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Parity violation in nuclear systems

Experimental considerations in the deuteron photodisintegration with polarized photons

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Abstract. Experimental measurements of Parity Non-Conserving (PNC) asymmetries in simple nuclear systems represent always a key-tool for the study of the weak nucleon-nucleon interaction and consequently an accurate experimental method for the determination of the meson-nucleon weak coupling constants of the underlying theory. Recent theoretical analysis on the deuteron photodisintegration with polarized photons, a few MeV above threshold, have drastically improved previous theoretical estimates. Based on that, the feasibility of measuring the photon asymmetry A_γ in the reaction $\bar{\gamma}+d \to n+p$ with the 10-MeV CW Linac at the Institute of Accelerating Systems and Applications (IASA) is considered here. A brief review on previous experimental results obtained in the deuteron photodisintegration and in the thermal-neutron radiative capture on protons (inverse reaction) is given. The most important parameters in the design of a nuclear parity experiment are presented and the crucial factors, such as beam intensity, beam polarization and neutron detection techniques with the required high accuracy are outlined.

PACS. 24.80.+y Nuclear tests of fundamental interactions and symmetries – 25.20.-x Photonuclear reactions

1 Introduction

The deuteron has played an important role in the study of the weak nucleon-nucleon interaction. Together with scattering experiments the studies of Parity Non-Conserving (PNC) transitions in the nucleon-nucleon system are very attractive because of the simplicity and the well understood structure of the system [1,2].

The first experiment which received a lot of attention during the 1970's was the "Lobashov" experiment. In this experimental study the Leningrad group has investigated the net polarization of the emitted photons in the radiative thermal neutron capture by proton, $n + p \to d + \gamma$. The experimental work was characterized by the novel techniques applied for measuring the integrated current. The nonzero polarization obtained in this reaction [3], $P_\gamma = -(1.3 \pm 0.45) \times 10^{-6}$, which is 30 times larger in magnitude than the theoretical prediction and, moreover, of opposite sign, motivated many theoretical calculations in the frame of strong and weak interaction models known at that time. Later experimental work for the circular polarization P_γ of the emitted 2.23 MeV photons reported values more consistent with theoretical estimates but with too poor accuracy to allow any definite conclusion about the strength of the PNC forces [4]. At present, a new PNC-asymmetry measurement for the radiative neutron-proton capture with polarized neutrons, $\bar{n} + p \to d + \gamma$, is in preparation at LANSCE in order to reduce the experimental error of the spatial asymmetry A_γ of the emitted photons [5,6].

Another tool to study PNC forces is the inverse reaction $\bar{\gamma} + d \to n + p$, where a deuteron is disintegrated by absorbing a circularly polarized photon. The asymmetry A_γ in this reaction near threshold is expected to be sensitive to the same components of the weak nucleon-nucleon interaction as the thermal neutron capture. A key measurement of this asymmetry has been also performed in the past at the Chalk River Nuclear Laboratories, established as a "Chalk River" experiment [7]. Unfortunately, the results of this measurement were characterized by poor control on the systematic errors, mainly due to beam instabilities. With the most recent advances in the beam instrumentation and in the detection techniques, taking also in account the new theoretical considerations on this subject, a measurement of A_γ becomes nowadays more realistic.

The feasibility of measuring the photon asymmetry A_γ in the deuteron photodisintegration at low energies with the 10-MeV CW Linac at the Institute of Accelerating Systems and Applications (IASA), Athens, is considered here. First, a brief review on the recent theoretical calculations and predictions of the expected asymmetry will be given. The most important parameters in the design of a nuclear parity experiment will be presented and the

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crucial factors, such as beam intensity, beam polarization and neutron detection techniques with the required high accuracy will be outlined. At the end, the IASA accelerator and the possibilities of using it as a dedicated machine for the nuclear parity study will also be discussed.

2 Theoretical calculations and predictions

The asymmetry in the deuteron photodisintegration $\bar{\gamma} + d \rightarrow n + p$ of an unpolarized target is defined as

$$A_\gamma = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

where σ_+ and σ_- denotes the total cross section using right- and left-handed polarized photons respectively. This asymmetry A_γ becomes asymptotically equal to the circular polarization P_γ of the emitted 2.23-MeV photons in the thermal neutron capture by protons (inverse reaction $n + p \rightarrow d + \gamma$) at threshold energy.

