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Measurements at 800 GeV"

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PRECISION NUCLEAR TARGETS FOR DRELL-YAN CROSS SECTION MEASUREMENTS AT 800 GEV

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Targets of iron, tungsten, carbon, and calcium of areal densities 2.3 to 5.8 g/cm² were fabricated to high precision for a fixed-target experiment performed in 1988 at Fermilab to measure relative Drell-Yan cross sections. The experiment used 800-GeV protons at an intensity of 2×10^{12} protons per 23-second spill. Areal densities were determined to an accuracy of approximately 1 part in 10^4 . The calcium targets were vacuum-encapsulated in stainless steel by electron-beam welding.

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1. Introduction

The targets described in this article were fabricated in Los Alamos for an experiment performed in 1987 at Fermilab designated as E772. The goal of this experiment was to measure cross sections for the reaction

$$p + A \rightarrow \mu^+ \mu^- + X$$

to a relative accuracy of 1% at an incident proton energy of 800 GeV. Here X denotes the sum of all undetected particles, and $\mu^+ \mu^-$ represents the oppositely charged muon pairs that were measured. Cross sections for $\mu^+ \mu^-$ production, known as the Drell-Yan process, were measured on nuclear targets of carbon, calcium, iron (in stainless steel), and tungsten relative to those on deuterium (D). The principal physics interest was to search for small deviations from unity in the ratio

$$\frac{\sigma_A(\mu^+ \mu^-)/A}{\sigma_D(\mu^+ \mu^-)/2},$$

where $\sigma_A(\mu^+ \mu^-)/A$ is the Drell-Yan cross section per nucleon on a target of atomic weight A. Deviations from unity indicate that quark and/or antiquark structure functions are modified by the nuclear medium. Expected deviations are at the level of 5%, thus a significant measurement requires the determination of the ratio to an accuracy of about 1%. Therefore, in the fabrication of the targets for this experiment, the composition, uniformity, and areal density needed to be known to an accuracy of a few parts in 10^3 .

The liquid deuterium target, made at Fermilab, was contained in a cylindrical target cell of 50-cm length and 7.6-cm diameter. It had an

areal density of 8.18 g/cm^2 and was operated at a temperature of 24° K . The 800 GeV proton beam traversed the target axially. The produced μ^+ and μ^- particles had typical energies of 100 GeV each and exited the target at small angles ($< 3^\circ$) relative to the beam. They then passed through 50 m of apparatus where they were analyzed for momentum and direction.

Each of the nuclear targets consisted of several disks held in a cylindrical tube, as shown in fig. 1. This tube was mounted with its axis parallel to that of the deuterium target. The targets were contained within a large vacuum box directly open to the beam line vacuum system, which had a pressure of approximately 10^{-6} torr.

For data-taking, two of these tubes were mounted in alignment frames below the deuterium target. The whole three-target assembly could be moved by remote control up and down relative to the beam axis so that any one of three targets could be placed into the beam. In a typical data cycle, lasting about 36 minutes, each of the three targets was exposed to twelve beam spills and these cycles were repeated for 5 to 10 days. The Fermilab beam spills for E772 lasted 23 sec. and there were 33 sec. between the end of one spill and the start of the next. Typical beam intensity was 2×10^{12} protons per spill.

2. Target measurements and errors

All weights and measurements are averages of at least three independent measurements. The balance used was a Mettler PC 440 which had been altered to read 0.001 g instead of the original 0.01 g. Fluctuations in the last digit were averaged in each independent weighing. The balance was calibrated with weights traceable to the U.S. National Bureau of Standards. In the case of graphite, the pieces were

the resulting casting was very porous and there was some reaction with the graphite crucible.

The successful casting was made by melting the calcium in situ in a steel pipe with a bottom welded in place. The mold is shown in fig. 2. The furnace enclosure was evacuated and backfilled with argon three times before melting of the calcium. The calcium oxide present in the source material floated on top of the molten Ca. Melt temperature was 980-1020 C; the casting weighed 2250.0 g. Because of the similar thermal expansion of iron and calcium, the calcium ingot did not separate from the steel can. The can was removed by machine cutting under mineral oil. Two castings were made, but the targets used in the experiment were all from the same casting. Analysis of the cast calcium showed a trace amount of strontium and no other impurities greater than 50 ppm.

3.2. *Machining and weighing*

The calcium ingot was cut and the target cylinders were machined under mineral oil. The machined disks were measured for thickness and diameter using a micrometer calibrated in a controlled environment. In addition, shadowgraph projection was used to check diameter, thickness, perpendicularity, flatness, and parallelism to 0.0001 (in 0.00025 cm). The finished cylinders were radiographed and tested with ultrasound for voids. None were detected. A cylinder from a different casting was distinguishable by a somewhat higher density of 1.548 g/cm³.

Each cylinder was cleaned with trichloroethylene in a flowing argon atmosphere, then transferred to an argon-atmosphere glove box for weighing. After weighing, the cylinder was replaced in oil. It was taken out of the glove box and carried to the welding area in oil.

