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Neutron Decay with PERC: a Progress Report

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Abstract.
The PERC collaboration will perform high-precision measurements of angular correlations in neutron beta decay at the beam facility MEPHISTO of the Forschungs-Neutronenquelle Heinz Maier-Leibnitz in Munich, Germany. The new beam station PERC, a clean, bright, and versatile source of neutron decay products, is designed to improve the sensitivity of neutron decay studies by one order of magnitude. The charged decay products are collected by a strong longitudinal magnetic field directly from inside a neutron guide. This combination provides the highest phase space density of decay products. A magnetic mirror serves to perform precise cuts in phase space, reducing related systematic errors. The new instrument PERC is under development by an international collaboration. The physics motivation, sensitivity, and applications of PERC as well as the status of the design and preliminary results on uncertainties in proton spectroscopy are presented in this paper.

1. Introduction

High-precision measurements of observables in neutron beta decay address a number of questions which are at the forefront of particle physics [1–3], and are generally complementary to direct searches in high-energy physics. Main emphasis lies on the search for new physics beyond the Standard Model (SM) of elementary particles and fields. Possible extensions require new symmetry concepts like left-right symmetry, fundamental fermion compositeness, new particles, leptoquarks, supersymmetry, supergravity, or many more [4, 5]. Free neutron decay is a very active field, with a dozen new instruments planned or under construction worldwide. For recent reviews see Refs. [2, 3, 6, 7]. With the new Proton and Electron Radiation Channel (PERC) [8] several symmetry tests based on neutron beta decay data become competitive [9].

In the modern form of the SM, the differential decay rate of neutrons can be written as [10]:

$$\mathrm{d}^3\Gamma \quad = \quad \frac{1}{(2\pi)^5}\frac{G_\mathrm{F}^2|V_\mathrm{ud}|^2}{2} p_\mathrm{e}E_\mathrm{e}\left(E_0-E_\mathrm{e}\right)^2 \mathrm{d}E_\mathrm{e}\mathrm{d}\Omega_\mathrm{e}\mathrm{d}\Omega_\nu \times$$

$$\xi\left[1+a\frac{\mathbf{p}_\mathrm{e}\cdot\mathbf{p}_\nu}{E_\mathrm{e}E_\nu}+b\frac{m_\mathrm{e}}{E_\mathrm{e}}+\frac{\langle\mathbf{s}_\mathrm{n}\rangle}{s_\mathrm{n}}\left(A\frac{\mathbf{p}_\mathrm{e}}{E_\mathrm{e}}+B\frac{\mathbf{p}_\nu}{E_\nu}+D\frac{\mathbf{p}_\mathrm{e}\times\mathbf{p}_\nu}{E_\mathrm{e}E_\nu}\right)\right]. \tag{1}$$

Here, G_F is the Fermi weak coupling constant, V_ud is the upper left element of the Cabibbo–Kobayashi–Maskawa (CKM) matrix [11, 12], $\mathbf{p}_\mathrm{e}$, $\mathbf{p}_\nu$, E_e, and E_ν are the electron (neutrino) momenta and total energies, respectively, E_0 is the electron spectrum endpoint total energy, m_e is the electron mass, $\mathbf{s}_\mathrm{n}$ is the neutron spin, and the Ω_i denote solid angles. Quantity ξ is a factor inversely proportional to the neutron decay rate, a, A, B, and D are the angular correlation coefficients, while b is the Fierz interference term. The neutrino electron correlation coefficient a and the Fierz term b are measurable in decays of unpolarized neutrons, while the beta asymmetry parameter A, the neutrino asymmetry parameter B, and the triple correlation coefficient D require polarized neutrons. We mention that in the presence of left-handed (LH) scalar (S) and tensor (T) couplings B depends on the electron energy: $B = B_0 + b_\nu\frac{m_\mathrm{e}}{E_\mathrm{e}}$, where b_ν is another Fierz-like parameter similar to b [10, 13]. We note that a, A, and B_0 are sensitive to non-SM couplings only in second order, while b and b_ν depend in first order on LH S and T couplings. A non-zero Fierz term b would indicate the existence of LH S and T interactions. A non-zero triple correlation D would violate time reversal invariance. The most sensitive measurement of D in nuclear beta decay has been conducted in the beta decay of polarized neutrons [14] (see also [15]).

