ANGULAR CORRELATIONS IN FREE NEUTRON DECAY

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Abstract

The study of particle angular correlations in free neutron decay provides important information about β-decay coupling constants, the structure of the hadronic weak current and possible extensions to the Standard Model. New experiments are expected to substantially reduce the uncertainty in the parity violating β-asymmetry A. The value of V_{ud}, which is currently derived from $J^{\pi}=0^{+}$ β-transition life times, might soon become available directly from neutron data. An experiment which looks for time reversal violation in internal pair creation following polarized neutron capture on is briefly discussed.

Neutron Decay and Fundamental Physics

The term 'fundamental interaction' suggests that the physical system under study is elementary and prototypical for a whole class of similar processes. In this sense the weak decay of the neutron is clearly fundamental. Although the neutron possesses a complex internal structure, its quark contents is udd, it is the simplest baryonic system which undergoes semileptonic β-decay.

A neutron decays into a proton, an electron and an anti-neutrino. During this process one of the down-quarks is changed into an up-quark, emitting a W-boson which itsself decays into a pair of leptons. Since free quarks have not been observed in an experiment, neutron β-decay is a very important source of information about the structure of the hadronic weak current and the weak coupling constants g_A and g_V. Their numerical values serve as input to nuclear astrophysics problems, Big Bang cosmology, neutrino reactions and many other nuclear physics processes[1].

Free neutrons are produced in large quantities at research reactors. From the reactor core they can be transported over long distances to an experimental set-up in total reflecting neutron guides. At the Institut Laue-Langevin the typical flux of thermal neutrons at the end of a guide is in the order of 10^{10} $s^{-1} \cdot cm^{-2}$. Neutrons can be polarized very efficiently to better than 98%.

Observables in Neutron β-Decay

In the terminology of nuclear β-decay, neutron decay is a superallowed transition between two states of an isospin dublet. The Q-value is 1.293 MeV. 782 keV are available as kinetic energy. The electron energy spectrum can be derived solely from phase space considerations:

$$\frac{dW}{dE_e} = F(E_e) \propto p_e E_e (E_e - E_0)^2 \qquad (1)$$

The following is a table of quantities in n-decay and their behaviour under space (P) and time (T) reversal.

Type	Quantity	P-odd ?	T-odd ?
Scalar	E_e, E_ν, E_p	NO	NO
Vector	$\mathbf{p}_e$, $\mathbf{p}_\nu$, $\mathbf{p}_p$	YES	YES
Axial vector	σ_n, σ_e, σ_ν, σ_p	NO	YES

The neutrino quantities on this list are experimentally not accessible but they are regularly used in theoretical expressions for decay probabilities. If more observables are available, these expressions become more complex. An example is the electron energy spectrum in polarized neutron decay

$$\frac{dW}{dE_e \cdot d\Omega_e} \propto p_e E_e (E_e - E_0)^2 \left(1 + A_0 \cdot \vec{\sigma}_n \frac{\vec{p}_e}{E_e}\right) \qquad (2)$$

This equation contains a parity violating term which describes the angular correlation between neutron spin and electron momentum. A_0 is the well-known β-asymmetry coefficient in polarized neutron decay. Other important angular correlations are

Correlation	Coefficient	P-odd ?	T-odd ?
$\vec{\sigma}_n \frac{\vec{p}_e}{E_e}$	$A_0 = -1.144(17)$	YES	NO
$\vec{\sigma}_n \frac{\vec{p}_\nu}{E_\nu}$	$B = 0.997(28)$	YES	NO
$\vec{\sigma}_n \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}$	$D = -(0.5 \pm 1.4) \cdot 10^{-3}$	NO	YES
$\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu}$	$a = -0.102(5)$	NO	NO
$\vec{\sigma}_e \frac{\vec{\sigma}_n \times \vec{p}_e}{E_e}$	$R \approx 0.07$ *(theory)*	YES	YES

They behave differently under P and T and are ideally suited for tests of fundamental symmetries and the structure of the weak interaction Hamiltonian.

g_A, g_V AND V_{ud}

The neutron life time and the correlation coefficients are both functions of g_A and g_V. This makes it possible to calculate these coupling constants from τ_n and, i.e., A_0. Experimental values for the neutron life have long been in disagreement with each other. Recently new measurements have produced very consistent results which allow us to calculate an average life time of (889.1±1.8) s based on all measurements published after 1970[2].

Also the β-asymmetry has a long history of measurements and is currently known to better than 1.7%. From the two coupling constants g_V is especially sensitive to A_0. With A_0=–0.1149(19) from Bopp et al.[3] one finds

$$g_V = 1.419(4) \cdot 10^{-62}\ \mathrm{Jm}^3, \quad g_A = -1.791(3) \cdot 10^{-62}\ \mathrm{Jm}^3.$$

In the Cabibbo-Kobayashi-Maskawa quark mixing scheme g_V should differ from the Fermi coupling constant G_F by a small factor V_{ud}. Also a small radiative correction has to be applied.

One finds V_{ud}=0.9767±0.0026 from "pure neutron" data. The Particle Data Group lists V_{ud}=0.9753±0.0004, a number that is derived from the ft-value of $0^+ \rightarrow 0^+$ nuclear β-decay transitions[4]. It would be preferable to derive solely from neutron decay, because the calculation of $ft^{0+\rightarrow 0+}$ requires complicated nuclear structure corrections. This means that the precision of correlation experiments has to be 6 times higher. A first step towards this goal is the PERKEO II experiment, which is currently under construction. This collaboration between the TU Munich, the University of Heidelberg and the ILL in Grenoble is aiming for a 0.4% measurement of A_0.

TIME REVERSAL INVARIANCE (TRI) TESTS

The correlations D and R change sign under time reversal. D is related to a phase angle of g_A relative to g_V and has been measured in two experiments [5,6]. Progress on the limit for D is highly desirable but only possible if the experimental count rates can be substantially increased. A measurement of R has never been attempted in neutron decay and has recently been proposed by a collaboration of the ILL, LAPP Annecy and the University of Groningen. This correlation is sensitive to a imaginary scalar-axialvector interference in the weak Hamiltonian[7]. TRI violating quantities can also be constructed from a suitable set of observables in internal pair creation following polarized neutron capture on ^{62}Ni. In this case the neutron polarization is fully transferred to the excited compound nucleus with polarization σ_A. The angular correlation

$$\vec{\sigma}_A \cdot \left(\vec{p}_{e^-} \times \vec{p}_{e^+}\right)$$

requires the coincident dectection of the pair electrons under 90°. An experiment to measure this correlation is currently under construction at the ILL.

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