The measured values and errors of disk diameters, thicknesses and weights are given in Table I. From these, the areal and volumetric densities were computed and are also given in the table.

3.3. *Electron beam welding of calcium containers*

Other methods considered were a) Brazing. This was rejected because the flow temperature is too close to calcium's melting point, causing possible problems with dimensional stability and solder flow onto calcium. b) Gas tungsten arc welding. This process was tested in a helium-filled glove box. Too much heat was deposited in the end foils, causing unacceptable wrinkling. c) Laser welding. This was not possible for this project because no vacuum or inert gas enclosure was available at the time.

Fig. 3 shows the can to be welded in the welding chuck which is held in a transfer device. Fig. 4 shows the can design. The end foils of 0.001 in. (0.0025 cm) type 304 stainless steel were cut with a Nd-YAG laser to obtain perpendicular edges. A hole about 0.005 in. (0.013 cm) in diameter was electron-beam-drilled in the can wall at 45 degrees to the wall before assembly, angled to miss the calcium. Its purpose was that of a positive evacuation path for atmospheric gases inside the can. The calcium cylinder and can parts were degreased before placing in the vacuum enclosure. The electron beam (EB) vacuum weld chamber was evacuated to 5×10^{-5} torr. The weld parameters were 150 KV, 0.75 mA, 15 inches per minute (38 cm per min.) travel speed. The spot was defocused above the surface to produce a spot size of about 0.010 in. (0.025 cm). After the can was sealed, the evacuation path hole was closed with an EB spot weld while still in the EB vacuum chamber. Fig. 5 shows a prototype calcium cylinder after enclosure in the can.

light enough to permit duplicate weighing on a Mettler H54AR analytical balance. The results of these second weighings were all within the stated error.

The errors for areal and volumetric density were calculated from errors in the individual measurements according to these equations:

$$A = \frac{W}{\left(\frac{\pi D^2}{4}\right)}, \quad \rho = \frac{W}{\left(\frac{\pi D^2}{4}\right)T}$$

$$\frac{\delta A}{A} = \left[\left(\frac{\Delta W}{W}\right)^2 + \left(\frac{2\Delta D}{D}\right)^2 \right]^{1/2}$$

$$\frac{\delta \rho}{\rho} = \left[\left(\frac{\Delta W}{W}\right)^2 + \left(\frac{2\Delta D}{D}\right)^2 + \left(\frac{\Delta T}{T}\right)^2 \right]^{1/2}$$

where

ρ - density	A - areal density	W - Weight
D - diameter	T - thickness	

3. Calcium targets

Because of the chemical reactivity of calcium, the target material had to be protected from oxidation throughout fabrication. The target disks had to be encapsulated for use; the enclosure material in the path of the beam had to be minimized.

3.1. Casting

The source material was Los Alamos AR Grade calcium nodules from Pfizer Minerals, Pigments and Metals Division. Three KHz induction heating was used to melt the charge. The standard method for most metals is to melt the metal in a graphite crucible and bottom-pour into the mold. The first casting used this method but was rejected because

3.4. Vacuum testing

The calcium targets had residual atmosphere in the cans of about 5×10^{-5} torr. They were tested in a vacuum of 10^{-6} torr. The small amount of wrinkling in the end foils vanished while under vacuum. No change in weight was detected in any target after vacuum testing. The targets were reweighed before shipping weeks later. Again, there was no weight change.

4. Carbon targets

Pyrolytic graphite was obtained from Pfizer, Inc. Minerals, Pigments and Metals Division, Easton, Pennsylvania. The material is specified to have a density in the range 2.18 to 2.22 g/cm³. The average density of our sample is 2.21 g/cm³. Pyrolytic graphite is formed by high temperature chemical vapor deposition. The machined disks were radiographed and tested by ultrasound. The radiographs did not show detectable density variation. There were ultrasonic reflections from the laminar structure of the graphite, making it impossible to detect voids by this method. Chemical analysis of typical Pfizer material gave 8 ppm total impurities.

Table II shows the measurements and errors of the target disks.

5. Stainless steel and tungsten targets

The steel disks were machined from type 304 stainless steel. Chemical analysis at Los Alamos National Laboratory gave its composition as

Cr	18.0%	Mo	0.4%
Ni	8.0	Si	0.6%
Mn	2.0	Fe	70.7

Table III shows the measurements for each target disk.

Tungsten sheet of thickness 0.3175 cm was obtained from Amax Specialty Metals Corporation, Livermore, California. Chemical analysis indicated total impurities of 26 ppm. Table IV gives the measurements for each disk.

6. Discussion

As can be seen from the Tables, the accuracy achieved in measuring the dimensions and weight of each disk gave a determination of the areal density to an accuracy of ≈ 1 in 10^4 for all disks. This exceeded the requirements of the experiment by an order of magnitude.