First calculations of A_γ done by Lee [8], up to photon energy 1 MeV above the disintegration threshold, show a reasonable result within the theoretical range of P_γ in this energy domain, where the regular transition M1 dominates. However, a later work by Oka [9], extended to higher photon energies $\omega_\gamma \simeq 35$ MeV, suggests that PNC effects are different compared to low photon energy, since the major contribution to the cross section comes now from the E1 transition (compare also Fig. 1). Due to the initiated parity-violating π-exchange contribution, it was predicted that A_γ shows a great enhancement at energies $\omega_\gamma \geq 5$ MeV. The experimental observation of this enhancement would provide an important and unambiguous determination of the weak πNN coupling constant h^1_π.

Unfortunately, a recent calculation of A_γ by Khriplovich and Korkin [10] showed critical contradictions to Oka's result, with a huge suppression of A_γ at energies $\omega_\gamma \geq 3$ MeV. It seems that in Oka's work, a non-vanishing value for the pion-exchange contribution to the asymmetry was obtained as a result of the incomplete account for P-odd mixing, since only the $^3P_1$ admixture to the deuteron ground state was included there. In order to examine the situation in a most accurate way, Liu, Hyun and Desplanques [11] did a careful calculation of this process by completing the missing parity-admixed components in the final state, in particular in the $^3P_1$ channel, and by including tensor and spin-orbit forces in the nucleon-nucleon interaction using the realistic Argonne AV18-potential. The result of this improved work confirmed the strong suppression of the π-exchange contribution to the asymmetry and is illustrated in Fig. 2.

At the same time, another independent theoretical work by Fujiwara and Titov [12] analyzed the energy dependence of the A_γ asymmetry in the deuteron photodisintegration. Although this second paper was based on the Paris potential with soft repulsion at short distances and the Hamada-Johnston potential, both studies come to consistent to each other results. The predicted theoretical values for the asymmetry A_γ of all mentioned models are summarized in Table 1.

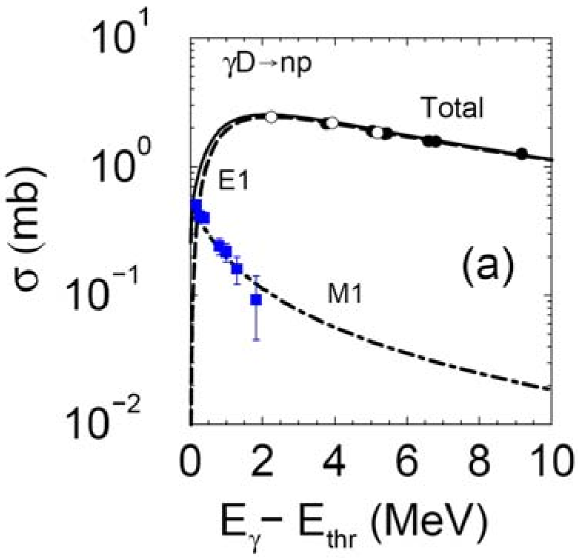

Fig. 1. Total cross section for the deuteron photodisintegration as a function of the energy excess above the disintegration threshold, calculated with the Paris potential (From [12]). The contributions of the M1 (*dot-dashed*) and E1 (*dashed*) transitions are shown together with experimental data

Table 1. Predicted values for the A_γ asymmetry in the $\bar{\gamma} + d \rightarrow n + p$ reaction

γ-Energy	A_γ	Dependence	Ref.
10 MeV	$\sim 2.4 \times 10^{-7}$	h^1_π	[9]
30 MeV	$\sim 5.7 \times 10^{-7}$	h^1_π	[9]
threshold	$\sim 1.0 \times 10^{-7}$	M1 dominance	[10]
3 MeV	$\sim 1.0 \times 10^{-8}$	M1 dominance	[10]
threshold	$\sim 2.5 \times 10^{-8}$	$h^0_\rho, h^2_\rho, h^2_\omega,$	[11],[12]

The experimental consideration following in the next section is based on the most realistic estimates by Liu, Hyun and Desplanques [11], which are in agreement with the results by Fujiwara and Titov [12]. The predicted value $A_\gamma \simeq 2.5 \times 10^{-8}$ near threshold will be the starting point for the discussion of possible future experiments measuring this asymmetry in the deuteron photodisintegration with polarized photons. From Fig. 2 it is clear that, when the photon energy gets larger, the asymmetry gets smaller; as the the photon energy reaches 1 MeV above the threshold, the asymmetry drops by an order of magnitude.

