Moon[3] and Storruste.[4] Bethe[5] has made similar calculations but using relativistic wave functions for the K electrons instead of the Thomas-Fermi distribution assumed by Franz. The compound effect of Rayleigh and Thomson scattering as calculated by Bethe is shown in Fig. 2.

Nuclear resonance scattering[6] should be very small except at resonance; the resonances should be less than 10^{-3} ev wide and spaced by at least several kev, hence one would be unlucky indeed to land near such a resonance. Measurements have also been made on Bi, Au, Pt which give very similar results to Pb. Thus nuclear resonance scattering is unlikely to contribute in any way to the measured results.

The experimental results for lead are plotted in Fig. 2, the horizontal bars indicating the angular resolution and the vertical bars, the standard statistical counting error. The measured cross sections agree with Bethe's calculation of Rayleigh-Thomson scattering at large angles, but are considerably lower at angles less than 90°.

Because the experimental difficulties all tend to make the measured cross sections come out too high, one is inclined to conclude (a) that the calculations of Rayleigh scattering at small angles are incorrect, or (b) that another scattering process is occurring which interferes destructively with the Rayleigh scattering to give the small cross sections actually observed. It does not seem likely that Bethe's calculation is wrong by a factor of five; hence the more probable conclusion is that potential scattering is responsible for the reduction of the cross section. Potential scattering would interfere destructively.

Now Rohrlich and Gluckstern[7] have calculated the potential scattering cross section in the forward direction and find it to be 0.6 millibarn per steradian at this energy. No calculation has been made as yet of the angular distribution. The curve plotted in Fig. 2 is on the assumption that the distribution is the same as that obtaining for a wave scattered by a black disk of radius $\hbar/mc$, i.e., diffraction scattering, and normalized to the theoretical result at zero degrees. The dashed curve marked "total scattering" is the result of compounding the amplitudes of the potential scattering and of the Rayleigh and Thomson scattering, assuming that they are exactly of opposite phase. That the measurements are in much better agreement with this curve can be taken as evidence for the occurrence of potential scattering, but this conclusion is subject to a refined calculation of the angular distribution of potential scattering and of the Rayleigh scattering at small angles.

I am grateful to H. A. Bethe, F. Rohrlich, and J. S. Levinger for many stimulating discussions.

---

* The measurements here reported were all made in 1951. Publication has been held up until now in the hope that the Rayleigh scattering could be calculated more accurately.

[1] R. R. Wilson, Phys. Rev. **82**, 295 (1951).

[2] W. Franz, Z. Physik **98**, 314 (1936).

[3] P. B. Moon, Proc. Phys. Soc. (London) **A63**, 1189 (1950).

[4] A. Storruste, Proc. Phys. Soc. (London) **A63**, 1197 (1950).

[5] H. A. Bethe, private communication; see also J. S. Levinger, Phys. Rev. **87**, 656 (1952); G. Brown and J. Woodward, Proc. Phys. Soc. (London) **A65**, 972 (1952).

[6] J. S. Levinger, Phys. Rev. **84**, 523 (1951).

[7] F. Rohrlich and R. L. Gluckstern, Phys. Rev. **86**, 1 (1952).

Inner Bremsstrahlung and the Magnetic Moment of the Neutrino

E. J. Hellund
Argonne National Laboratory, Lemont, Illinois
(Received March 23, 1953)

Recent measurements on the beta-spectrum of H^3 establish an upper limit of 250 ev for the neutrino rest mass.[1] It is of some interest to point out that the question of the magnitude of the neutrino rest mass is intimately related to the question of the magnitude of its magnetic moment.

During beta-decay, the neutrino is ejected from the neighborhood of the parent nucleus with a velocity very nearly equal to light velocity. Assuming the particle possesses a finite Pauli magnetic moment, one can calculate the intensity of inner bremsstrahlung.[2] The result shows that the total intensity is directly proportional to the square of the moment and inversely proportional to the square of the neutrino rest mass. Confirmation of this relation can be obtained also by a purely classical calculation in the manner outlined by Chang and Falkoff.[3]

A polar vector interaction in an allowed transition yields the following result for the intensity of neutrino inner bremsstrahlung (integrated over all directions):

$$I(k)dk\approx\frac{2\alpha}{\pi}\left(\frac{m}{\mu}\right)^2 g^2k^2(W_\nu-k)^2dk,\quad \mu\rightarrow 0 \tag{1}$$

where α is the fine structure constant, m the electron rest mass, μ the neutrino rest mass, k the photon energy, W_ν the initial neutrino energy measured in units of mc^2, and g is the neutrino moment in Bohr magnetons.

