on the cross sections:

$$\pi^+N\to K^0\mu+\dots$$
$$\to\Lambda^0\mu+\dots,\quad p(\mu)\geq 2\ \mathrm{GeV}/c. \qquad (2)$$

Note that, in the conventional charm scheme, a large fraction of associated charm production will yield these signatures [cf. relation (1)]. These upper limits are 10.0 and 2.0 μb, respectively.

While some sets of data are under additional scrutiny at this time, we see no conclusive evidence for muon-associated production of long-lived states decaying into two, three, four, or five charged hadrons at the microbarn level. We are currently starting an improved version of this experiment, which will give us a tenfold increase in statistics while, at the same time, improving the muon enrichment by a factor of 3.

We are indebted to Professor W. K. H. Panofsky, Director of SLAC, who made quick scheduling of this experiment possible. The enthusiastic help of the Santa Cruz and SLAC technical support staffs, headed by W. Nilsson and L. Schwarcz, allowed a rapid transformation of the μ-scattering setup into the present system. The dedication of the SLAC operating crews as well as the scanning crews of both institutions is gratefully acknowledged.

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†Visitor from DESY, Hamburg, Germany.

[1] Y. Hara, Phys. Rev. 134, B701 (1964); B. J. Bjørken and S. L. Glashow, Phys. Lett. 11, 255 (1964).

[2] S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D 2, 1285 (1970).

[3] F. J. Hasert *et al.*, Phys. Lett. 46B, 121, 138 (1973).

[4] J. P. Boymond *et al.*, Phys. Rev. Lett. 33, 112 (1974); J. A. Appel *et al.*, Phys. Rev. Lett. 33, 722 (1974).

[5] S. L. Glashow, in *Experimental Meson Spectroscopy*, AIP Conference Proceedings No. 21, edited by D. Garelick (American Institute of Physics, New York, 1974), p. 387. We first discussed our approach at the Twelfth Course of the International School of Physics, Erice, 1974: C. A. Heusch, in *Lepton and Hadron Structure*, edited by A. Zichichi (Academic, New York, 1975).

[6] C. del Papa *et al.*, Phys. Rev. D 13, 2934 (1976); also see R. Mozley, in *Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Stanford, California, 1975*, edited by W. T. Kirk (Stanford Linear Accelerator Center, Stanford, Calif., 1975); C. A. Heusch, in *Proceedings of the Seventeenth International Conference on High Energy Physics, London, England, 1975*, edited by J. R. Smith (Rutherford High Energy Laboratory, Didcot, Berkshire, England, 1975).

[7] This procedure uses in part the smoothing package available with the SLAC plotting program KIOWA. [See Jerry Friedman and Roger Chaffee, SLAC Computation Group Technical Memorandum No. 146, 1973 (unpublished)].

[8] To estimate these quantities, we adopt standard assumptions as outlined in M. K. Gaillard, B. W. Lee, and J. L. Rosner, Rev. Mod. Phys. 47, 277 (1975).

Transient Field of ^{19}F Ions Recoiling in Nickel Interpreted by a Spin-Dependent Molecular-Orbital Promotion Mechanism*

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Transient magnetic fields have been observed from a phase shift of the time-differential perturbed angular correlation of ^{19}F nuclei recoiling into a nickel host. The Larmor precession associated with the phase shift grossly exceeds the Lindhard and Winther prediction. A spin-dependent electron-promotion mechanism via molecular orbitals is suggested which results in an intermittent K-shell spin polarization.

The magnetic fields acting at the site of the nucleus of ions during a slowing-down process in polarized ferromagnetic foils (transient fields) are a subject of still growing interest. By adjusting the Lindhard and Winther (LW) theory,[1] which describes the scattering of polarized electrons by the moving ion, it was possible to reproduce the Z dependence of the transient fields. Recently, however, transient fields have been measured with light ions which exceed the LW prediction by a factor of 2.[2,3] These fields have been interpreted to be due to the capture of polarized electrons into vacancies of the moving ion. In the case of ^{12}C a transient field in iron has been observed which exceeds the LW prediction by even 2 orders of magnitude.[4]

By means of time-differential perturbed angular correlation (TDPAC) with a pulsed beam we have measured the hyperfine field of ^{19}F recoiling into a polarized nickel foil at temperatures between 80 and 603 K. The long-lived $\frac{5}{2}^+$ state ($\tau = 128$ nsec) of ^{19}F allows one to observe a phase shift of the time-differential hyperfine angular-correlation pattern. The order of magnitude of this phase shift suggests the interpretation—similar to the case of ^{12}C ions in Fe—that the hyperfine fields of polarized 1*s* electrons act during a considerable fraction of the slowing-down time. Since electron promotion via molecular orbitals (MO) is the dominant process for creation of K-shell vacancies in the fluorine projectile at the energies used in this experiment, a mechanism for a spin-dependent production of these vacancies is proposed. It is suggested that in a collision with Ni atoms, only 1*s* electrons of F with spin direction opposite to the direction of the (polarized) 3*d* electron spins of Ni can be promoted via the 3*d* MO, since the exit channel is open only for these electrons.