If the electron spin $\mathbf{s}_\mathrm{e}$ is observed more correlation coefficients called G, N, Q, and R appear in the differential decay rate of neutrons [10]:

$$\begin{aligned}\mathrm{d}^2\Gamma &= \frac{1}{(2\pi)^4}\frac{G_\mathrm{F}^2|V_\mathrm{ud}|^2}{2}p_\mathrm{e}E_\mathrm{e}\left(E_0-E_\mathrm{e}\right)^2\mathrm{d}E_\mathrm{e}\mathrm{d}\Omega_\mathrm{e}\times\xi\left[1+b\frac{m_\mathrm{e}}{E_\mathrm{e}}+A\frac{\langle\mathbf{s}_\mathrm{n}\rangle}{s_\mathrm{n}}\frac{\mathbf{p}_\mathrm{e}}{E_\mathrm{e}}\right.\\ &\left.+\,\mathbf{s}_\mathrm{e}\left(G\frac{\mathbf{p}_\mathrm{e}}{E_\mathrm{e}}+N\frac{\langle\mathbf{s}_\mathrm{n}\rangle}{s_\mathrm{n}}+Q\frac{\mathbf{p}_\mathrm{e}}{E_\mathrm{e}+m_\mathrm{e}}\left(\frac{\langle\mathbf{s}_\mathrm{n}\rangle}{s_\mathrm{n}}\cdot\frac{\mathbf{p}_\mathrm{e}}{E_\mathrm{e}}\right)+R\frac{\langle\mathbf{s}_\mathrm{n}\rangle}{s_\mathrm{n}}\times\frac{\mathbf{p}_\mathrm{e}}{E_\mathrm{e}}\right)\right].\end{aligned} \tag{2}$$

We note that N and R depend linearly on S and T couplings. First experimental limits on N and R have been presented in [16, 17].

Another observable is C, the proton asymmetry relative to the neutron spin. Neglecting recoil-order effects and radiative corrections, the proton asymmetry C is expressed by [13, 18]:

$$C = -x_C(A + B_0), \tag{3}$$

where $x_C = 0.27484$ is a kinematical factor[1].

The present status on the correlation coefficients a, A, B, C, D, N, and R, the Fierz terms b and b_ν, and the neutron lifetime τ_n is summarized in Ref. [3]. According to the Particle Data Group's (PDG) 2011 review [19], the relative errors on a, A, B, and C are 4 %, 0.9 %, 0.3 %, and 1 %, respectively. Recently, three beta asymmetry experiments have completed their analyses, namely UCNA [20], PERKEO II [21][2], and PERKEO III [23]. The PERKEO III collaboration improved the uncertainty on A by about a factor of 5 compared to the PDG 2011 average (preliminary). For D, R, b, and b_ν only upper limits have been derived.

Within the framework of the SM, neutron beta decay is described as a purely left-handed, V−A interaction. Then, $b = 0$ and $b_\nu = 0$, and also $D = 0$ if time reversal invariance is assumed, and the correlation coefficients a, A, B, and C depend only on the ratio $\lambda = g_\mathrm{A}/g_\mathrm{V}$ of the weak axial-vector to the vector coupling constant:

$$a=\frac{1-|\lambda|^2}{1+3|\lambda|^2},\quad A=-2\frac{|\lambda|^2+\lambda}{1+3|\lambda|^2},\quad B=2\frac{|\lambda|^2-\lambda}{1+3|\lambda|^2},\quad\text{and}\quad C=x_C\frac{4\lambda}{1+3|\lambda|^2}. \tag{4}$$

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[1] Note that we define the proton asymmetry parameter C with opposite sign compared to [13]. This retains the convention that a positive asymmetry indicates more particles to be emitted in the spin direction.

[2] Publication of the result of the last PERKEO II run [22] is underway.

