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MASTER

FACILITY FOR PARITY AND TIME REVERSAL EXPERIMENTS WITH INTENSE EPITHERMAL(eV) NEUTRON BEAMS*

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A facility for polarized epithermal neutrons of high intensity is set up at the Los Alamos National Laboratory for parity-violation and time reversal experiments at neutron resonances over a wide range of neutron energies. The beam is polarized with the aid of a polarized proton target used as a neutron-spin filter. Total cross section measurements as well as capture gamma-ray experiments will be carried out. The main features of this system will be discussed.

1. INTRODUCTION

Since the discovery of parity violation in β -decay in the late fifties, one has been looking for parity-violating effects in nuclear reactions and in electromagnetic transitions in nuclei due to the admixing of states with opposite parities. This is a consequence of weak parity-violating interactions added to the parity-conserving nuclear and electromagnetic forces. Several review articles are available on this subject; e.g./1-5/. The amount of mixing of levels with different parities is governed by $F = \langle \psi^{\pi} | H_{pv} | \chi^{-\pi} \rangle / (E_{\psi} - E_{\chi})$, where H_{pv} is the parity-violating part of the hamiltonian, ψ and χ are the wavefunctions of the normal state and the admixed state with opposite parities and energies E_{ψ} and E_{χ} . Normally F is expected to be of the order of 10^{-7} . A way to detect parity violations in nuclear reactions is to look at rates of transitions which are otherwise absolutely forbidden. An example is α -decay between the 2^{-} level of ^{16}O at 8.87 MeV to the 0^{+} groundstate of ^{12}C . Due to the admixing of 2^{+} levels into this 2^{-} level as a consequence of parity violating forces a weak α -decay is possible /2,3/. It is found to be of the order of 10^{-16} in strength compared to normal α -decay. Another way to detect parity-violation is to look for admixing of irregular components in γ -transitions. The parity violating effect is proportional to FR , where $R = \langle \psi_f | O'(L') | \chi_i \rangle / \langle \psi_f | O(L) | \psi_i \rangle$. In suitable cases strong enhancements may occur when the normal transition (L) is inhibited and the irregular (L') not; making $R \gg 1$. An interesting case is the 501 keV E3+M2 transition between the 8^{-} isomer of ^{180}Hf to its 6^{+} rotational level, which has an irregular E2 component due to admixing positive parity into the 8^{-} isomer /5/. The nuclear structure effects make it difficult to analyse parity-violation effects properly; that is, the talk presented by H Postma

in neutron reactions; e.g. /12/. The effect E at p-resonances in the transmission of polarized neutrons through unpolarized nuclei is:

$$E = -Nt\sigma P_n (\langle \mathbf{g} | H_{pv} | \mathbf{p} \rangle / (E_s - E_p)) (\Gamma_s^n / \Gamma_p^n)^{1/2}, \quad (3)$$

where σ is the resonance peak cross section, Nt is the sample thickness in nuclei/cm², E_i are the energies of the interfering resonances (s and p), and Γ_i^n are their neutron widths. There is no obvious reason that only small parity-violating effects should occur. Bunakov showed that they may be very large under suitable conditions /13/.

3. TIME REVERSAL EXPERIMENTS

Following the discovery of parity violation, attention has been paid to the breaking of other symmetries. An important question concerns the validity of time reversal invariance. The property of time reversal (T) is intimately connected with the parity operator (P) and charge conjugation (C) via CPT conservation. Thus the observed CP violation in K_0 -decay, may be considered as evidence for violation of time reversal invariance. For a further search of time reversal violation, low-energy neutron reactions can be very useful. Here the situation is quite different compared to parity experiments since an unquestioned detection of time-reversal violation at only one resonance would already be of great fundamental interest. The possible detection of time-reversal violation with epithermal neutrons has recently gained considerable attention /14/. It may be manifest in experiments related to terms like

$$s_n \cdot k \times I \quad \text{and} \quad (s_n \cdot k \times I)(k \cdot I). \quad (4)$$

Since the first term has P-odd/T-odd character it may be related to weak interactions. The second term has P-even/T-odd character; it may therefore be related to strong forces. These experiments need, in addition to polarized neutrons, targets of polarized or aligned nuclei.

4. LANSCE NEUTRON BEAM FACILITIES

An intense neutron beam has been established at the Los Alamos Neu-

Fig.1. The Los Alamos neutron beam facilities at LAMPF. The H^- beam is directed to the Proton Storage Ring, which compresses the beam into 0.27 μ sec pulses. These are brought to the LANSCE target (TGT 1). In addition the MeV white neutron source is shown (TGT 4).

tron Scattering Center (LANSCE) for parity-violation and time reversal experiments. Fig.1 shows the general lay-out of the LAMPF accelerator and the neutron beam facilities. An 800-MeV H^- beam at LAMPF, accelerated together with the main H^+ beam, is injected into the Proton Storage Ring (PSR). From this ring proton pulses of 0.27 μ sec are injected into a heavy metal target at a rate of 12 pulses per second. About 25 neutrons are produced in the spallation process for each 800-MeV proton. The neutrons are partially moderated with slabs of hydrogen containing materials close to the spallation source. In this way a source of epithermal neutrons is obtained with a flux Φ of:

$$\Phi = 4 \times 10^{10} d\Omega \times (\Delta E/E) \times I \text{ neutrons/sec,} \quad (4)$$

where $d\Omega$ is the beam aperture in steradian and I is the proton current in μ A. The maximum proton current is 100 μ A. Fig.2 shows the time of flight energy resolution at two distances from the neutron source. The partial neutron moderation, source and detector dimensions influence the time resolution.

