

Journées Prospectives de l'IN2P3/DAPNIA

Dynamique et Structure Nucléaire

Interactions Fondamentales (groupe 5)

Abstract: Through beta decay, the nucleus provides a laboratory for studying fundamental interactions and symmetries. At the IN2P3, such studies are pursued at low energy nuclear physics facilities by two approaches: measuring super-allowed beta transition properties (by mass spectrometry and nuclear spectroscopy) and measuring correlation observables (by looking at the kinematics of the decay). The physics is briefly described and a *resumé* of the experimental effort (investment and manpower) currently dedicated to this work is made.¹ A projection for the continuation of this work - as well as other possible (related) orientations is then given.

Introduction

The Standard Model of particle physics provides the theoretical framework in which the electromagnetic, weak, and some aspects of the strong interactions can be described to considerable precision - in a single, coherent picture using baryons, leptons, and three families of quarks. Baryon number is conserved in the Standard Model and several lepton number conservation laws also hold.

The protons and neutrons (i.e., baryons) constituting the nucleus are composed of quarks whose interactions are mediated by bosons. Leptons, governed by the weak interaction, are insensitive to the strong interaction. However the quark mass eigenstates are not identical to the weak eigenstates but rather formed by mixing, the composition of which is determined by the Cabibbo-Kobayashi-Maskawa matrix.

An excellent description of the relation of the Standard Model and underlying forces and symmetries to nuclear physics, can be found in the report of the NuPECC Long-Range Plan Report 2004: Chap 5. *Fundamental Interactions*: (http://www.nupecc.org/lrp02/long_range_plan_2004.pdf)

Since the strong interaction is not completely described (nor understood) in the context of the Standard Model, it is the underpinning electroweak sector that must be used to probe its speculative extensions and eventually, for new physics which ought to lie beyond.

Within the IN2P3, two particular axes of research related to nuclear physics (or associated techniques) are pursued with the goal of testing the Standard Model and searching for new physics (note: this document concerns low-energy nuclear experiments associated with the beta decay of short-lived nuclides and NOT quasi-stable species that are candidates for e.g., double-beta decay).

¹ Note that the study of fundamental interactions pursued by phenomena such as double-beta decay (the NEMO experiment, for example) are covered by a different working group.

Nuclear structure for testing standard model: Superallowed beta decay properties

The unitarity condition of the CKM matrix implies that $V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$. V_{ud} , determined from the weak interaction vector coupling constant divided by that of the muon, has the highest weight. A result of over 100 independent measurements, it is in fact the most precisely known: 0.9740(5).

Beta decay has two components depending on the angular momentum of the emitted particles: Gamow-Teller and Fermi. For pure Fermi decays, the initial and final decay states have the same angular momentum and in the special case where there is no change in isospin is called a superallowed transition. Such decays are found along the $N=Z$ line and are especially interesting since the Matrix element for this type of decay M_F becomes trivial and the vector coupling constant G_V is very easily extracted from the comparative half-life, or so-called ft value (where f is a statistical rate function and t is the half-life of the transition).

$$ft = K / G_V^2 \langle M_F \rangle^2 + G_A^2 \langle M_{GT} \rangle^2 \quad \text{where } \langle M_F \rangle^2 = T(T+1) - T_z T_{zf}$$

where K is a product of fundamental constants, so that for superallowed decays $M_F = 2$ and $M_{GT} = 0$.

However (would that life were so simple), since the transformation of an up-quark to a down-quark takes place within the nuclear volume, certain corrections are required. Two of these are radiative and calculated from QED arguments. One, the so-called Coulomb correction δ_C , requires a microscopic nuclear physics calculation. Because of the difficulties of such calculations, δ_C is the main focus and in fact, the undermining element in this game.

In order to evaluate ft , three experimental quantities are required: the half-life of the transition, the branching ratio (sometimes very small), and the Q -value of the decay. Since beta-spectroscopy is unable to determine the Q -value with the necessary precision, direct measurements (using Penning traps) of the parent and daughter nuclide are required. Note that f depends on the Q -value to the fifth power.

A recent review on Mass Measurements has recently been published by D. Lunney, J.M. Pearson and C. Thibault in Rev. Mod. Phys 75 (2003) 1021.