Near the value $\lambda = -1.27$, the sensitivities of a, A, B, and C to λ are:

$$\frac{\mathrm{d}a}{\mathrm{d}\lambda} = 0.298, \qquad \frac{\mathrm{d}A}{\mathrm{d}\lambda} = 0.374, \qquad \frac{\mathrm{d}B}{\mathrm{d}\lambda} = 0.076, \qquad \text{and} \qquad \frac{\mathrm{d}C}{\mathrm{d}\lambda} = -0.124. \tag{5}$$

The size of the weak coupling constants is important for applications in cosmology (e.g., primordial nucleosynthesis), astronomy (e.g., solar physics), and particle physics (e.g., neutrino detectors) [2, 3, 6]. The value of λ can be determined from several independent neutron decay observables, each with different sensitivity to non-SM physics. Comparing the various values of λ therefore provides an important test of the validity of the SM (see, e.g., [9, 24]).

The neutron lifetime τ_n is inversely proportional to $|V_\mathrm{ud}|^2(1+3|\lambda|^2)$ [25]. Hence, independent measurements of τ_n and of an observable sensitive to λ allow the determination of V_ud. Along with V_us and V_ub from K-meson and B-meson decays, respectively, the unitarity of the CKM matrix is tested [19, 26].

2. Facility PERC

PERC is a new type of beam station for the measurement of angular correlations in the beta decay of free neutrons. In contrast to existing neutron decay spectrometers, PERC is a user instrument which delivers at its exit not neutrons but an intense beam of decay electrons and protons, under well defined and precisely variable conditions. Depending on the observable, different secondary spectrometers can be used, cf. Secs. 2.3 and 2.4. Thus, with PERC, we can measure the shapes and magnitudes of electron or proton energy spectra from polarized or unpolarized neutron decay, in pulsed or continuous neutron beam mode, with or without electron spin analysis. Many quantities can be derived from such spectra, some for the first time. From single particle spectra we can obtain:

- the correlation coefficients a, A, and C,
- the Fierz interference term b, yet unmeasured in neutron beta decay, and
- the electron helicity H_e.

We note that the achievable accuracies of a and C depend heavily on the systematic uncertainties in the spectroscopy of decay protons, which have not yet been completely analyzed, cf. Sec. 2.3. From the measured values of a, b, A, C, and the precise energy or momentum spectra, we derive:

- the ratio λ of the weak axial-vector to the vector coupling constant,
- the element V_ud of the CKM quark-mixing matrix,
- the neutrino asymmetry parameter B and the Fierz-like parameter b_ν,
- scalar g_S and tensor g_T admixtures,
- mass m_2 and mixing angle ζ of a W_R boson, mediating right-handed interactions,
- the weak magnetism f_2 and second class g_2 form factors, etc.

PERC will be built by an international collaboration with the Universities of Heidelberg and Mainz, the Technische Universität München, the Institut Laue-Langevin in Grenoble, and the Vienna University of Technology. The instrument will be set up at a new position of the beam facility MEPHISTO of the Forschungs-Neutronenquelle Heinz Maier-Leibnitz (FRM II) in Munich, Germany.

The final design of PERC has to be fixed in close cooperation with the manufacturers. In the following, we discuss only one possible layout.

