cidence of this order of magnitude with the observed lifetime of a neutral meson decaying into two photons could be accidental; still, it suggests the possibility of some connection between the apparent lifetime of unstable particles and a finite duration of the interaction between the particles which take part in the production and decay processes.

[1] E. Gora, Phys. Rev. **84**, 1119 (1951).
[2] B. Ferretti, Nuovo cimento **8**, 108 (1951); F. J. Dyson, Phys. Rev. **83**, 608 (1951); H. S. Snyder, Phys. Rev. **83**, 1154 (1951).
[3] For the notation used, see W. Heitler, *Quantum Theory of Radiation* (Clarendon Press, Oxford, 1944), second edition, Chap. III, p. 16.

Mass of K^{40}†

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THE determination of a decay scheme for K^{40} depends upon the magnitudes of the gamma- and beta-ray energies. In the past, a number of somewhat widely varying values have been reported. These varying values lead to an uncertainty in the decay scheme. Recent experiments suggest that a decay scheme having K^{40} decay to Ca^{40} by a beta-decay, and to A^{40} by a K capture followed by a gamma-ray emission is correct. In order to substantiate this conclusion, I have measured the masses of K^{40}, A^{40}, and Ca^{40} employing a double-focusing mass spectrometer.[1] The total energy differences between the three nuclides, found from the masses, can be compared with the beta- and gamma-ray energies.

A sample of potassium containing 7.74 percent of K^{40}, obtained from the Electromagnetic Separation Plant in Oak Ridge, Tennessee, on allocation from the Isotope Division, U. S. Atomic Energy Commission, was used as a source of potassium ions. In earlier determinations of the masses of A^{40} and Ca^{40}, the hydrocarbon fragment $(C^{12})_3(H^1)_4$ was used as a comparison peak. This it not a good fragment to use because of the large $(C^{12})_2C^{13}(H^1)_3$ unresolved satellite. While correction has been made for this, it is a possible source of error. In the present work, this difficulty has been eliminated by employing the fragment $(C^{12})_2O^{16}$ from acetic acid. Normal calcium metal was used as a source of Ca^{40} ions.

In this experiment, a run consisted of eight C_2O-A^{40} traces, ten C_2O-K^{40} traces, and then eight more C_2O-A^{40} traces. From each run, the C_2O-K^{40} result was compared with an average of the two C_2O-A^{40} results to obtain the mass difference of the $K^{40}-A^{40}$ doublet. In a similar manner, the doublet $Ca^{40}-A^{40}$ was determined. This method had to be employed because the K^{40}, A^{40}, and Ca^{40} ion peaks were not resolved in the mass spectrometer.

In the case of the potassium runs, a small correction had to be made because of the unresolved residual A^{40} peak, while in the calcium runs, because of the much larger beam current, no correction for residual A^{40} was necessary. A small calcium impurity found in the spectroscopic analysis of the K^{40} sample could cause a low $K^{40}-A^{40}$ result. Because of peak shape consistencies, this error was believed to be less than 10 percent of the $K^{40}-A^{40}$ difference.

The weighted averages of four calcium-argon runs for the doublets C_2O-A^{40}, C_2O-Ca^{40}, and $Ca^{40}-A^{40}$ yield 32.756 ± 0.010, 32.557 ± 0.009, and 0.201 ± 0.015 millimass units, respectively. The averages of five potassium-argon runs for the doublets C_2O-A^{40}, C_2O-K^{40}, and $K^{40}-A^{40}$ yield 32.735 ± 0.024, 31.140 ± 0.081, and 1.595 ± 0.071 mMU, respectively. The masses of the three nuclides may be calculated using C^{12} to be 12.003842 ± 4 [1] and O^{16} to be exactly 16 atomic mass units. The masses of K^{40}, Ca^{40}, and A^{40} are then 39.97654 ± 8, 39.975127 ± 11, and 39.974940 ± 15 aMU, respectively. The argon mass is determined from a weighted average of all the argon data. The disagreement between the Ca^{40} and A^{40} masses reported here and those previously reported[2] may be attributed to several improvements in the instrument and to the elimination of the large C^{13} correction, necessary in the previous work.

From the masses, the total energies for the decay of K^{40} to Ca^{40} and A^{40} are 1.30 ± 0.07 and 1.49 ± 0.07 Mev, respectively. The energy released in the decay to Ca^{40} agrees well with the most recent beta end-point determinations which gave energies of 1.40 ± 0.03,[3] 1.36 ± 0.05,[4] 1.28 ± 0.03,[5] and 1.325 ± 0.015 [6] Mev. The result disagrees with earlier determinations which in several cases gave values higher than 1.45 Mev.[7,8] Two of the earlier determinations which gave lower values were 1.3 [9] and 1.35 [10] Mev. Several recent determinations of the gamma-ray energy for the K^{40} decay gave values of 1.47 ± 0.03,[11] 1.462 ± 0.01,[12] and 1.459 ± 0.007[13] Mev. Because the gamma-ray energy is greater than the total energy available in the decay to Ca^{40}, it must be associated with the decay to A^{40}, as is true in the presently accepted decay scheme.

