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LETTER TO THE EDITOR

The Hanle effect in Penning-excited ions†

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Abstract. A thermal beam of helium (2^3S_1) metastable atoms was used to excite coherently the $^2P_{3/2}$ levels of Ca, Sr and Ba in a Penning ionising collision. The coherent excitation of the ions appears as a linear polarisation of the optical emission from the excited ions. The degree of linear polarisation is 5·5, 3·5 and 0·5% for Ca, Sr and Ba, respectively, with the polarisation parallel to the beam direction. Hanle effect signals from the $^2P_{3/2}$ level of Sr were observed and the radiative decay rate measured.

The rate at which angular momentum states are populated in beam excitation processes is attracting increasing attention since such studies can yield detailed information about the kinetics of the collision process. Collisional excitation of an atomic system in general leads to an anisotropic excited state; i.e. a non-random population of the angular momentum substates. Such anisotropic distributions appear as linear and vector polarisations of line radiation, coherence effects, orientation and alignment of the excited species, and the non-uniform distribution of collision fragments, among others (Fano and Macek 1973). These collisional excitation processes have employed electron excitation (Kleinpoppen 1969), ion impact (Thomas 1972), or beam–foil techniques (Tillman *et al* 1973). Recently Kempter and co-workers extended such observations to collisions between two neutral particles, K + Ar (Alber *et al* 1975). They observed an alignment of the potassium excited states which they attributed to a non-statistical population of the Π and Σ molecular states correlating with the $K(^2P_{3/2}) + Ar(^1S_0)$ states of the separated atoms. We have also reported briefly similar observations in which a neutral 800 eV helium (1^1S_0) beam coherently excites atomic targets of Sr and Ca (Fahey and Schearer 1978). In each of the above instances, the excitation energy is derived from the kinetic energy of the particle beam; i.e. a collision of the first kind.

Here we report the observation of the coherent excitation and corresponding alignment of excited atomic ions which are produced in Penning ionising collisions between an unpolarised thermal beam of helium metastable atoms and group II metal vapour targets (Sr, Ca and Ba). We have utilised the coherent excitation of the $Sr(^2P_{3/2})$ ion by this collision process to observe zero-field level crossing signals (Hanle effect) and have measured the radiative decay rate. This represents a case in which the excitation energy is derived from the internal energy of the beam particle; i.e. a collision of the second kind. In the only other example we are aware of in which the excitation energy is not derived from the kinetic energy of one of the collision partners, Jonah *et al* (1972) observed a weak linear polarisation of the optical emission from electronically

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excited BaO molecules formed in the chemi-luminescent reaction between Ba and NO_2. The polarisation in this case was attributed to a partitioning of angular momenta between the rotational angular momentum of the BaO and the recoil angular momenta of the reaction products.

In many of the heavy particle collisions, the anisotropic excited states produced are closely associated with the formation of a quasi-molecule during the collision. The observed alignment is then interpreted as a coherent excitation of the quasi-molecule. Micha and Nakamura (1975) have demonstrated the utility of the quasi-molecular states in the united atom limit in explaining some of the features of the Penning ionisation process. The Penning process is then viewed as a transition between quasi-molecular states, namely:

$$\begin{aligned} \mathrm{He}(2^3\mathrm{S}_1) + \mathrm{Sr}(^1\mathrm{S}_0) &\rightarrow \mathrm{HeSr}^+(^2\Sigma, {}^2\Pi) + \mathrm{e} + \mathrm{KE} \\ &\rightarrow \mathrm{He}(^1\mathrm{S}_0) + \mathrm{Sr}^+(^2\mathrm{P}_{3/2,1/2}) + \mathrm{e} + \mathrm{KE}. \end{aligned} \tag{1}$$

If one assumes with Micha and Nakamura (1975) that the electron comes off in a σ orbital, the conservation of angular momentum along the interatomic axis permits only the formation of the $^2\Sigma$ state of the quasi-molecule. One then expects to find that the $m_l = 0$ levels of the $Sr^+(^2P)$ ion, referenced to the collision axis, are preferentially populated. If the scattering cross section is non-isotropic (i.e. if the distribution of the orientations of the molecular axes at ionisation is anisotropic), then the light emitted by the radiative decay of the $Sr^+(^2P_{3/2})$ ions reveals this anisotropy through the polarisation of the emitted light. The ion alignment with respect to the beam axis is a consequence of the coherent state of the ion formed in the Penning process. This coherence between Zeeman levels can be destroyed by the application of a magnetic field which lifts the degeneracy of the Zeeman levels. The accompanying change in the polarisation of the emitted radiation is well known as the Hanle effect (Hanle 1924).

