symmetry axis as the line through the shallower of the two minima in figure 7, that is, $\frac{1}{4}\delta_2 = 57°$. The symmetry axis appears to be very close to the direction of the recoiling ^{12}C which is the direction of momentum transfer by the excited ^{18}O nucleus.

The same reaction has recently been studied in greater detail at the Nuclear Physics Laboratory in Oxford (Goldring *et al* 1972). In this measurement the geometrical arrangement of figure 7 was taken over but the ^{18}O particle detector was replaced by a magnetic spectrometer which resolved the ^{18}O into the component predominant charge states, 8^+, 7^+, 6^+, and the angular correlation of the gamma rays was determined separately for each charge state. The gamma detectors were 3×3 in^2 NaI scintillation counters. They were placed at fixed positions indicated in figure 8, the counters in the reaction plane at positions corresponding to 0°, 45° and 90° with respect to the presumed symmetry axis (ie at $(\frac{1}{2}\pi, \frac{1}{4}\delta_2)$, $(\frac{1}{2}\pi, \frac{1}{4}\delta_2+\frac{1}{4}\pi)$ and $(\frac{1}{2}\pi, \frac{1}{4}\delta_2+\frac{1}{2}\pi)$), and a fourth counter at 90° to the symmetry axis and 60° out of the plane $(\theta, \phi) = (\frac{1}{6}\pi, \frac{1}{4}\delta_2+\frac{1}{2}\pi)$.

The measured angular distributions are shown in figure 9. The 8^+ distribution represents the unperturbed distribution and it is seen to resemble rather closely a pure $2 \to 0$, $I_z = 0$ distribution with z along the symmetry axis. The strong perturbation in the 7^+ charge state and the rather weak perturbation in the 6^+ state suggest again that these ions are predominantly in their respective ground states.

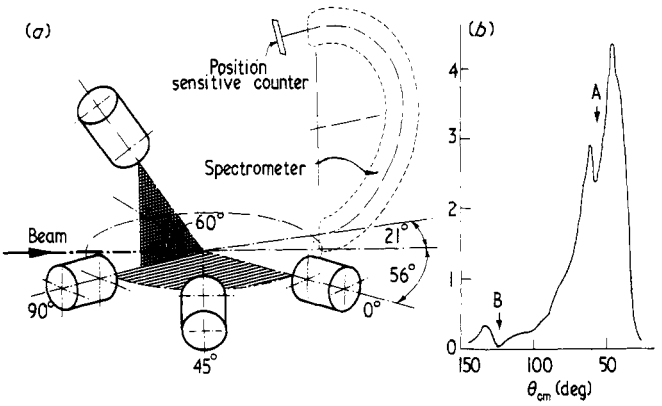

Figure 8. (*a*) Schematic view of spectrometer and counter assembly. The three scintillators in the reaction plane are at laboratory angles of 52·7°, 97·7° and 144·7° to the beam, or 0°, 45° and 90° (in the $^{18}O^*$ rest frame) with respect to the symmetry axis at $\frac{1}{4}\delta_2 = 56°$ (lab). The 'ϕ' detector is also at 90° but inclined 60° to the reaction plane. In the system of co-ordinates used in the text, the four counter angles are (in the $^{18}O^*$ rest frame) at $(\frac{1}{2}\pi, \frac{1}{4}\delta_2)$, $(\frac{1}{2}\pi, \frac{1}{4}\delta_2 + \frac{1}{4}\pi)$, $(\frac{1}{2}\pi, \frac{1}{4}\delta_2 + \frac{1}{2}\pi)$ and $(\frac{1}{6}\pi, \frac{1}{4}\delta_2 + \frac{1}{2}\pi)$ respectively. (*b*) Measured differential cross section of inelastically scattered $^{18}O(E_{^{18}O} = 35\,\text{MeV})$. Arrows refer to the spectrometer acceptance angles for $^{18}O^*$(A) and the kinematically coincident ^{12}C(B).

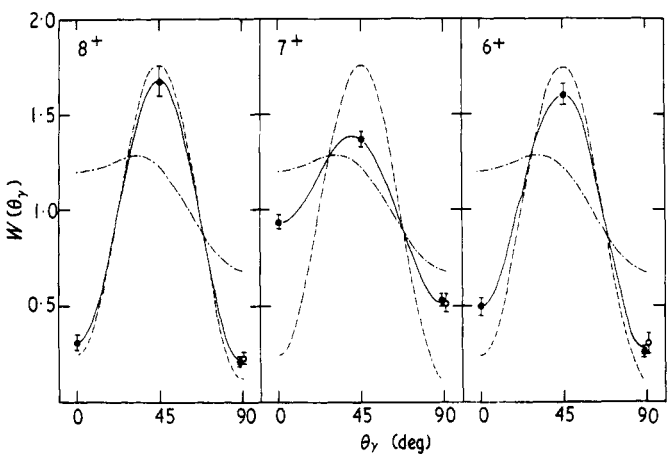

Figure 9. Angular distributions of gamma rays in coincidence with ^{18}O ions in the 8^+, 7^+ and 6^+ charge states. Full data points represent reaction plane detectors and open circles signify the out of the plane detector. Counting rates have been corrected for movement of the gamma emitting source. Also shown are calculated curves for a pure $2 \rightarrow 0$, $I_z = 0$ correlation and for maximum (hard core) perturbation.