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[1] Collins, Nier, and Johnson, Phys. Rev. **84**, 717 (1951).
[2] A. O. Nier and T. R. Roberts, Phys. Rev. **81**, 507 (1951).
[3] D. E. Alburger, Phys. Rev. **75**, 1442 (1949).
[4] Bell, Weaver, and Cassidy, Phys. Rev. **77**, 399 (1950).
[5] M. L. Good, Phys. Rev. **83**, 1054 (1951).
[6] L. Feldman and C. S. Wu, Phys. Rev. **87**, 1091 (1952).
[7] S. Franchetti and M. Giovanozzi, Phys. Rev. **74**, 102 (1948).
[8] L. H. Borst and J. J. Floyd, Phys. Rev. **74**, 989 (1948); **75**, 1106 (1949).
[9] W. J. Henderson, Phys. Rev. **55**, 238 (1939); **71**, 323 (1947).
[10] Dzelepow, Kopjova, and Vorobjov, Phys. Rev. **69**, 538 (1946).
[11] Pringle, Standil, and Roulston, Phys. Rev. **77**, 841 (1950).
[12] P. R. Bell and J. M. Cassidy, Phys. Rev. **79**, 173 (1950).
[13] M. L. Good, Phys. Rev. **81**, 891 (1951).

Angular Distribution of Neutrons of the *d-d* Reaction

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WE have recently measured the angular distribution of neutrons from the $H^2(d,n)He^3$ reaction using 50-kev incident deuterons. The deuteron beam was furnished by a radio-frequency ion source of the type described by Moak *et al.*[1] and was focused on a deuterium target prepared by bombarding to saturation a thin copper plate. The diameter of the deuterium spot on the copper plate was approximately 3.5 mm.

Seven Ilford C-2 nuclear plates with emulsions 100 microns thick were positioned radially around the target at laboratory angles of 15°, 30°, 75°, 90°, 105°, 120°, and 135° with the deuteron beam. The plates were exposed to the neutron flux for forty hours. To discriminate against proton-recoil tracks caused by neutrons scattered on the plates by surrounding material, only those tracks whose visible horizontal projection was equal to or greater than 40 microns and whose angle with the neutron beam was equal to or less than $\sin^{-1}0.4$ were counted. The entire thickness of the emulsion was examined for each field of view. Five traverses, each 2 cm long, which were made across an unexposed background plate revealed only one acceptable track; consequently, background corrections were not considered necessary.

It is customary in angular distribution experiments to analyze the results so as to determine the values of asymmetry coefficients. At low deuteron bombarding energies, this amounts to selecting that value of A in the expression $N'(\theta')=N'(90°)(1+A\cos^2\theta')$, where primed quantities are in center-of-mass coordinates, which

TABLE I. The number of recoil protons $N(\theta)$ at different laboratory angles θ, with transformation to center-of-mass coordinates θ'. $g(\theta)$ is the transformation factor connecting $N(\theta)$ and $N'(\theta')$.

θ	θ'	$N(\theta)$	$g(\theta)$	$N'(\theta')$
15°	15.7°	423	0.918	388
30°	31.4°	398	0.925	368
75°	77.8°	343	0.977	335
90°	92.9°	256	1.000	256
105°	107.8°	340	1.024	348
120°	122.5°	350	1.047	366
135°	137.0°	366	1.068	391

yields the best fit for the experimental data. These data and the transformations from laboratory to center-of-mass coordinates are shown in Table I.

The value of the asymmetry coefficient A was determined by the method of least squares. The method yielded a value of 0.25 ± 0.05, which is in agreement with the value of 0.30 ± 0.03 for the protons of the reaction[2] and with the value of $0.15+0.0027E$ for the neutrons.[3] The photographic method appear to be in agreement with other methods for angular distribution measurements.

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[1] Moak, Reese, and Good, *Nucleonics* **9**, 18 (1951).
[2] Bretscher, French, and Seidl, Phys. Rev. **73**, 815 (1948).
[3] I. Bartholdson, Arkiv. Fysik **2**, 271 (1950).

The Concept of Spin-Lattice Relaxation in Ferromagnetic Materials

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IN the literature on the high frequency properties of ferromagnetic materials, it is often assumed that the distinction between spin-spin and spin-lattice relaxation will be as valid here as it is in paramagnetic relaxation and paramagnetic resonance. In fact, often the assumption is made that the two types of relaxation enter in exactly the same way as in the paramagnetic case, and thus that the Bloch equations of motion are valid. This letter contends that this cannot be the case.