The experimental details are similar to our previous measurements.[5] A 4.94-MeV α beam has been pulsed with a repetition rate of 1 MHz. The 197-keV γ rays from the reaction ^{19}F(α, $\alpha'\gamma$)^{19}F have been observed in a 1.5-in.× 1-in. NaI(Tl) detector placed at a fixed angle of 135° with respect to the beam. The targets were prepared by evaporating a layer of 150 μg/cm^2 CaF$_2$ onto a 2.54-μm nickel foil. The nickel backing was polarized by means of a small permanent magnet producing a magnetic field of 0.23 T. During the measurement the magnet was turned by 180° at 5-min intervals in order to provide opposite field directions.

The origin $t = 0$ of the time scale of the angular correlation $W(T, H_{\text{ext}}, t)$ at a temperature T and external field direction H_{ext} was determined by replacing the CaF$_2$ target by a thin ^{7}Li target (100 μg/cm^2 LiOH on a copper foil). The time spectra of the (Compton-scattered) γ rays of the ^{7}Li nuclei ($E = 480$ keV, $\tau = 10^{-13}$ sec) have the form of a Gaussian distribution of width $\sigma = 1.6$ nsec, centered at the time $t = 0$ (prompt curve). Careful successive observations of the origin of the time scale proved to agree within 0.5 nsec.

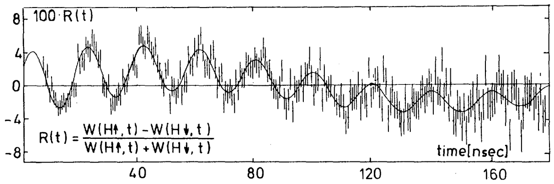

FIG. 1. One example of the measured ratio $R(t)$ for ^{19}F in Ni at a target temperature of 144 K. The full line represents the result of a least-squares fit using Eq. (2).

To analyze the data, the usual ratio $R(t)$ of counting rates for opposite directions of the external field has been formed. As an example, Fig. 1 shows the experimental data $R(t)$ for a target temperature of $T = 144$ K. Performing analytically the convolution of the appropriate theoretical expression with the prompt curve, one obtains for $t \gtrsim 2\sigma$ and for frequencies ω such that $\omega\sigma \ll 1$

$$R(t) = -B_2 \exp(-2\omega^2\sigma^2) \sin[2\omega(t - \sigma^2/\tau)], \qquad (1)$$

where $\omega = -g\mu_N H_{\text{eff}}/\hbar$ and H_{eff} is the static magnetic field acting on the ^{19}F nucleus. Least-squares fits have been performed using the standard expression for spin-rotation measurements:

$$R(t) = B_2^{\,0} \sin(2\omega_{H_{\text{ext}}} t) + B_2^{\,1} \exp(-\lambda t) \sin[2(\omega t + \varphi)] + C. \qquad (2)$$

The first term accounts for those ^{19}F ions which are stopped already in the target itself and subject only to the external field H_{ext}. In the second term, a phenomenological factor $\exp(-\lambda t)$ has been introduced to account for the attenuation of the initial amplitude $B_2^{\,1}$. The (anomalous) temperature dependence of the hyperfine frequencies ω of the ^{19}F ions in the nickel host will be discussed elsewhere.[6] Here we concentrate on the phase shift φ which results from a hyperfine interaction within a time interval much shorter than the time resolution of the experiment. The possibility to observe short lived but intense fields by a phase shift in TDPAC has been used previously under much less favorable conditions.[7] The phases φ obtained from least-squares fits to twelve data sets from temperatures in the range 80 to 603 K are shown in Fig. 2. There seems to be no trend with temperature and we adopt a mean value of $\bar{\varphi} \approx 0.15$ rad. This corresponds to measured time shifts $\Delta t = \varphi/\omega$ between 1.0 nsec at 144 K and 1.9 nsec at 603 K, thus exceeding a

