Nuclear Instruments and Methods in Physics Research A 612 (2009) 46–49

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Nuclear targets for a precision measurement of the neutral pion radiative width

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ARTICLE INFO

Article history:
Received 3 December 2008
Received in revised form
11 July 2009
Accepted 24 September 2009
Available online 17 October 2009

Keywords:
Solid nuclear targets
Area density
X-ray attenuation

ABSTRACT

A technique is presented for precision measurements of the area densities, ρT, of approximately 5% radiation length carbon and ^{208}Pb targets used in an experiment at Jefferson Laboratory to measure the neutral pion radiative width. The precision obtained in the area density for the carbon target is $\pm 0.050\%$, and that obtained for the lead target through an X-ray attenuation technique is $\pm 0.43\%$.

1. Introduction

Photo and electro-nuclear experiments performed at the high duty factor, high intensity electron accelerators such as Jefferson Laboratory and the MAMI Laboratory are continually pushing towards higher levels of precision. With the dramatic increase in beam intensity and beam quality available at these labs, and the availability of fully developed state-of-the-art detection systems, the relative importance in minimizing the uncertainty in the target area density, ρT, has increased. Examples of experiments that require precise target information include measurements of elastic electron scattering form factors, and the quasi-free electron scattering response functions on nuclear targets.

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doi:10.1016/j.nima.2009.09.063

Recently at Jefferson Lab, the PRIMEX collaboration [1] made a precision measurement of the neutral pion radiative width through a measurement of Primakoff cross-sections on carbon and lead. A precision measurement of the neutral pion lifetime is regarded as one of the definitive tests of quantum chromodynamics at low energy, and the experimental value for the radiative width $7.84 \pm 0.56\,\mathrm{eV}$ provides textbook confirmation for $N_c = 3$. Next-to-leading-order calculations [2], which include quark mass effects and $\pi^0 - \eta$ mixing, are expected to be accurate at the percent level, while the Particle Data Group average for the π^0 radiative width has an error of 7%. The goal of the PRIMEX experiment is to reduce the error on the π^0 radiative width to the level where theories can be tested.

For the PRIMEX experiment to succeed it was necessary to measure absolute differential cross-sections for coherent $\gamma A \to \pi^0 A$ with unparalleled statistical and systematic accuracy. Initial plans for the experiment had allowed for errors as large as $\pm 0.7\%$ in the target area densities. This article presents the techniques that allowed us to go under the budgeted 0.7% error by a factor of 14 for the carbon target, and a factor of 1.6 for the lead target.

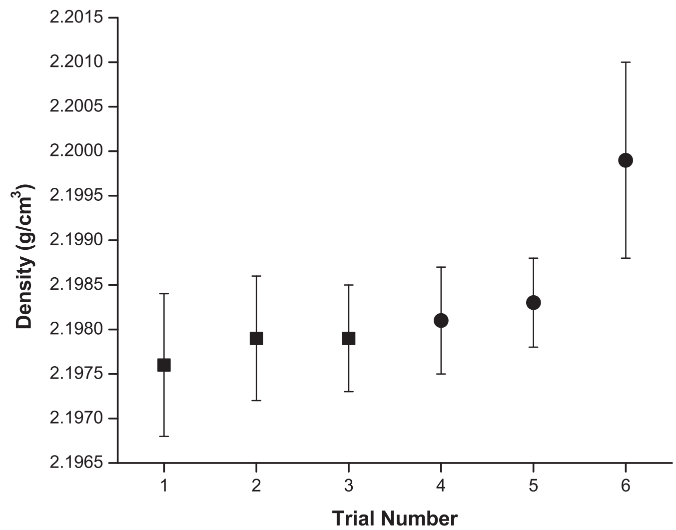

Fig. 1. Measurements of carbon target mass densities in units of g/cm^3. The square data points are from target block #1 and the round data points are from target block #2.

2. Carbon target

The carbon target was machined from a block of highly ordered/oriented pyrolitic graphite (HOPG) obtained from SLAC. HOPG is produced using high temperature (3273 K) chemical vapor deposition furnace technology, which creates atomic layers of carbon in an ordered pattern. An advantage of HOPG compared to normal graphite is very low porosity of the HOPG, 1% as compared to graphite's 10% porosity.