The simplest physical explanation of the situation results from considering why, in the paramagnetic case, it is necessary to make the distinction between the two types of relaxation. In the paramagnetic case we apply an external field H_z which causes energy splittings large compared to the interaction energies between the spins. It is now true that these interactions can broaden the paramagnetic resonance line, and also they can cause the components S_x, S_y of the total spin perpendicular to the external field to relax toward the equilibrium value zero (these two effects being in fact equivalent). On the other hand, if energy is absorbed from some external magnetic field (usually rf or microwave) thus causing the component of total spin S_z to change, an entirely different relaxation mechanism is required to bring the sytsem back to thermal equilibrium. This is because the spins and their interactions are incapable of accepting this energy, which may be shown in two ways: in the first place, the energy is in the form of "Zeeman quanta" μH_z, which are large compared with the interaction quanta $\mu H_{\text{Loc}}\sim\mu^2/r^3$; in the second place, the specific heat of the "spin system" is due almost entirely to the interaction with the external field H_z, so that there is simply no tendency to redistribute the energy which has been acquired among the spins alone; their interactions simply are not big enough to accept the energy. Thus interaction with the crystal lattice, "spin-lattice relaxation," is the only way in which thermal equilibrium can be re-established and S_z can relax to its original value. This interaction is often relatively slow, and spin-lattice relaxation can then be measured as a separate effect.

The situation in ferromagnetism is quite obviously entirely different. Here the exchange fields acting on the spins are large compared to the external field in all situations, and the specific heat of the spin system as a whole is large compared to that due to the interaction with the external field, being comparable with the lattice's specific heat. In such a situation we see that, if spin-spin interactions are capable of causing the major part of the line breadth, they will obviously be capable also of accepting the energy of the "Zeeman quanta" fed in by an external field, and, unless the total energy fed in is comparable with that necessary to heat the whole system to the Curie point, no effects due to saturation of the spin system as a whole can possibly occur.

Another way of phrasing this is to point out that changing the total spin S in any way other than the formation of domains of macroscopic size requires an energy of this same large order of magnitude (about $H_E M_S$, where H_E is the exchange field, $\sim10^6$ oersteds, and M_S is the saturation moment) and thus that in most experiments S_x and S_y cannot be independent of S_z; it is then hard to see how any relaxation formula containing two constants rather than one can be applicable. We see also that, if S cannot change, only interactions capable of changing S_z will be capable of relaxing S_x and S_y, and causing broadening.

Finally, we shall give an indication of the circumstances under which spin-lattice relaxation might actually be observed[1] in a typical relaxation experiment. In order to saturate the spin system, an energy $E_0=H_E M_S$ is required. Power can be fed into the system at ferromagnetic resonance at a rate

$$P_i=\chi''\omega_0 H_1^2\simeq(\gamma H_0)(H_1^2)(M_s)/(\Delta H),$$

where ΔH is the line width, H_1 the applied rf field. H_1 must be $\leq\Delta H$ or the system will be saturated spin-spinwise, so we set $H_1=\Delta H$ for a maximum possible energy input. Then the time T in which the energy input is large enough to saturate the whole spin system is

$$T=\frac{E_0}{P_i}\simeq\frac{H_E}{H_0}\left(\frac{1}{\gamma\Delta H}\right)=\frac{H_E}{H_0}\text{ (spin-spin relaxation time).}$$

Thus the time T is of order 10^3-10^4 times the spin-spin relaxation time, and unless the spin-lattice relaxation time is slower than this (of order 10^{-4}–10^{-5} sec, that is) no effect can be observed. In addition, the pulses of input power must also be of this length, which has not been the case in Damon's experiments on relaxation.[1]

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[1] Unless direct spin-lattice relaxation due to interaction of the lattice with the zero wave-number spin wave into which the energy is fed is the primary broadening mechanism. This probably is not the case, according to calculations of D. Polder and J. K. Galt, unpublished; C. Kittel and J. M. Luttinger (reported in paper of C. Kittel, to be published in January, 1953, Revs. Modern Phys.); and R. W. Damon, thesis, Harvard University, 1951, unpublished.

Relativistic Corrections to Magnetic Moments of Nuclear Particles*

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RELATIVISTIC corrections to magnetic moments of nuclear particles have been of special interest in connection with the determination of the proportion of the ^3D state contained in the ground state of the deuteron and the additivity of magnetic moments of nucleons. The problem has been treated by various authors[1–6] with inconclusive results.

For the case referred to[5,6] as the scalar, the result of Sachs[4] for the deuteron, neglecting the ^3D state, is

$$(CF)_{2S}=1-\langle W/M\rangle+\langle T/3M\rangle, \tag{1}$$

where W and T are respectively the energy and kinetic energy of internal motion, and CF is the correction factor to the Dirac part of the proton's magnetic moment; $c=1$ in the units used. The corresponding calculation of Breit and Bloch[5] contained an error, the existence of which was inferred by Adams.[6] Although the Hamiltonian used by Sachs in this and the vector case is not covariant in the required order, the direct employment of the field to which a particle is exposed is justifiable, as may be inferred from the material below. For the two-body vector case the same manipulative slip (BB) entered,[5] and the employment of $\mathbf{p}$ in place of $\boldsymbol{\alpha}$ by Sachs is mainly responsible for a difference from the correct result, namely,

$$(CF)_{2V}=1,\quad (^3D\text{ neglected}). \tag{2}$$