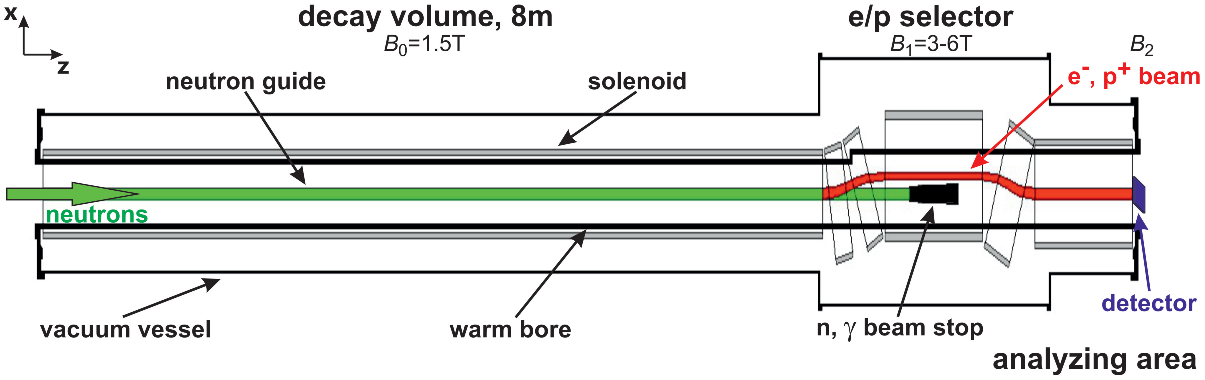

Figure 1. Scheme of the facility PERC: Cold neutrons (green) pass through the decay volume where only a small fraction decays. The decay products (red) are guided by the strong magnetic field towards the detector (blue). The superconducting coils are drawn in gray. We note that the tilted coils are also solenoids; their view is due to different longitudinal and transverse scales of the drawing. The equipment for neutron beam preparation, like velocity selector, polarizer, spin flipper, or chopper, is located in front of the instrument (to the left of the scheme) and not shown here. For details see [8].

2.1. Measurement principles and instrument

PERC is a beam station, which delivers at its exit neutron decay products. The set-up is schematically shown in Fig. 1 and in Ref. [8]; its design principles are thoroughly discussed in [8]. Here, we will only summarize the essential parts: Cold neutrons pass through an 8 meters long neutron guide, with a cross section of $6 \times 6\,\mathrm{cm}^2$, where about 10^6 neutrons decay per second and per meter of guide. The neutron guide is surrounded by a superconducting solenoid ($B_0 = 1.5\,\mathrm{T}$) of equal length. Decay electrons and protons are guided by the strong longitudinal magnetic field towards the electron/proton (e/p) detection system, i.e., detectors specialized for certain tasks (see also Secs. 2.3 and 2.4). This combination provides the highest phase space density of decay products. The count rates of neutron decay products will be increased by a factor of 100 compared to competing experiments, with the exception of PERKEO III[3]. At the end of the neutron guide, the decay products can be separated from the neutron beam by means of bending coils. In the e/p selector, the decay products pass a region of strongly enhanced magnetic field $B_1 > B_0$ ($B_1 = 3 - 6\,\mathrm{T}$) before they reach the detector (at, e.g., $B_2 = 0.5\,\mathrm{T}$), as can be seen from Fig. 2. The field B_1 acts as a magnetic mirror and transmits only the fraction $(1 - \cos\theta_\mathrm{C})/2$ ($\approx B_0/4B_1$, for $B_0 < B_1$) of all decay products, namely those emitted upstream under angles $\theta_0 \leq \theta_\mathrm{C} = \arcsin\sqrt{B_0/B_1}$ to the $z-$axis.

Field variations $B(z)$ must be slow enough such that the decay electrons and protons are transported adiabatically. Then, the magnetic transport no longer depends on the energy of the decay products. The condition for adiabatic transport can be formulated as the requirement that the quantity γ, defined in [28] as:

$$\gamma = \frac{2\pi p_\mathrm{e}\cos\theta_0}{eB^2}\left|\frac{\partial B}{\partial z}\right|, \tag{6}$$

is small ($\gamma \ll 1$). Our magnetic field calculations show that adiabatic transport is guaranteed along the particle trajectories, for all design concepts under consideration.

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[3] In PERKEO III, the count rates have already increased by about an order of magnitude [27].

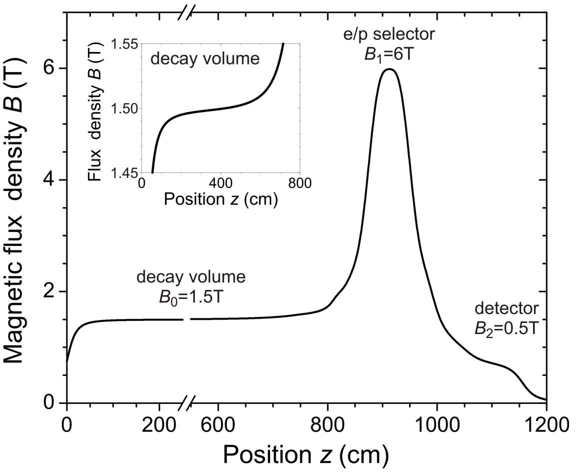

Figure 2. Magnetic flux density $B(z)$ along the central field line (preliminary), for $B_1 = 6\,\mathrm{T}$. The magnetic mirror field ratio B_1/B_0 determines the divergence of the emerging beam of decay electrons and protons by the cut-off angle $\theta_\mathrm{C} = \arcsin\sqrt{B_0/B_1}$.