Given the high accuracy in the determination of the volumes and masses of the disks, and the high purity of our samples, it is of interest to compare the volumetric densities found for different disks of a given material. From Table III we see that the variation in the densities for the five steel disks is $\pm 0.002 \text{ g/cm}^3$ which is less than the error of 0.005 g/cm^3 for any one disk. Similarly, the variations in densities for the tungsten disks are less than the error for any one disk. Thus, for the steel and tungsten disks, there is no evidence for density variations at a level of 1 part in 10^4 .

For the graphite and calcium disks there is evidence for small density variations. The graphite densities vary by $\pm 0.0032 \text{ g/cm}^3$ about a mean value of 2.2097 g/cm^3 . This is more than the 0.0007 g/cm^3 accuracy in each value. The theoretical density of pyrolytic graphite is 2.26 g/cm^3 [1]. Thus, small voids may have existed in our graphite sample, and these may have produced the 1 in 10^3 variations in density observed.

The density variations observed in the five calcium disks are $\pm 0.002 \text{ g/cm}^3$ about a mean value of 1.535 g/cm^3 . The accuracy in each density determination is 0.0002 g/cm^3 . The generally accepted value of density for calcium is 1.54 to 1.55 g/cm^3 . Our value is a little below this, again indicating the possible existence of small voids. These may have produced the 1 in 10^3 variation in density observed.

In summary, precision machining, measuring, and weighing of cylindrical targets has allowed us to fabricate nuclear targets with areal densities known to ≈ 1 in 10^4 . Variations in volumetric densities in pyrolytic graphite and a cast calcium ingot were observed at a level of 1 in 10^3 .

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References

- [1] J. Pappis and S. L. Blum, J. Am. Ceramic Soc. 44 (1961) 592.

Table I Measurements of calcium targets

Target No.	Diameter cm	Thickness cm	Weight g	Areal Density g/cm ²	Density g/cm ³
1	6.9540	2.5400	148.166	3.9011	1.536
2	6.9533	2.5400	148.243	3.9040	1.537
3	6.9538	2.5403	147.847	3.8930	1.533
4	6.9530	2.5400	148.062	3.8995	1.535
5	6.9527	2.5395	148.076	3.9001	1.536
Error	0.0003 ^a	0.0003 ^a	0.003 ^a	0.0003 ^b	0.0002 ^b

^aError for each disk, determined from several independent measurements on each disk.

^bError for each disk, based on errors in weight and dimension measurements.

Table II Measurements of graphite targets

Target No.	Diameter cm	Thickness cm	Weight g	Areal Density g/cm ²	Density g/cm ³
1	7.2796	1.0163	93.444	2.2452	2.2092
2	7.2766	1.0197	93.785	2.2552	2.2116
3	7.2771	1.0189	93.459	2.2470	2.2053
4	7.2766	1.0198	93.797	2.2555	2.2117
5	7.2771	1.0171	93.521	2.2485	2.2107
Error	0.0003 ^a	0.0003 ^a	0.003 ^a	0.0002 ^b	0.0007 ^b

^aError for each disk, determined from several independent measurements on each disk.

^bError for each disk, based on errors in weight and dimension measurements.

Table III Measurements of stainless steel targets

Target No.	Diameter cm	Thickness cm	Weight g	Areal Density g/cm ²	Density g/cm ³
1	7.2800	0.50985	167.406	4.0218	7.888
2	7.2805	0.51016	167.522	4.0239	7.888
3	7.2798	0.51057	167.641	4.0263	7.886
4	7.2798	0.51034	167.572	4.0247	7.885
5	7.2799	0.51011	167.507	4.0244	7.889
Error	0.0003 ^a	0.00003 ^a	0.003 ^a	0.0003 ^b	0.005 ^b

^aError for each disk, determined from several independent measurements on each disk.

^bError for each disk, based on errors in weight and dimension measurements.

Table IV Measurements of tungsten targets

Target No.	Diameter cm	Thickness cm	Weight g	Areal Density g/cm ²	Density g/cm ³
1	7.2781	0.2979	238.238	5.7266	19.221
2	7.2779	0.2997	239.433	5.7556	19.203
3	7.2776	0.2997	239.408	5.7554	19.202
4	7.2776	0.2987	238.921	5.7437	19.229
5	7.2776	0.2982	238.708	5.7385	19.244
Error	0.0003 ^a	0.0003 ^a	0.003 ^a	0.0005 ^b	0.019 ^b

^aError for each disk, determined from several independent measurements on each disk.

^bError for each disk, based on errors in weight and dimension measurements.

Figure captions

- Fig. 1 Mounting arrangement of five target disks for placement in
 the 800-GeV proton beam at Fermilab
- Fig. 2 Casting mold for calcium
- Fig. 3 Can containing calcium disk in welding chuck held in
 transfer device
- Fig. 4 Calcium target container mounted in welding chuck, as shown
 in the photo in fig. 3.
- Fig. 5 Calcium target disk enclosed in welded stainless steel can

Fig 1

Fig 4