3 The future experiment

In the "Chalk River" experiment the obtained results for the A_γ asymmetry were mainly affected by the big systematic errors. The final values reported there $A_\gamma = (2.7 \pm 2.8) \times 10^{-6}$ at $E_\gamma = 4.1$ MeV and $A_\gamma = (7.7 \pm 5.3) \times 10^{-6}$ at $E_\gamma = 3.2$ MeV [7] put an experimental upper limit on the value of the PNC effect. But, as this experimental study

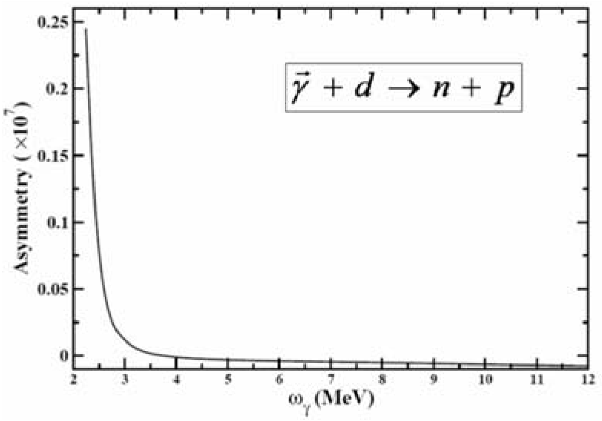

Fig. 2. Theoretical prediction for the asymmetry A_γ in the deuteron photodisintegration with polarized photons. The calculation is based on the DDH best values, taking in account tensor as well as spin-orbit forces in the nucleon-nucleon interaction (From [11])

concluded, "... it is possible to consider future measurements with techniques similar to those used in the present measurement but having improved beam intensity, beam polarization and control of systematics" [7].

The experimental goal is therefore to reduce the systematic errors to a level better than 10^{-8} in measuring the neutron asymmetry of the reaction in the deuteron photodisintegration with polarized photons. The most important factors in the design of such an experiment are:

– Reasonable flow of polarized photons
– An improved neutron detection system
– Beam quality and stability with fast feedback systems

Starting with some conservative numbers all experimental requirements are presented in the following section.

3.1 Experimental considerations

The polarized photons are produced via Bremsstrahlung with a high density polarized electron beam and a gold radiator. Development of a highly polarized electron beam with energy stability on the level of a few 10^{-6} can be routinely achieved. Having in mind a recent Letter-Of-Intent presented at JLab for a similar project [13], following parameters are outlined here for the proposed apparatus:

– Beam energy in the range $2.3 - 8$ MeV ($200 \mu A$)
– Beam polarization $P_e \sim 80\%$
– Photon production target (radiator) made of 1mm Au plate
– 30 cm long Liquid Deuterium (LD_2) target
– Main detector consists of two components (slow neutrons & photons)
– Lead shielding to reduce the intensity of scattered photons on neutron detectors
– Heavy water moderator to slow down neutrons
– Additional Compton detectors for monitoring

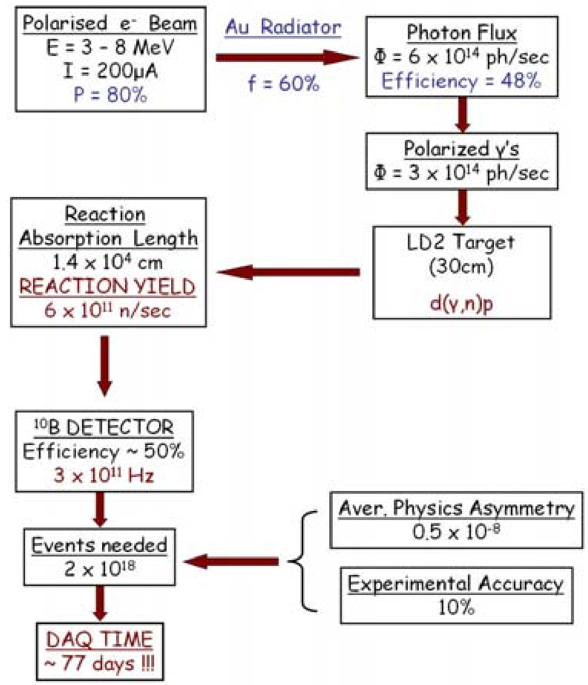

Fig. 3. Experimental statistics expected in a future experiment and the required acquisition time for data taking

Statistics obtained with the above mentioned parameters are presented in the diagram of Fig. 3. It is clear from this simple analysis, that the Data Acquisition (DAQ) time needed to successfully perform such an experiment and to reach the required accuracy comes to the order of several months!

The experimental apparatus is shown in Fig. 4. The main detector has segmentation on the forward and the back parts to get sensitivity to the directional asymmetry in addition to PNC asymmetry in the total cross section. The expected high counting rate of the neutron detectors ($\sim 10^{12} Hz$) will help to study tiny systematic effects. The choice of the spin flip frequency has to be optimized for minimum fluctuation of the beam energy and position.