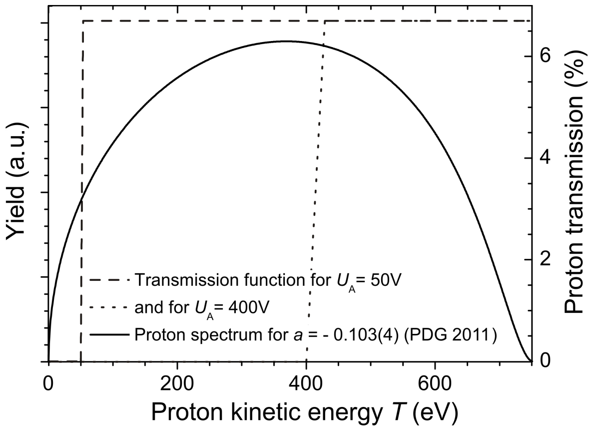

Figure 3. The dashed and dotted line indicate the transmission function for protons in unpolarized neutron decay (preliminary), for $B_1 = 6\,\mathrm{T}$ and *a*SPECT as detection system, with $B_2 = 0.4\,\mathrm{T}$ and $U_\mathrm{A} = 50\,\mathrm{V}$ respectively $U_\mathrm{A} = 400\,\mathrm{V}$. For elucidation, the solid line shows the proton energy spectrum.

2.2. Measurement uncertainties and systematics

The magnetic mirror serves to limit the phase space precisely, reducing related systematic errors. Systematic errors related to electron spectroscopy have been shown to be on the level of 10^{-4}, more than 10 times better than that achieved today [8]. There is one exception related to the knowledge of the neutron beam polarization, where presently the error is on the 10^{-3} level [29]. Techniques for the polarization of a roughly monochromatic ($\Delta\lambda/\lambda \approx 10\,\%$) cold neutron beam will be improved towards the 10^{-4} level, cf. Sec. 2.4.

Further details on the sensitivity and the applications of PERC may be found in [8]. For details on the neutron beam preparation and polarization analysis we refer to [30–32].

2.3. Dominant uncertainties in the analysis of decay protons

Depending on the decay parameters studied with PERC, the analysis of the decay electrons and protons will be performed with specialized detectors. As far as electrons are concerned, this can be done with an energy sensitive detector. For protons, PERC will feed a charged particle spectrometer, for instance an adapted spectrometer which can partially be based on the *a*SPECT [33–36] detection system. *a*SPECT is a retardation spectrometer which measures the proton recoil spectrum by counting all decay protons that overcome an electrostatic barrier U_A. Such a measurement allows the determination of the correlation coefficients a and C. The most important associated systematic uncertainties for *a*SPECT as detection system for PERC are:

- *Homogeneity of the magnetic field*: In the adiabatic approximation, the transmission function as shown in Fig. 3 can be calculated analytically, cf. Refs. [33, 34]. Our initial calculations indicate that the magnetic fields B_0, B_1, and B_2 must be controlled at the level of $\Delta B_0/B_0 < 1\,\%$, $\Delta B_1/B_1 = 1 \times 10^{-4}$, and $\Delta B_2/B_2 = 1 \times 10^{-4}$, respectively, in order to keep $\Delta a/a < 0.1\,\%$. The condition $\Delta B_0/B_0 < 1\,\%$ can be fullfilled in pulsed neutron beam mode. Then, the decay products will be counted in the detector only while the neutron pulse is fully contained within the central, homogeneous part of the magnetic field, as can be seen from Fig. 2 (zoom to the decay volume). Our magnetic field calculations show that the condition $\Delta B_1/B_1 = 1 \times 10^{-4}$ is fulfilled within the flux of neutron decay products. For aSPECT, it has been shown that $\Delta B_2/B_2$ is on the level of 10^{-4} [37].