The machined HOPG target block had dimensions of $.94 \times .94 \times .38\,\mathrm{in.}^3$. A micrometer with precision of ± 0.05 mils was used to map the thickness of the HOPG target in the 0.38 in. direction over the surface area of the target. The thickness was found to vary by approximately $\pm 0.04\%$ over the central 0.4 in. region of the target.

The mass density of the HOPG material was measured using the water immersion technique. HPLC grade H_2O was used, which is submicron filtered, packed under inert gas, and has a maximum limit of impurities at 1 ppm. Corrections were made for the temperature dependence of the water density. A microgram scale was used to weight the target block in air and in the water. The mass densities of two identical HOPG blocks were measured three consecutive times, and the results are shown in Fig. 1. The mass density used for calculating the area density of the target was the average of the first five measurements; trial #6 was excluded from the average. The error in mass density is taken from trial #3.

Two corrections are applied to ρT to obtain the effective area density for the target. The first correction accounts for impurities in the target, which can produce neutral pions through the Primakoff process. This effect was estimated using the known functional form of the Primakoff cross-section on nuclear targets [3], and the known elastic electron scattering form factors [4]. Impurities in the HOPG material were determined using (i) optimum combustion methodology, which detects C, H, N, and O, and (ii) PIXE analysis, which detects 72 heavier elements. The correction factor to the density was approximately +0.1%. Calculations [5] indicate that magnetic Primakoff production from ^{13}C is reduced by a factor of approximately 10^6 compared to Coulomb Primakoff production. Therefore, the Primakoff cross-sections on ^{13}C and ^{12}C can be treated as equal, and no correction is needed to account for the ^{13}C content in the natural isotopic HOPG target.

The second and larger correction accounts for the attenuation of the incident photon beam in the target. The NIST XCOM database [6] was used to calculate the effect of incident beam absorption. The error in the attenuation coefficient is estimated [7] at 1.5%. The final result for the effective number of ^{12}C atoms/cm^2 at target center is $N_{\mathrm{eff}}(^{12}\mathrm{C}) = 1.0461 \times 10^{23}$ atoms/cm$^2 \pm 0.050\%$.

3. ^{208}Pb target

The ^{208}Pb target, manufactured by Oak Ridge National Laboratory [8], is a 1 in. diameter circular foil of 99.09% enriched ^{208}Pb, with an approximate thickness of 12 mil (1 mil = 0.001 in.). Because the lead target is a thin, soft foil that can be easily bent and dented, it was decided to minimize the number of micrometer measurements over the surface of the target. The technique used is based on X-ray attenuation. X-rays from a 10 μCi activity ^{241}Am source are collimated to a spot size of approximately 2 mm on the lead target, and the transmitted X-rays are detected in a 1 in. diameter NaI crystal coupled to a photomultiplier. Fig. 2 shows pulse-height spectra taken with several different lead absorbers, ranging from no absorber up to 16.96 mil of Pb. Also shown is the background distribution with no X-ray source present. The prominent peak at the center of the spectrum is the 60 keV X-ray line from ^{241}Am. The figure demonstrates the strong correlation between the strength of the transmitted 60 keV line and the lead absorber thickness, which is utilized to deduce the thickness of the target.

The transmitted 60 keV X-ray intensity can be represented by

$$I(T) = I_0 B(T,\lambda) e^{-T/\lambda} \tag{1}$$

where I is the transmitted intensity, I_0 the unattenuated intensity, T the foil thickness in cm, and λ the 60 keV X-ray attenuation length for lead in units of cm. $B(T,\lambda)$ is the build-up factor [9] which accounts for X-rays Compton scattering into the acceptance of the NaI detector, which depends critically on the specific experimental setup for the measurement. Measurements over a wide range of lead foil thicknesses showed that the build-up factor can be represented by

$$B(T,\lambda) = 1 + \alpha \frac{T}{\lambda} \tag{2}$$

where α is a dimensionless constant. Terms of order $O(T/\lambda)^2$ and higher were not significant.