We note here that the observed Penning ion alignment requires only that the Σ and Π molecular states be non-statistically populated. Thus, the assumption that the electron comes off in a σ orbital is unnecessarily restrictive. One can show, moreover, that with the measurement of the ion alignment reported here and a knowledge of the interaction potential, that the relative populations of the quasi-molecular states can be determined (Fahey *et al* 1979).

The metastable beam source and a description of the optical system utilised to observe the Penning process have been reported elsewhere (Fahey *et al* 1979). The linear polarisation of the optical emission from the $^2P_{3/2}$–$^2S_{1/2}$ resonance transitions in Ca, Sr and Ba were measured with the results shown in table 1. In all cases the emission was polarised parallel to the metastable beam direction.

It is seen from table 1 that the observed alignment decreases with increasing Z of the target atom. We believe this observation to be a direct consequence of the increased polarisability of the He^m–target-atom system leading to an increased well depth of the

Table 1. Observed polarisation for group II Penning ions.

	P(%)	Transition	Wavelength (nm)
Ca	5·5	$4^2P_{3/2}$–$4^2S_{1/2}$	393·4
Sr	3·5	$5^2P_{3/2}$–$5^2S_{1/2}$	407·8
Ba	0·5	$6^2P_{3/2}$–$6^2S_{1/2}$	455·4

interaction potential in the incoming channel. Ebding and Niehaus (1974) in their studies of the angular distributions of Penning electrons pointed out that the increased well depth tends to result in an increasingly isotropic average orientation of the molecular axis at ionisation. Thus, the observed linear polarisation decreases as the strength of the interaction increases.

In the classical Hanle effect linear polarised light is employed to excite coherently the system to be studied. Fano and Macek (1973), among others, have considered the situation in which an atomic beam is the source of the excitation. In our experiment it is the Penning ionisation process that coherently excites the ion levels.

For the Hanle measurements a uniform magnetic field was applied to the reaction region. The magnetic field was generated by an Helmholtz pair which could be modulated linearly over 100 G. The homogeneity and field calibration were accurately determined with the aid of an optically pumped helium magnetometer. The field was directed along the observation axis and perpendicular to the beam direction. The variation in intensity of the polarisation components, parallel and perpendicular to the metastable beam, with magnetic field was recorded on a digital signal averager and the two signals subtracted.

Figure 1 displays the results obtained. The full line is a computer fit to a Lorentzian whose width at half height is 37·2 G. Using a g factor of 1·33 we obtain a decay time of $4{\cdot}7\times10^{-9}$ s for the $^2P_{3/2}$ level of strontium with an estimated uncertainty of ±20%. No variation in the half width of the curve with either strontium vapour pressure or beam current was apparent. The radiative lifetime obtained in this manner is in reasonable agreement with the Hanle measurements obtained by optical excitation in the classical manner (Gallagher 1967, Kelly *et al* 1974, Rambow and Schearer 1976).

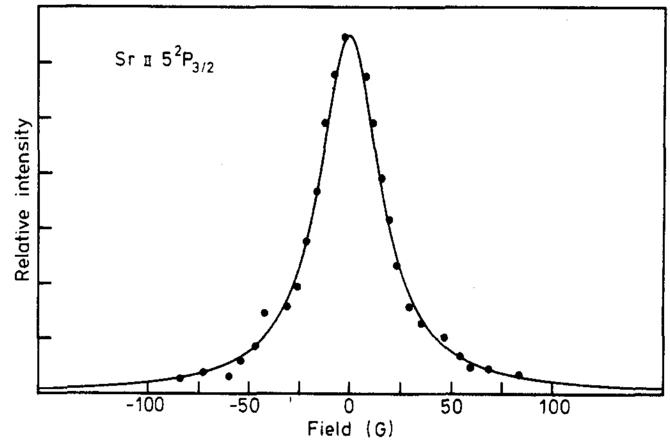

Figure 1. Hanle signal for the Sr II $5^2P_{3/2}$ level.

We have observed an alignment of Ca, Sr and Ba in the $^2P_{3/2}$ state produced in a Penning ionising collision between a helium metastable beam and the target vapour. The alignment of these ion levels is a consequence of the non-statistical population of the molecular states with respect to the collision axis, and the optical polarisation and Hanle signals are a consequence of the non-symmetrical distributions of the interatomic axis of the quasi-molecule when ionisation occurs. The observed ion polarisation is an important new parameter in the description of Penning ionisation. The observation of zero-field level crossing signals in ions excited by Penning collisions further extends this important technique for measuring radiative decay rates.

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