- *Homogeneity of the electric field*: Our first estimates demonstrate that the electric potential between decay volume, e/p selector, and electrostatic barrier will have to be known with an accuracy of better than 10 mV, comparable to aSPECT and Nab [38].
- *Doppler effect due to neutron motion*: Unlike in aSPECT or Nab, the Doppler effect is not negligible as the neutron beam is collinear to the detection system. For a Gaussian neutron spectrum, preliminary estimates show that the mean neutron energy has to be known with a precision of better than 10^{-2}, whereas the uncertainty in width of the spectrum is negligible. An approximately Gaussian neutron spectrum can be obtained, e.g., by a neutron velocity selector.
- *Adiabaticity of proton motion*: For the determination of a, adiabatic transport must be guaranteed between decay volume and electrostatic barrier. Equation 6 is a first estimate for the adiabaticity of the proton motion.
- *Residual gas*: Simulations for aSPECT and Nab [39] have demonstrated that changes in the extracted value of a are tolerable if the residual gas pressure can be reduced to 10^{-8} mbar independent of the type of gas, and negligible if the pressure can be reduced to 10^{-9} mbar.
- *Particle trapping*: Surface potential variations in the order of 100 mV have been found in electrodes prepared within the aSPECT project [35]. Such variations can lead to local field extrema within the decay volume, the e/p selector, or the electrostatic barrier, and can therefore give rise to potential penning traps. For the same reason, local magnetic field minima must be avoided.

All these systematic effects are on the simulation agenda, and will be analyzed in due course. Measures to reduce and to precisely control systematic errors, like an online NMR system for monitoring of the magnetic field with 10^{-4} accuracy [37] or investigations of the patch effect with surface potential variations < 10 mV [24] (see also [40]), have already been initiated.

2.4. Sub-Projects

In spring 2010, the PERC instrument was approved by the German Research Foundation (DFG). Within the Priority Programme (SPP) 1491 ‘Precision experiments in particle and astrophysics with cold and ultracold neutrons’ the DFG established seven projects which comprise, among others, the design and the construction of

- the superconducting magnet system,
- a non-depolarizing neutron guide,
- a pulsed spatial neutron magnetic spin resonator [30, 31],
- detectors for electron energy spectroscopy and proton spectroscopy,

the design of

- a spectrometer for simultaneous electron and proton momentum spectroscopy,
- a spectrometer for proton spectroscopy, and
- the neutron beam line (neutron polarization and polarization analysis with 10^{-4} accuracy; first results of the development phase see [32]).

The neutron beam line will be provided by the FRM II.

3. Summary

The new beam station PERC is under development by an international collaboration. The collaboration plans high-precision measurements of correlation coefficients in neutron beta decay, some of them for the first time. With PERC, the sensitivity of neutron decay studies will be improved by one order of magnitude. Thus, precise symmetry tests of various kinds are coming within reach with the new facility PERC.

The instrument PERC received approval by the DFG in spring 2010. It will be set up at the beam facility MEPHISTO of the FRM II in Munich, Germany. The first milestone, the design of the magnet system together with magnetic field calculations for strong magnetic fields, has been achieved. We are now ready for the call for tenders for the superconducting magnet system.

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References

[1] Severijns N, Beck M and Naviliat-Čunčić O 2006 *Rev. Mod. Phys.* **78** 991

[2] Abele H 2008 *Prog. Part. Nucl. Phys.* **60** 1

[3] Dubbers D and Schmidt M G 2011 *Rev. Mod. Phys.* , in print URL `arXiv:1105.3694v1 [hep-ph]`