Complementing superallowed beta decay for deriving the vector coupling constant are neutron decay and pion decay. The former has the great advantage that there is no nucleus, hence no nuclear structure considerations for extricating the matrix element. On the other hand, neutron decay is a mixture of GT and Fermi transition, requiring an added experiment to determine the two contributions. The latter, being a pure Fermi transition, avoids this particular problem however the branching ratio for the decay in question is only 10^{-8} ! Nonetheless, these three types of contributions have now resulted in a deviation from unitarity of more than two standard deviations.

For a recent discussion of the nuclear data and the status of the subject see J.C. Hardy and I.S. Towner in J. Phys. G Nucl. Part. Phys. 29 (2003) 197.

Beta decay kinematics: correlation parameters and search for new physics

The general description of the weak interaction at low energies involves different types of Lorentz invariants corresponding to vector (V), scalar (S), axial-vector (A) and tensor (T) interactions. As yet, only vector and axial-vector interactions have been observed and as such, only those have been incorporated into the Standard Model. Pure Fermi decays are sensitive to the V and S interactions and pure Gamow-Teller decays are sensitive to the A and T. These interactions can be probed by observing different types of correlations between the spins and momenta of the particles involved in the decay process. The comparison of precision correlation measurements with predictions made within the SM can provide access to physics *beyond* the Standard Model, as manifested by scalar and tensor interactions.

The coefficients which characterize the correlations between the kinematic vectors of the decay can probe interactions having different properties with respect to space and time transformations. For instance, the search for mechanisms inducing deviations from maximal parity violation requires precision measurements of pseudo-scalar quantities like the beta-asymmetry coefficient, A or the beta longitudinal polarization, P_L , or still combinations of these. On another side, searches for new sources of T-violation can be performed by measurements of triple correlation terms appearing in the decay rate function. So far only the terms driven by the parameters D or R have been measured in a very limited number of transitions: the neutron, ^8Li and ^{19}Ne . A coefficient which is sensitive to all kinds of contributions, whatever the parity and time-reversal transformations is the beta-neutrino angular correlation, a . This coefficient has been measured in the past in several transitions and the results provide the experimental foundation for the $V-A$ nature of the weak interaction.

A review describing the sensitivities of the different correlation and the present status of precision measurements will appear in Rev. Mod. Phys., by N. Severijns, M. Beck and O. Naviliat-Cuncic.

Current Situation

At present, three IN2P3 labs (CENBG, CSNSM, IRES) are involved in superallowed beta studies and one (LPCC) pursues correlation measurements. The CSNSM has a strong tradition in mass spectrometry having completely developed instruments and established experimental programs as well as the atomic mass table - a global evaluation (and not *compilation*) of world data. Both CENBG and IReS have developed pioneering techniques in spectroscopy and detection techniques with both labs having active experimental and developmental programs. LPCC has developed a unique tool based on a transparent Paul trap surrounded by detectors with the aim to reconstruct the decay kinematics. The LPCC participates also in precision measurements of a time reversal violating correlation in the decay of free polarized neutrons. A summary is given in the table below.

SUPER-ALLOWED BETA DECAY PROPERTIES				
Lab	Activity	Experiments	Facility	Manpower
CSNSM	High precision mass Measurements and Global mass evaluation	74Kr, 74Rb (2003) 62Ga, 62Zn (2004) 22Mg (2004)	ISOLDE	2 DR, 1 CR, 1 EC, 2 doc
IReS	Nuclear structure N=Z	62Ga (2004)	ISOLDE, GANIL	2 CR, 1 EC, 1 doc
CENBG	High precision half-live measurements	62Ga (2003)	GANIL, JYFL	1 DR, 2 CR, 1 EC, 1 doc
IPNO	Calculation of Coulomb correction			1 DR, 1 CR
IPNL	Mean-field calculations N=Z			1 EC
BETA-DECAY CORRELATIONS				
LPCC	Beta-neutrino correlation from decays of trapped ions	⁶ He (2004-2005)	GANIL	4 EC, 1 DR, 1 CR, 2 doc
LPCC	Search for new sources of T-violation, transverse beta polarization measurements	Cold neutrons (2004-2005)	PSI	2 EC, 1 doc

Prospectives

Progress in this field must be made at both the theoretical and experimental level. Concerning measurements there are two complementary directions: the present superallowed data set must be extended to higher mass number and have the precision improved. Extending the data set requires not only an improvement in production technique, but also in instrumentation since the heavier superallowed beta decay will be more short lived and more fragmented. Improving precision will require major developments in instrumentation. The production of heavier superallowed decay nuclides will require fusion-evaporation reactions with particularly emphasis on beam purity and superior beam quality. These conditions would be met by a next-generation ISOL facility.