If in the angular distribution (7) $a_2 = 1$, the two remaining parameters, a_0 and δ_0 are also determined, and $a_0 = (1 + a_2)/\sqrt{6}$, $\delta_0 = \pi$. In this case the angular distribution reduces to the $I_z = 0$ distribution

$$W(\theta, \phi) \propto 4 \sin^2(2\Theta) \tag{9}$$

where Θ signifies the polar angle with respect to the symmetry axis in the direction $(\frac{1}{2}\pi, \frac{1}{2}\delta_2)$, and

$$\cos\Theta = \sin\theta \cos(\phi - \tfrac{1}{4}\delta_2).$$

The measured 8^+ distribution comes close to the pure distribution (9), but it allows a small component which does not have cylindrical symmetry. The three parameters a_2, a_0, δ_0 can be determined from (i) the 8^+ distribution in the reaction plane, (ii) a comparison of the angles $(\frac{1}{2}\pi, \frac{1}{4}\delta_2 + \frac{1}{2}\pi)$ and $(\frac{1}{6}\pi, \frac{1}{4}\delta_2 + \frac{1}{2}\pi)$ in the 8^+ distribution, and (iii) a similar comparison in the 7^+ distribution. With these values of the parameters the perturbation parameter η can be determined according to equation (4). One finds, however, that the contribution of the noncylindrically symmetrical part to the perturbation is quite insignificant. The computation of the parameter η can therefore be simplified by assuming the distribution to be strictly cylindrically symmetrical around the axis $(\frac{1}{2}\pi, \frac{1}{4}\delta_2)$ and applying equations (2) and (3).

By comparing the 6^+ and 7^+ correlations with the unperturbed 8^+ correlation one can evaluate the attenuation coefficients for those two charge states. The attenuation parameter for the 7^+ ions can be expressed as

$$\eta(7) = p_7(1s)\frac{1}{(2I+1)^2}\frac{(\omega\tau)^2}{1+(\omega\tau)^2} \qquad I = 2$$

where $p_7(1s)$ is the fraction of ions in the 1s configuration. One obtains from the measurements

$$p_7(1s)\frac{(\omega\tau)^2}{1+(\omega\tau)^2} = 0{\cdot}688 \pm 0{\cdot}028. \tag{10}$$

Without independent information on the distribution of electronic excitations, only limits can be set on the parameter $p_7(1s)$ and one gets

$$1 > p_7(1s) > 0{\cdot}65$$

the lower limit corresponding to hard core perturbation. The upper limit for $p_7(1s)$ implies

$$|g| > 0{\cdot}2.$$

An indication of considerably higher ground state occupation in the 7^+ ions is furnished by recent measurements on the relative electron pick-up cross section to the 2s state for 6^+ carbon ions for comparable velocity (D E Murnick, M Leventhal and H Kugel, private communication). A value of $(2{\cdot}2 \pm 1{\cdot}0)\%$ was found, implying predominant ground state population. This result is in good agreement with Born approximation calculations (Schiff 1954), according to which some 0·8 of these ions are formed in the ground state, and another fraction R reach it from the 2p state in time to cause a perturbation. Here

$$R = \frac{\tau}{\tau + \tau_{2p}} \times 0{\cdot}07$$

and τ_{2p} is the mean life of the 2p level calculated to be 0·4 ps (Bethe and Salpeter 1957).

On the basis of these values and considerations one obtains

$$p_7(1s) > 0{\cdot}86$$

and

$$0{\cdot}36 > |g| > 0{\cdot}20.$$

The upper limit on the absolute value of the g factor is of interest because the dominant components of the $^{18}O[2^+]$ wavefunction, $(d_{5/2})^2$ and $d_{5/2}, s_{1/2}$, imply values of g

ranging from $-0{\cdot}76$ to $-0{\cdot}51$ (Talmi 1971). However, a small admixture of $d_{5/2}$, $d_{3/2}$ could account for a negative g factor of the magnitude quoted (I Talmi, private communication). A recent calculation (J Millener, private communication) with Kuo–Brown wavefunctions yielded a value

$$g = 0{\cdot}246$$

in good agreement with the experimental value.

4. Conclusions relating to population patterns

The limits and estimates for the population parameter $p_7(1s)$ indicate that the 7^+ ions are predominantly in their ground states. This conclusion is consistent with the findings of Faessler *et al* (1971) mentioned above for the first excited state of ^{20}Ne. Thus quite generally, either the ions are formed in their ground states or they are formed in states which decay to the ground state in times which are short compared with the nuclear lifetime. The population of the ground state via long cascades is ruled out since most atomic transitions are considerably slower than the $2p \rightarrow 1s$ decay.