The expression must be integrated over the neutrino spectrum corresponding to the probability for emission with energy W_ν. As superimposed on the normal β inner bremsstrahlung, the neutrino spectrum would appear as a spurious "line." Adopting the value 1/5000 Bohr magneton allowed by ionization measurements,[4] and Langer's upper bound for μ, the peak of this line would be about three times as great as the corresponding β inner bremsstrahlung for kinetic energies for both particles of 1 Mev. Identification of the entire inner bremsstrahlung by actual experimental observation as β-radiation[5] clearly necessitates the adoption of a smaller value for the upper limit of the neutrino moment, consistent with the limits of experimental error. Detection of the anomalous line would constitute direct observation of the neutrino.

---

[1] L. M. Langer and R. J. D. Moffat, Phys. Rev. **88**, 689 (1952). Later measurements indicate an upper limit of 100 ev.

[2] J. K. Knipp and G. E. Uhlenbeck, Physica **3**, 425 (1936); F. Bloch, Phys. Rev. **50**, 272 (1936).

[3] C. S. Wang Chang and D. L. Falkoff, Phys. Rev. **76**, 365 (1949). One only has to change the expression for the current density, i.e., $\mathbf{J}=C\nabla\times\mathbf{M}$ where $\mathbf{M}$ is the moment density, to make their derivation apply to the neutrino.

[4] M. E. Nahmias, Proc. Cambridge Phil. Soc. **31**, 99 (1935).

[5] T. B. Novey, Phys. Rev. **89**, 672 (1953); Bolgano, Madansky, and Rasetti, Phys. Rev. **89**, 679 (1953).

Possible Breakdown of Isotopic Spin and Charge Parity Selection Rules

D. H. Wilkinson
Cavendish Laboratory, Cambridge, England
(Received March 9, 1953)

It is of interest to determine the purity of isotopic spin[1] and charge parity[2] states. In nuclei of moderate excitation it appears that the contamination of such states may amount to a few percent in *amplitude* from the two probable violations of the selection rules so far reported;[3] the many examples of the success of the rules are consistent with such a purity. A contamination of this order is expected even under perfect charge independence or charge symmetry of the specifically nuclear forces in view of the Coulomb perturbation.[4] It must be anticipated that at higher excitations these concepts of isotopic spin and charge parity will cease to have much significance, and effectively complete breakdown of the rules must be expected. This note indicates one probable and two possible breakdowns.

The reaction $N^{15}(p,\alpha)C^{12}$ (ground state) is strongly resonant, for a particular angle of observation, at a proton energy of 1020 kev; the total width of the resonance is about 160 kev.[5] The reaction $N^{15}(p,\gamma)O^{16}$ (ground state) is strongly resonant at a proton energy of 1050 kev with a total width of about 150 kev.[5] It seems reasonable to identify these resonances and to ascribe their small separation in energy to effects of neighboring levels. The first observation permits the spin of the compound state to be (0+)(1−)(2+), etc.; the second observation eliminates (0+). If we take (1−), we have $E1$ radiation with $(2J+1)\Gamma_\gamma=450$ ev and $(2J+1)|M|^2=0.29$ in excellent accord with other $E1$ transitions in light nuclei;[6] if we take (2+), we have $E2$ radiation with $(2J+1)\Gamma_\gamma = 250$ or 1250 ev and $(2J+1)|M|^2 = 135$ or 675, which seems improbable. (1−) is therefore the most plausible assignment; it is made almost certain by the angular distribution of the alpha-particles (A. V. Cohen and A. P. French, private communication). If we are correct in the identification and assignment, we have a breakdown of the isotopic spin and charge parity rules; the emission of alpha-particles demands here $T=0$, even charge parity, while the emission of $E1$ radiation demands here $T=1$, odd charge parity;[1,2,7] yet both widths are large ($\Gamma_\gamma = 150$ ev; $\Gamma_\alpha = 75$ kev) and neither may be supposed to have suffered a very large measure of discouragement. We may not rule out the possibility that there are two resonances and that what we are observing is the rules in action rather than their violation, though this seems unlikely in view of the agreement in position and width. The excitation in O^{16} is 13.1 Mev and the first $T=1$ level may be expected at about 12.5 Mev.[8]