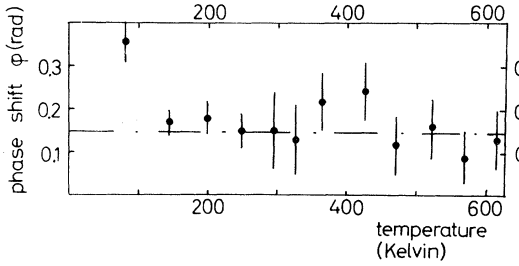

FIG. 2. The phase shifts φ obtained from least-squares fits to the data $R(t)$ for temperatures from 80 to 603 K.

possible error of 0.5 nsec due to the uncertainty of the origin of the time scale. The finite time resolution σ and the bending of the α beam in the external magnetic field introduce negligible phase shifts of some milliradians only. We interpret the phase shift $\overline{\varphi}$ as being produced by the action of transient fields in the course of the slowing-down process. The magnitude of these fields exceeds the LW prediction by a factor of about 30.

The magnetic field produced by a single 1s electron at the site of the ^{19}F nucleus is 122 MG.[8] The orientation of the electronic angular momentum $J=\frac{1}{2}$ may be regarded as fixed if the coupling of J to the exchange field of the nickel lattice exceeds the coupling of J and I. In an opposite coupling scheme the electronic angular momentum will behave like in a free ion. Assuming the first coupling, the field of 122 MG has to exist within an accumulated time interval of 0.17 psec in order to account for the net Larmor precession corresponding to $\overline{\varphi}\approx 0.15$ rad. The slowing down time of F in Ni is roughly 0.4 psec but a reliable value is not easily obtained. In any case a rather high degree of polarization of 1s electrons must prevail in order to produce the measured precession. The lifetimes of 1s vacancies for not too highly stripped ions of low charge Z are governed by the rates of the Auger processes. For ^{19}F the lifetime of 1s vacancies is about 3×10^{-15} sec.[9] Thus, in the slowing-down history of a recoiling ^{19}F ion at least 50 1s vacancies have to be created by repeated excitation of an electron with spin opposite to the external field H_{ext}.

In atomic collisions the production of inner-shell vacancies proceeds by two mechanisms[10]: by Coulomb interaction in direct collisions or by electron promotion via a molecular orbital. A measure of the relative importance of these mechanisms is provided by the parameter

$$\eta=\left(\frac{v_{\text{ion}}}{v_e}\right)^2=\frac{E}{\lambda u_K}, \qquad (3)$$

where E and v_{ion} are the energy and the velocity of the recoiling ion, u_K and v_e are the binding energy and orbital velocity of the 1s electrons, and λ designates the ratio of the masses of the ion and the electron. In the case under discussion, $E\lesssim 1$ MeV, $\eta\lesssim 0.04$, the promotion of 1s electrons by MO largely dominates. From the correlation diagram appropriate to F and Ni as collision partners[11] it can be seen that 1s electrons of ^{19}F can be promoted only to the 3d subshell of Ni. The corresponding cross section is not known experimentally. By inspecting similar data for other collision partners[10] one concludes that the cross section may be as large as 10^{-17} cm^2, provided the electron shells involved in the promotion have about the same binding energies. This condition of "level matching" is fulfilled for the fluorine K and the nickel L shells.

It is a well known fact that the chance of electron promotion depends on whether or not the corresponding exit channel of the promotion is vacant.[10] Applying this fact to 3d ferromagnets one may conclude that the electron promotion via a 3d MO should be spin dependent. As a consequence, in nickel as a strong ferromagnet (3$d\uparrow$ sub-band filled) only electrons with spin direction opposite to the external field H_{ext} could be promoted, leaving 1s electrons polarized parallel to H_{ext} in the fluorine ion. Therefore, not only the electron capture into 1s vacancies would then be a spin-dependent process, but also their creation by the promotion. The low-energy limit for this to be possible is expected to be about 50 keV. Assuming a vacancy-production cross section of 10^{-17} cm^2, one concludes that a K vacancy in a slowing-down ^{19}F ion, previously filled by an Auger process, will be restored within 4×10^{-15} sec (1% of the stopping time). Thus it seems possible that a spin-dependent MO promotion at least partly accounts for the measured phase shift. To check the hypothesis further, experiments are in progress.

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[1] J. Lindhard and A. Winther, Nucl. Phys. A166, 413 (1971).

[2] J. L. Eberhardt, G. van Middelkoop, R. E. Horstmann, and H. A. Doubt, Phys. Lett. 56B, 329 (1975).

[3] M. Forterre, J. Gerber, R. P. Vivien, M. B. Gold-

berg, and K. H. Speidel, Phys. Lett. 55B, 56 (1975).