The predominance of the ground state occupancy can be understood within the framework of the Dmitriev theory in the following way: the ions are presumed to be stripped down to a charge state whose ground state has a characteristic velocity v_1 which matches the translational velocity of the ions. The ions can also be formed in excited states within the matching width corresponding roughly to a factor of two in velocity. For hydrogen-like ions produced with a velocity matching the 1s level, the $n = 2$ level is barely within the matching width and all higher levels are excluded.

The above considerations also explain the radically different pattern of hyperfine interaction encountered in heavy nuclei, namely, perturbations characterized by long and complex cascades of optical transitions (Ben-Zvi *et al* 1968). In these cases the ions have ground states with large principal quantum numbers implying in general a large level density and consequently a large number of levels within the matching width.

Another striking example of the 'cold' type of ionization considered above is found in a recent study of the perturbation of the second excited state in ^{41}K at 1·294 MeV excitation, with $J^\pi = 7/2^-$ and $\tau = 10{\cdot}5 \pm 0{\cdot}3$ ns, travelling in argon gas and following the capture reaction $^{40}\mathrm{Ar}(p, \gamma)^{41}\mathrm{K}[\frac{7}{2}^-]$ at $E_p = 1{\cdot}1$ MeV (A Szily Lépine, W A Seale and O Sala, private communication). The perturbation was studied as a function of gas pressure, and led to the conclusion that the two prolific charge states, K (neutral) and K^+, are both formed predominantly in their respective ground states. This behaviour is again in accord with the ionization patterns discussed above since both these ions—respectively a closed shell atom and a closed shell plus single electron atom—have well isolated ground states.

A measurement relating to hyperfine fields associated with the $n = 2$ atomic state is reported in (Berant *et al* 1971). It concerns the 3^- state in ^{16}O at 6·13 MeV with a mean life of 24 ps. Both 1s and 2s fields are expected to be turned on for this state. Attenuation coefficients for atoms recoiling into vacuum were determined within a large range of velocities. The results indicate that (i) with regard to the principal quantum number n, most ions are in their ground state configuration, and (ii) the 2s and 2p levels are populated with equal *a priori* probabilities.

This state of affairs is again readily explained in terms of the finite width of the velocity matching condition; the $n = 2$ level is still sufficiently isolated to be preferentially

populated, but the 2p–2s separation is much less than the velocity matching widths, and these two levels are therefore populated with equal *a priori* probability.

Finally, we return to two points raised in the beginning, namely, the fact that the theory of Dmitriev is adequate for very high states of ionization but inadequate for low ionizations, and the notable difference in gas stripping of say, oxygen and iodine at energies corresponding to tandem terminal voltages. In oxygen the mean charge is not very different from that obtained in a foil stripper, whereas in iodine the mean charges in the two types of stripper differ by about a factor of two. This can now be seen to relate very closely to the other features of stripped ions discussed above. The highly stripped ions are produced predominantly in the ground state and in the states immediately above it. These are the conditions which fit most closely the basic assumption of the Dmitriev theory and this is also the case where the intermediate decays characteristic of gas stripping are expected to be of least significance for the charge distribution.

We note in conclusion that stripped atoms exhibit two very distinct regimes. One is characterized by a dominant ground state occupation and the other by a complex pattern of excitation in highly excited states. The distinctive feature which determines the pattern is the degree of isolation of the ground state, or more precisely: the number of states within the width of the velocity matching function.

References

Ben-Zvi I *et al* 1968 *Nucl. Phys.* A **121** 592–611
Berant Z *et al* 1971 *Nucl Phys.* A **178** 155–71
Bethe H A and Salpeter E E 1957 *Handb. Phys.* **35** 88–436
Bohr A 1959 *Nucl. Phys.* **10** 486–91
Cramer J G and Eidson W W 1964 *Nucl. Phys.* **55** 593–612
Dmitriev I S 1957 *Sov. Phys.–JETP* **5** 473–7
Faessler M, Povh B and Schwalm D 1971 *Proc. Conf. on Hyperfine Interactions in Excited Nuclei, Rehovot* 1970 eds G Goldring and R Kalish (London: Gordon and Breach) pp 968–9
Goldring G *et al* 1972 *Phys. Rev. Lett.* **28** 763–6
Lawson P G 1968 *PhD Thesis*, Oxford University
Ryding G, Wittkower A and Rose P H 1971 *Particle Accelerators* **2** 13–6
Schiff H 1954 *Can. J. Phys.* **32** 393–405
Talmi I 1971 *Proc. Conf. on Hyperfine Interactions in Excited Nuclei, Rehovot* 1970 eds G Goldring and R Kalish (London: Gordon and Breach) pp 1133–69