Fig.2. The resolution at LANSCE for flight path lengths of 7 and 50 meters.

5. POLARIZING EPITHERMAL NEUTRON BEAMS

An epithermal neutron beam can be polarized by transmission through a polarized sample of an isotope which has a considerable difference in total cross section $\sigma_{\pm}$ for neutron spins parallel respectively antiparallel to the polarized nuclei, that is:

$$\sigma_{\pm} = \sigma_0 (1 \pm p P_s), \quad (5)$$

where σ_0 is the total cross section for unpolarized nuclei, P_s is the degree of nuclear polarization and p is a spin-dependent factor. Suitable isotopes for this neutron-spin filter technique are 1H /15/ and 3He /16/. Their p -values are -0.82 respectively -1.0. A great advantage of 1H is its constant total cross section over a wide energy range (≈ 1 eV to 50 keV). Because of its p -value 3He is in principle a more effective neutron-spin filter; however, its cross section decreases with neutron energy E_n according to: $\sigma_0 = 8447 \times E_n^{-1/2}$ barn with E_n in eV. 3He can be polarized as a rather dense gas (≈ 5 bar) with the aid of optical pumping using a scheme developed at Princeton /17/. It has recently been used as a neutron-spin filter below ≈ 5 eV /18/. Larger polarized 3He cells (in diameter as well as thickness) are needed to apply them as neutron-spin filters for

parity experiments.

Protons can be polarized with the aid of microwave pumping in various materials containing free protons /19/. For the application as a neutron-spin filter crystals of $(\text{La}, 0.5\% \text{Nd})_2 \text{Mg}_3(\text{NO}_3)_{12} \cdot 24\text{H}_2\text{O}$, abbreviated as LMN, have been used /15,20/. Its density is 2.07 gr/cm^3 ; the free proton total cross section is 20.5 barn between 1 eV and 50 keV. The additional cross section due to the other nuclei in LMN is 8 barn at 1 eV; it decreases slightly with neutron energy.

An unpolarized neutron beam traversing a polarized nuclear target becomes polarized according to:

$$P_n = -\tanh(N\sigma_0 t p P_s), \quad (6)$$

where N is the number of polarized nuclei per cm^3 and t is the sample thickness. The transmission T of the neutron beam through the polarized sample is given by:

$$T = \exp(-N\sigma_0 t) \times \cosh(N\sigma_0 t p P_s) \times \exp(-\sum N_i \sigma_i t), \quad (7)$$

where σ_i are cross sections of additional unpolarized nuclei inside the target and N_i are their densities (in the last factor of eq.7 the materials of the target holder and windows can be included).

Considering counting statistics the optimum thickness $D_0 = (N\sigma_0 t)_{\text{opt}}$ for a fixed value of polarization P_s is given by:

$$\tanh(D_0 p P_s) = [-1 + (1 + 8p^2 P_s^2)^{1/2}] / 2p P_s. \quad (8)$$

For a small degree of polarization the optimum sample thickness is $D_0 = 2$; at higher degrees it lowers slightly to 1.86 at $p P_s \approx 0.55$ and thereafter it increases rapidly; see fig.3.

Fig.3. Optimum target thickness D_0 for neutron-spin filters as a function of polarization $p P_s$.

To compare neutron-spin filters $f = P_n^2 T$ can be used as a figure of merit. The solid curves in fig.4 show f for polarized protons and ^3He with the current state of technology available at Los Alamos; that is for both 60% polarization. For protons $N\sigma_0 t = 1.86$ is chosen, which is the optimum thickness given by eq.8. For ^3He we assumed 5×10^{20} ^3He atoms per cm^2 as achieved by the Princeton group in a demonstration at Los Alamos for the usefulness of optically polarized ^3He as a neutron-spin filter below a few eV /18/. In the case of ^3He the figure of merit is constant for $E_n \leq 1$ eV. Due to the energy variation of the ^3He cross section its figure of merit decreases above its optimum thickness which occurs at 0.04 eV for the given number of ^3He

atoms/cm². The dashed curves represent future expectations with 90% polarization for ¹H and ³He, and a three times larger thickness for ³He; that is 1.5×10^{21} /cm². The optimum thickness for ¹H is 1.95.

Another important aspect concerns the diameter of the neutron-spin filter. For optically polarized ³He the cell diameter is currently limited to 1 to 2 cm; in the case of polarized protons the diameter is easily three times as large, thus giving an order of magnitude larger neutron count rate.