The reaction $B^{11}(p,\alpha)Be^8$ (ground state) is resonant at somewhat over 1 Mev[9] in proton energy; $B^{11}(p,\gamma)C^{12}$ (ground state) is strongly resonant at 1.4 Mev[10] with a large radiative width. This may be a similar example but is not so clear-cut. The reactions $Be^9(p,\alpha)Li^6$ and $Be^9(p,d)Be^8$ are resonant at 0.94 Mev,[11] while $Be^9(p,\gamma)B^{10}$ has a strong, almost certain, $E1$ resonance of similar width at 0.998 kev;[12] but these may well involve two different states. In these last two examples we are in a region of excitation containing $T=1$ states.

---

[1] R. K. Adair, Phys. Rev. **87**, 1044 (1952).
[2] N. M. Kroll and L. L. Foldy, Phys. Rev. **88**, 1177 (1952).
[3] G. A. Jones and D. H. Wilkinson, following Letter [Phys. Rev. **90**, 722 (1953)].
[4] L. A. Radicati, Proc. Phys. Soc. (London) **A66**, 139 (1953).
[5] Schardt, Fowler, and Lauritsen, Phys. Rev. **86**, 527 (1952).
[6] D. H. Wilkinson, Phil. Mag. (to be published).
[7] L. E. H. Trainor, Phys. Rev. **85**, 962 (1952); L. A. Radicati, Phys. Rev. **87**, 521 (1952).
[8] T. Lauritsen, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1952), p. 67.
[9] T. Huus, private communication.
[10] T. Huus and R. B. Day, Phys. Rev. **85**, 761 (1952).
[11] Thomas, Rubin, Fowler, and Lauritsen, Phys. Rev. **75**, 1612 (1949).
[12] W. A. Fowler and C. C. Lauritsen, Phys. Rev. **76**, 314 (1949).

The Purity of Isotopic Spin or Charge Parity States

G. A. JONES AND D. H. WILKINSON
Cavendish Laboratory, Cambridge, England
(Received March 9, 1953)

We have carried out two experiments to attempt to assess the purity of isotopic spin or charge parity states[1–3] of moderate excitation.

O^{16} possesses[4] a (1−) state at 7.12 Mev, a (2+) state at 6.91 Mev, a (3−) state at 6.14 Mev and a (0+) state at 6.05 Mev; the ground state is (0+). All these states are expected[5] to have $T=0$; if we think in terms of charge symmetry alone, the charge parity is probably even. The (1−) state decays to the ground state thereby violating the isotopic spin[6] or charge parity[7] rule. The $E2$ decay to the (3−) state is uninhibited by the special rules; we have shown it to occur at least 120 times less probably than the forbidden $E1$ transition. We have also shown that the (2+) state decays to the ground state at least 200 times more readily than to the (3−) state, although, in the absence of the special rules this latter $E1$ transition would be preferred. The single-particle matrix elements[8] seem to be unexpectedly reliable[9] for the prediction of $E1$ radiative widths, and there is no evidence that they are grossly wrong for $E2$ transitions in light nuclei; if we apply them to this case, we obtain the result that the contamination of the (1−) state is more than 0.2 percent in *amplitude* and that that of the (2+) and (3−) states is less than 3 percent in amplitude (assuming the ground state to be pure $T=0$). These estimates are probably reliable to a factor of five or better.