With the increasing diversity in experimental approaches and observables, experiments requiring significant statistics and repeated systematic (and sometimes redundant) study now suffer from lack of beam time. Moreover, the increased call for post-accelerated beams makes for a lack of time available for low-energy beams which are more favorable for the high-precision required.

International Context

Experimentally, in addition to "classical" beta-gamma spectroscopy, the concept of "total absorption spectroscopy" is especially important (conversion electrons spectroscopy can also play an important rôle). IRES, together with a group from Valencia, is currently the only collaboration performing such work and their creation - *Lucrecia*, at ISOLDE - a unique instrument.

Masses have to be measured with a Penning trap since no other technique can achieve the required accuracy. The CSNSM is an active partner in the ISOLTRAP collaboration at ISOLDE where two superallowed candidates have already been measured. Other Penning traps exist at ANL, JYFL/IGISOL, TRIUMF (soon), MAFF (soon), MSU (very soon) and are proposed for GSI.

The use of such sensitive and high-performance apparatus at newer high-intensity facilities will require concomitant development in associated beam preparation and discrimination techniques. This has been addressed in the EURISOL Design Study, recently approved by the EC.

Studying decay correlations require dedicated instruments. In particular, the measurement of the beta-neutrino angular correlation is now being prepared at GANIL using the LPCTRAP. Such measurements need especially high intensities and frequent beam time access. The rejection criteria for false kinematic events must be extensively studied to be beyond question. The same physics goals are being pursued elsewhere using atomic trapping techniques (Berkeley, Vancouver, Los Alamos, Stony Brook, and soon KVI and LNL) and also using a spectrometer based on a Penning ion trap (ISOLDE), however the LPC approach is complementary to all others.

keywords

Production:	ISOL facility (fusion-evaporation reactions); low beam energy, high beam purity and quality, frequent and extended data taking periods
Instrumentation:	Total Absorption Spectrometer; Penning trap; open-geometry traps; detection and spectroscopy; beam preparation (cooling, bunching) devices
Theory:	Increased basis and higher precision for Coulomb mixing calculations

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Executive Summary

Through beta decay, the nucleus provides a laboratory for studying fundamental interactions and symmetries. At the IN2P3, such studies are pursued at low energy nuclear physics facilities by two approaches: measuring super-allowed beta transition properties (by mass spectrometry and nuclear spectroscopy) and measuring correlation observables (by looking at the kinematics of the decay).

At present, three IN2P3 labs (CENBG, CSNSM, IRES) are involved in superallowed beta studies and one (LPCC) pursues correlation measurements. The CSNSM has a strong tradition in mass spectrometry having completely developed instruments and established experimental programs as well as the atomic mass table - a global evaluation (and not *compilation*) of world data. Both CENBG and IRES have developed pioneering techniques in spectroscopy and detection techniques with both labs having active experimental and developmental programs. LPCC has developed a unique tool based on a transparent Paul trap surrounded by detectors with the aim to reconstruct the decay kinematics. The LPCC participates also in precision measurements of a time reversal violating correlation in the decay of free polarized neutrons.

The present superallowed data set must be (1) extended to higher mass number and (2) have the uncertainties reduced. Improving precision will require major developments in instrumentation. Measurement of the correlation coefficients requires enhanced precision and independent experimental approaches. The production of heavier superallowed decay nuclides will require fusion-evaporation reactions with particular emphasis on beam purity and superior beam quality. These conditions would be met by a next-generation ISOL facility. The use of such sensitive and high-performance apparatus at newer high-intensity facilities will require concomitant development in associated beam preparation and discrimination techniques. This has been addressed in the EURISOL Design Study, recently approved by the EC.

With the increasing diversity in experimental approaches and observables, experiments requiring significant statistics and repeated systematic (and sometimes redundant) study now suffer from lack of beam time. Moreover, the increased call for post-accelerated beams makes for a lack of time available for low-energy beams which are more favorable for the requisite high precision.

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