6. LANSCE POLARIZED NEUTRON BEAM

With the current state of technology polarized protons are superior to polarized ³He as a neutron-spin filter for the planned parity and time-reversal experiments. During the past few months a mothballed LMN polarized proton target, originally used for experiments by Keyworth et al./20/ to determine spins of neutron resonances, has been repaired and installed at one of the LANSCE neutron beams. The target consists of 6 flat LMN crystals forming a block of 3.5x3.5 cm² in cross section and 1.78 cm thick. They are placed inside a microwave cavity and cooled by a pumped helium bath (1.15 K). The Nd³⁺ ions serve as the microwave pumping medium; the magnetic g-factor is highly anisotropic; that is $g_{||}=0.36$ and $g_{\perp}=2.702$. The crystals are cut in such a way, that their c-axes are perpendicular to the neutron beam direction. A magnetic field of 2.02 Tesla, produ-

Fig.4. Comparison of figures of merit for polarized protons and ³He as neutron-spin filters. The solid lines concern the current state of technology; the dashed lines indicate future expectations. See text for further explanations.

ced by a superconducting magnet, is along the beam direction. This magnet is in the same pumped He bath as the LMN-sample and cavity. Its homogeneity is 10^{-4} over the sample volume. Inserts intruding from the wall of the inner vessel into the pumped bath close to the cavity collimate the beam to 10 cm² and restrict the amount of helium the neutron beam has to traverse. Another helium bath at atmospheric pressure acts as a thermal shield and, via a needle valve, as a continuous supply for the pumped He bath. A large rotary/roots pump system (1400 l/s) is used to reduce the pressure of the inner He-bath, which has a boil off of approximately 4 l/h under running conditions with the microwave power on. A liquid N₂-vessel serves as another thermal shield inside the cryostat. About 120 l of liq. He

and 100 l of liq. N_2 are needed daily under normal steady-state running. The microwave frequency is ≈ 76.5 GHz. The microwave/magnetic-field combination can be set such that either one of the two "forbidden" electron-proton transitions is saturated, leading to proton polarizations parallel or anti-parallel to the neutron beam direction. With this system 55% proton polarization has been achieved. In fig.5 the neutron polarization P_n , the transmission T and the figure of merit f are given as a function of the proton polarization. Cross sections of nuclei other than the free protons in LMN have been taken into account for calculating T . The proton polarization P_s can be monitored with the NMR sweep method, and by measuring the difference in neutron transmission with the target polarized and unpolarized. The latter provides a value of $\cosh(N\sigma_0 t p P_s)$ and thus of P_s . This method is preferred since it gives the averaged proton polarization as seen by the neutron beam.

The polarized proton target has been placed at a position 7m away from the neutron source.

Fig.5. The degree of neutron polarization P_n , transmission T and figure of merit f of the installed neutron-spin filter as a function of sample polarization P_s .

6. REVERSAL OF NEUTRON BEAM POLARIZATION AND NEUTRON DETECTION

To enable difference measurements the neutron spins should be reversed rapidly and frequently in order to reduce systematic errors. By retuning the microwave frequency from one of the forbidden proton-electron transitions to the other, the proton polarization is reversed, and hence the neutron polarization. This process takes about 2 h. A rapid reversal of the neutron polarization (≈ 1 s) can be achieved with a spin-rotator consisting of two solenoids parallel and one coil perpendicular to the beam. Rotation of the field along the beam must be slow compared to the distance L a neutron travels during one Larmor precession. L is given by:

$$L = 4.8 \times 10^{-4} \times E_n^{1/2} / B, \quad (9)$$

with E_n in eV and the magnetic field B in Tesla. Little neutron depolarization is expected even if the Larmor frequency is only a few times the angular variation of B . Applying both methods for neutron spin reversal gives all combinations of field and polarization direc-

tions, which is important for the reduction of systematic errors.

Three detector stations are available at 11, 25 and 60 m from the neutron source. Currently ^6Li -glass detectors (0.5 cm thick) are in use. Their detection efficiency is 50% at 30 eV. Both pulse- and current-mode measurements of the neutron flux are possible.

7. GAMMA-RAY EXPERIMENTS

Emission of γ -radiation following resonance neutron capture is of interest for further parity-violation experiments. That kind of work will become possible at various laboratories with the increase of neutron flux. Some work has already been started in this direction, so far mainly dealing with low energy γ -transitions. Detection of primary γ -transitions is of great interest for a number of reasons. i) Irregular transitions may be enhanced with respect to the regular transitions; e.g. E1 might be mixed into M1 transitions. ii) Channel-spin mixing may vary considerably over the primary γ -transitions in case of p-wave resonances with total spin $J=I\pm 1/2$, where I is the spin of the capturing nucleus. iii) Parity-violation can be observed for partial γ -widths. Larger parity-violation effects may occur in individual γ -transitions compared to the parity-violation effects so far observed in total cross sections.

8. FIRST POLARIZATION EXPERIMENTS AT LANL

Transmission experiments with polarized neutrons through targets of unpolarized nuclei have very recently been started at LANL using samples of ^{139}La , ^{165}Ho , ^{232}Th , ^{233}U , ^{235}U and ^{238}U .

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