The first state with $T=1$ in B^{10} is at 1.74 Mev; the first excited state of Be^{10} is at 3.37 Mev and is (2+). A doublet exists in B^{10} at 5.11 and 5.16 Mev; there is another state at 4.8 Mev. It seems that one member of the doublet should have $T=1$. We have measured the excitation function of the reaction $Li^6(\alpha,\gamma)B^{10}$. We locate the lowest state at 4.75±0.02 Mev ($\omega\Gamma \sim 0.15$ ev) and the upper element of the doublet at 5.162±0.008 Mev ($\omega\Gamma \sim 0.2$ ev), but we find no trace of the 5.11-Mev level ($\omega\Gamma < \sim 0.004$ ev). The obvious explanation, that the 5.11-Mev state has $T=1$ and its formation is inhibited by the isotopic spin rule, is rendered unlikely by the implied "discouragement factor" of more than 2×10^4 (if we guess an "uninhibited" width of about 100 ev for the $l=2$ alpha-particles of 1.1 Mev), Radicati[10] having calculated that there is probably about 0.25 percent in *intensity* of $T=1$ in the ground state of Li^6.

It is then possible that the 5.16-Mev level has $T=1$ with an implied discouragement factor of order 500, which is consistent with Radicati's estimate. It is known[11] that one or other element of the doublet is (1−) or (2−); (1−) we cannot admit, as the $E1$ transition to the lower $T=1$ level (0+) would be allowed. We therefore suggest that this 5.11-Mev level may be (2−) and would then see in its small width the operation of the isotopic spin selection rule on $E1$ transitions [the ground and first excited states of B^{10} are (3+) and (1+), respectively]; we would then be on fairly safe ground in inferring a contamination of less than 2 percent in *amplitude* (assuming the lower states to be pure $T=0$).

These observations of two possible violations and two possible successes of the pure isotopic spin or charge parity selection rules seem to accord with what might be expected from complete specifically nuclear charge independence or charge symmetry when the effect of the Coulomb perturbation is taken into account.

---

[1] R. K. Adair, Phys. Rev. **87**, 1044 (1952).
[2] N. M. Kroll and L. L. Foldy, Phys. Rev. **88**, 1177 (1952).
[3] D. H. Wilkinson, preceding Letter [Phys. Rev. **90**, 721 (1953)].
[4] For all energies and characteristics quoted here, we refer the reader to F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).
[5] T. Lauritsen, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1952), Vol. 1, p. 67.
[6] L. A. Radicati, Phys. Rev. **87**, 521 (1952).
[7] L. E. H. Trainor, Phys. Rev. **85**, 962 (1952).
[8] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951).
[9] D. H. Wilkinson, Phil. Mag. (to be published).
[10] L. A. Radicati, Proc. Phys. Soc. (London) **A66**, 139 (1953).
[11] F. Ajzenberg, Phys. Rev. **88**, 298 (1952).

Angular Distribution of γ-Rays from Stripping Reactions

G. R. SATCHLER
Clarendon Laboratory, Oxford, England
(Received March 19, 1953)

The angular distribution (about the recoil axis) of the γ-radiation following a deuteron-stripping reaction has been treated both in terms of the channel spin of the capture process[1,2] and in terms of the total angular momentum j of the captured particle.[3]

Stripping reactions enable nucleons to be captured into low-lying excited levels where the Mayer $j-j$ coupling scheme is

TABLE I. γ-ray angular distributions predicted by the shell model. J_i = spin of initial nucleus; j = total angular momentum (spin + orbital) of captured particle; J_e = spin of excited nucleus after capture; L = multipole order of γ-ray; J_f = nuclear spin after emission.

J_i	(j)	J_e	(L)	J_f	A_2	A_4
0	(3/2)	3/2	(1)	1/2	−0.500	···
			(1)	3/2	+0.400	···
			(1)	5/2	−0.100	···
			(2)	7/2	+0.143	···
0	(5/2)	5/2	(1)	3/2	−0.400	···
			(1)	5/2	+0.457	···
			(1)	7/2	−0.143	···
			(2)	1/2	+0.571	−0.571
3/2	(3/2)	2			Isotropy*	
5/2	(5/2)	2	(2)	0	−0.204	−0.367
5/2	(5/2)	4	(2)	2	+0.160	+0.139

* Isotropy in this case is a numerical coincidence.