[4] Herczeg P 2001 *Prog. Part. Nucl. Phys.* **46** 413

[5] Ramsey-Musolf M J and Su S 2008 *Phys. Rev.* **456** 1

[6] Nico J S 2009 *J. Phys. G: Nucl. Part. Phys.* **36** 104001

[7] Soldner T *et al.* (eds) 2009 *Proceedings of the International Workshop on Particle Physics with Slow Neutrons, Grenoble, France, 2008* (Nucl. Instr. and Meth. A **611**)

[8] Dubbers D *et al.* 2008 *Nucl. Instr. and Meth. A* **596** 238 ,
for an extended version, see URL `arXiv:0709.4440v1 [nucl-ex]`

[9] Konrad G *et al.* 2011 *Proceedings of the 5th International Conference Beyond 2010, Cape Town, South Africa* ed Klapdor-Kleingrothaus H V, Krivosheina I V and Viollier R (World Scientific, Singapore) p 660 ISBN 978-981-4340-85-4 URL `arXiv:1007.3027v2 [nucl-ex]`

[10] Jackson J D, Treiman S B and Wyld H W 1957 *Phys. Rev.* **106** 517

[11] Cabibbo N 1963 *Phys. Rev. Lett.* **10** 531

[12] Kobayashi M and Maskawa T 1973 *Prog. Theor. Phys.* **49** 652

[13] Glück F, Joó J and Last J 1995 *Nucl. Phys. A* **593** 125

[14] Mumm H P *et al.* 2011 URL `arXiv:1104.2778v2 [nucl-ex]`

[15] Soldner T *et al.* 2004 *Phys. Lett. B* **581** 49

[16] Kozela A *et al.* 2009 *Phys. Rev. Lett.* **102** 172301

[17] Kozela A *et al.* 2011 *Acta Physica Polonica B* **42** 789

[18] Glück F 1996 *Phys. Lett. B* **376** 25

[19] Nakamura K *et al* (Particle Data Group) 2010 *J. Phys. G: Nucl. Part. Phys.* **37** 075021 and 2011 partial update for the 2012 edition URL `http://pdg.lbl.go`

[20] Liu J *et al.* 2010 *Phys. Rev. Lett.* **105** 181803

[21] Abele H 2009 *Nucl. Instr. and Meth. A* **611** 193

[22] Mund D 2006 Ph.D. thesis Ruprecht-Karls-Universität Heidelberg

[23] Mest H 2011 Ph.D. thesis Ruprecht-Karls-Universität Heidelberg

[24] Konrad G 2011 Ph.D. thesis Johannes Gutenberg-Universität Mainz , in progress

[25] Marciano W J and Sirlin A 2006 *Phys. Rev. Lett.* **96** 032002

[26] Czarnecki A, Marciano W J and Sirlin A 2004 *Phys. Rev. D* **70** 093006

[27] Märkisch B *et al.* 2009 *Nucl. Instr. and Meth. A* **611** 216

[28] Kruit P and Read F H 1983 *J. Phys. E* **16** 313

[29] Kreuz M *et al.* 2005 *Nucl. Instr. and Meth. A* **547** 583

[30] Gösselsberger C *et al.* 2011 *Physics Procedia* , accepted,
see also: Badurek G, Gösselsberger C and Jericha E 2011 *Physica B* **406** 2458

[31] Gösselsberger C *et al.* 2011 *J. Phys.: Conf. Series* , these proceedings

[32] Klauser C *et al.* 2011 *J. Phys.: Conf. Series* , these proceedings

[33] Zimmer O *et al.* 2000 *Nucl. Instr. and Meth. A* **440** 548

[34] Glück F *et al.* 2005 *Eur. Phys. J. A* **23** 135

[35] Baeßler S *et al.* 2008 *Eur. Phys. J. A* **38** 17

[36] Konrad G *et al.* 2009 *Nucl. Phys. A* **827** 529c

[37] Ayala Guardia F 2011 Ph.D. thesis Johannes Gutenberg-Universität Mainz , in progress

[38] Počanić D *et al.* 2009 *Nucl. Instr. and Meth. A* **611** 211

[39] Alarcon R *et al.* 2010 Nab proposal update and funding request
`http://nab.phys.virginia.edu/nab_doe_fund_prop.pdf`

[40] McGovern S 2010 Master's thesis University of Virginia