[4] M. B. Goldberg, G. J. Kumbartzki, K.-H. Speidel, M. Forterre, and J. Gerber, to be published.

[5] F. Bosch and O. Klepper, Z. Phys. 240, 153 (1970).

[6] O. Klepper and W. Salm, to be published.

[7] O. Klepper, H. Spehl, and N. Wertz, Z. Phys. 217, 425 (1968); H. Spehl and N. Wertz, Z. Phys. 243, 431 (1971).

[8] H. Kopfermann, *Nuclear Moments* (Academic, New York, 1958).

[9] E. J. McGuire, Phys. Rev. 185, 1 (1969).

[10] J. D. Garcia, R. J. Fortner, and T. M. Kavanagh, Rev. Mod. Phys. 45, 111 (1973).

[11] M. Barat and W. Lichten, Phys. Rev. A 6, 211 (1972).

Velocity Dependence of Na-Ar and Na-Xe Fine-Structure-Changing Collisions*

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The velocity dependence of the total fine-structure-changing cross section has been measured for collisions of Na(3p) with Ar and Xe using a new velocity-selection technique based on the Doppler shift. The velocity dependence agrees with recent theoretical predictions of Pascale and Olson, but the magnitudes of the cross sections do not.

We report measurements of the velocity dependence of the fine-structure-changing cross section in collisions of excited sodium with the ground-state rare gases Ar and Xe, e.g.,

$$\mathrm{Na}^*(3p_{3/2})+\mathrm{Ar}\rightarrow\mathrm{Na}^*(3p_{1/2})+\mathrm{Ar}+\Delta E\,,$$

where $\Delta E = 17\ \mathrm{cm}^{-1}$. These measurements are the first systematic study of the velocity dependence of this simple inelastic collision process in an alkali–rare-gas system (except for the elegant temperature-dependent measurements of Gallagher on Rb and Cs collisions[1]) and they are sufficiently accurate to discriminate among recent theoretical calculations of the Na–rare-gas cross sections.[2-4] The measurements are the first to apply our recently proposed technique of velocity selection using the Doppler shift (VSDS)[5] which uses one interaction of the laser field with the system under study to provide velocity-selective excitation; previous VSDS techniques have used two laser-system interactions to select and monitor the initial velocity[6] or the momentum transfer.[7,8]

In the VSDS technique monochromatic laser light is used to excite selectively atoms with a definite component of velocity, v_z, along the laser beam:

$$v_z = c(\Delta\nu/\nu_0)=\lambda_0\Delta\nu\,, \tag{1}$$

where $\Delta\nu$ is the detuning of the laser frequency from the natural frequency of the atomic resonance, ν_0. The number of excited-state atoms is determined from the total fluorescence, $F_b(\Delta\nu)$, and the number of atoms transferred to the unexcited fine-structure level is determined from the fluorescence of that level, $F_t(\Delta\nu)$. In our experiment $F_t \ll F_b$ so that the average transfer coefficient at fixed v_z could be found from

$$\langle v_{\mathrm{rel}}Q(v_{\mathrm{rel}})\rangle_{v_z} = F_t(\Delta\nu)/F_b(\Delta\nu)\tau_{\mathrm{Na}}n_x\,, \tag{2}$$

where τ_{Na} is the excited-state lifetime of the laser-excited state and n_x is the density of the rare-gas target. The notation $\langle v_{\mathrm{rel}}Q(v_{\mathrm{rel}})\rangle_{v_z}$ emphasizes that the relative velocity is affected by the unselected components of velocity of the primary and target atoms even though v_z is accurately known [from Eq. (1)].

The experiment was conducted in a heated aluminosilicate glass tube 8 mm i.d., which was suspended in a vacuum vessel (see Fig. 1). The

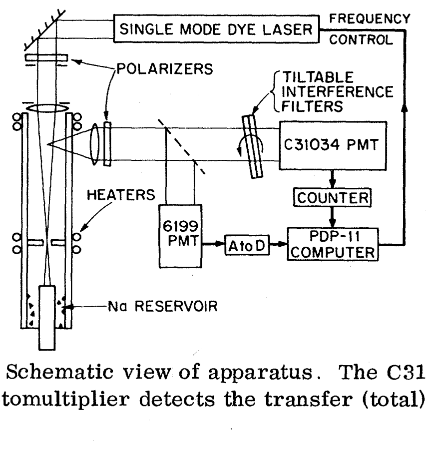

FIG. 1. Schematic view of apparatus. The C31034 (6199) photomultiplier detects the transfer (total) fluorescence.