3.2 The IASA electron accelerator

A 10-MeV CW linear electron accelerator has been already installed at the Institute of Accelerating Systems & Applications (IASA), which is currently under commissioning. This machine comprises a thermionic electron gun, a 100 keV-Line with a buncher-chopping system followed by a 5 MeV Linac with RF structures of the side-coupled type and a 4m-booster section of the same type [14]. Both are powered with a 500 kW multi-cavity CW klystron amplifier at 2380 MHz. The machine is hosted in the basement of the IASA building, which is extended with a new experimental hall (Fig. 5).

The IASA accelerator meets exactly the needs for a future parity-violation experiment as previously discussed. The energy range is optimally covered by this machine and

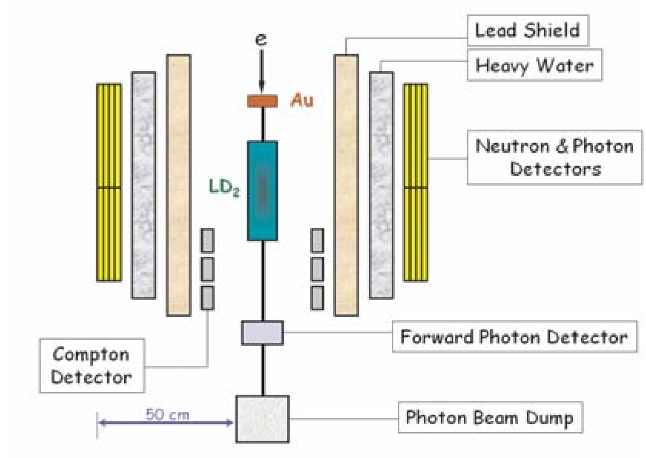

Fig. 4. Experimental setup for the study of the $\bar{\gamma} + d \to n + p$ reaction in a future experiment

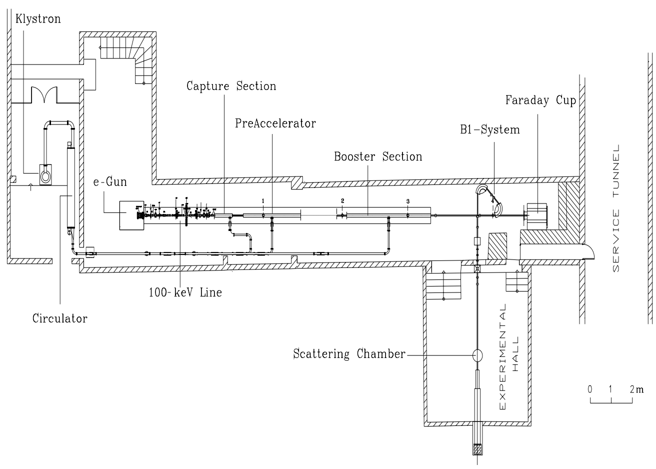

Fig. 5. The 10-MeV CW electron linear accelerator at IASA

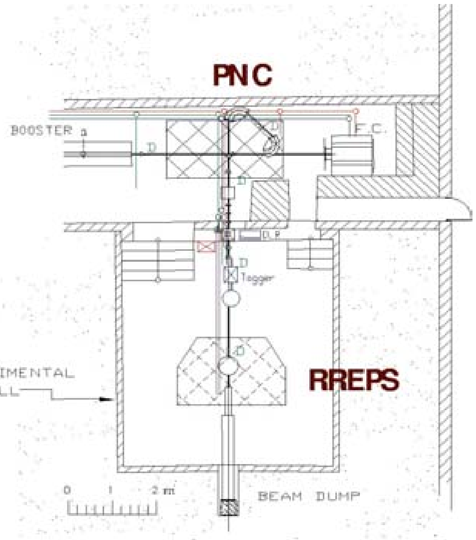

Fig. 6. Experimental area in the accelerator vault. Indicated are the area reserved for the future parity experiments (PNC) together with the area devoted to novel radiation sources (RREPS)

the beam current and beam characteristics, already measured at 100 keV, could guarantee a high quality beam. At present, the beam is not polarized, but there are future plans for the installation of a high intensity polarized electron gun. Space has been already reserved in the accelerator vault for future parity experiments as indicated in Fig. 6. Taking into account the long acquisition time required by the parity-violation experiments, the IASA 10-MeV electron accelerator could ideally be devoted to the research of the PNC studies in the deuteron photodisintegration.

4 Conclusion

Parity Non-Conserving (PNC) experiments at low energy got large attention in the last years. With the recent theoretical improvements in the calculation of the asymmetry in the deuteron photodisintegration induced by polarized photons a few MeV above threshold and with the technical progress in the accelerator domain with polarized beams, a precise measurement of parity-violating forces seems to be feasible. The 10-MeV IASA electron accelerator could serve as a machine dedicated to this kind of research.

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