

BRIEF REPORTS

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Cu(p, X)²⁴Na cross section from 30 to 800 GeV

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(Received 22 February 1991)

The Cu(p, X)²⁴Na cross section was measured at energies of 30, 150, 400, and 800 GeV. Proton fluences were determined with beam current transformer systems which were calibrated electrically *in situ*. The ²⁴Na produced in Cu targets was assayed by comparing the intensity of its 1368-keV γ ray with that of the 1332-keV γ ray from ⁶⁰Co standard sources. Results are consistent with an energy-independent cross section of 3.59 ± 0.14 mb.

The idea that cross sections for proton-induced target fragmentation reactions should become independent of energy, the hypothesis of *limiting fragmentation*, has been explored for a number of target systems at multi-GeV energies.¹⁻⁶ The cross-section scale for these studies is based on a limited number of determinations of absolute cross sections for "monitor" reactions such as ¹²C(p, pn)¹¹C,^{7,8} ²⁷Al($p, 3pn$)²⁴Na,^{1,9} and Cu(p, X)²⁴Na,^{10,11} at ~ 30 and ~ 400 GeV. A typical absolute measurement at one accelerator and energy will use techniques for beam and activity measurements which differ in some way from those employed to determine the same cross section at other energies at another accelerator. As a consequence, systematic errors of the independent measurements whose magnitudes may be difficult to estimate become the major contributor to the uncertainty in the energy dependence of a cross section. An analysis¹¹ of existing data indicated energy independence within $\sim 8\%$ for the two above-mentioned simple nuclear reactions but suggested that the cross section for the more complex Cu(p, X)²⁴Na fragmentation reaction increased by $\sim 10\%$ between 30 and 400 GeV. Goals of the present experiment, E776 at the Fermi National Accelerator Laboratory (FNAL), were to extend absolute cross-section measurements for the Cu(p, X)²⁴Na reaction to 800 GeV at the Tevatron, and to examine the energy dependence of this reaction using identical experimental procedures over the wide range of lower energies which were also available at that facility.

Abort procedures are intended to eject the circulating proton beam quantitatively from the Tevatron or Main Ring of the proton synchrotron complex at FNAL in one turn (21 μ sec) into transfer (abort) lines leading to a secure beam dump. Beam energy can be varied by changing the time of the abort pulse in the acceleration cycle. Measurements described in this paper were performed

in an area of the abort lines illustrated schematically in Fig. 1. The beams exit vacuum pipes through 58-mg/cm² Ti windows and are in air for ~ 60 cm. Instrumentation here includes segmented wire ion chambers (SWIC's) for the observation of beam positions and profiles and beam transformers (toroids) for the determination of proton intensities from the inductively coupled signals. The toroids are electrically isolated from the beam pipes and other structures in this area. Abort beam intensities can also be estimated from that of the circulating beam just prior to ejection as measured by toroids in the rings. Monitors at several locations confirm that losses during ejection are insignificant under most conditions.

Access to the abort area is limited to accelerator shutdown periods; hence, a motorized wheel was provided for the remote insertion into and removal of targets from either beam line. Each target consisted of three nominal 113-mg/cm² Cu foils with 16-mg/cm² Cu foils on the up- and downstream sides to compensate for recoil losses. Several targets could be mounted on the wheel at the end of one shutdown, kept out of the beam lines during several weeks of running, and then irradiated immediately prior to the next shutdown. Results described herein were obtained in eight running periods (runs). The first run was devoted to setting up and establishing that foils were not significantly activated ($< 0.2\%$) while they were on the wheel but not intentionally exposed to beam. Several target stacks were irradiated in each of the subsequent runs at different energies (two in runs 2-7 and three in run 8) for a total of 15 irradiations. Individual irradiations were short (≤ 10 min) compared to the 900-min half-life of ²⁴Na, and proton fluences were in the range $(6-11) \times 10^{13}$. Although each of the abort lines had a toroid, only one set of electronics was available for their calibration and readout. It was switched between toroids

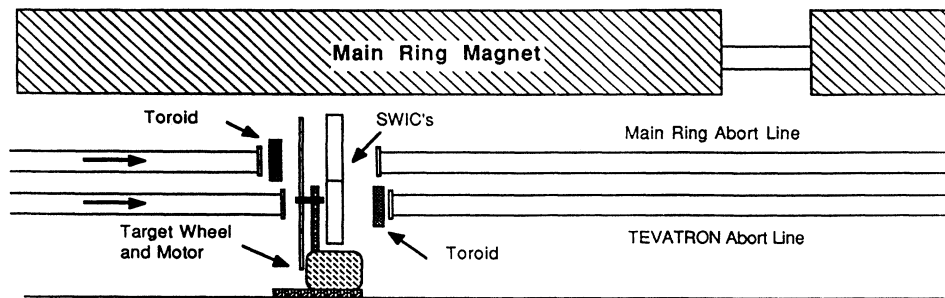


FIG. 1. Schematic view of the abort line irradiation facility at the Fermi National Accelerator Laboratory used to measure relative and absolute cross sections for the $\text{Cu}(p, X)^{24}\text{Na}$ reaction.

depending on the energies to be studied; 800, 400, and 150 GeV in the Tevatron mode and 150 and 30 GeV in the main-ring mode.

After the end of a run, the two or three target stacks were recovered, disassembled, and a target foil from each stack was sent to the participating laboratories for the assay of ^{24}Na . Procedures were similar to those described previously.¹¹ In brief, they entailed a comparison using Ge detectors of the intensity of the 1368-keV γ ray of ^{24}Na with that of the 1332-keV γ ray from ^{60}Co sources which had been calibrated by the National Institute of Science and Technology or the International Atomic Energy Agency. Small corrections were applied for the energy difference and for γ -ray summing on the basis of known properties of the detectors, and then the disintegration rates of ^{24}Na were extrapolated to the midtime of each irradiation.

As an initial step in the data analysis, each disintegration rate was normalized to unit target thickness and corrected for the production of ^{24}Na by secondary particles. Secondary effects have been studied¹¹ extensively at 400 GeV and corrections from that work were applied to the present data at that energy. Corrections at the other energies were scaled from those at 400 GeV by the multiplicity of shower particles observed in $p+\text{Cu}$ and $p+\text{emulsion}$ interactions.^{12,13} Corrections varied from 0.4% for the upstream foil at 30 GeV to 3.0% for the downstream one at 800 GeV. Statistical errors on many of the disintegration rates were $\leq 1\%$. An additional 1.5% was added to these nominal errors in consideration of possible nonstatistical effects such as target thickness variations, the influence of sample position and size on the assays, and uncertainties in the secondary corrections. The 15 triplets of corrected ^{24}Na disintegration rates were then examined for internal consistency. Good agreement was noted in results from two laboratories (lab1 and lab2). Their mean ratio was 1.01 ± 0.01 . Differences were at or below the one standard deviation level for 13 of the irradiations, 2.2 and 2.8 times larger for the remaining two. In contrast, results from the third laboratory (lab3) were in poor agreement with those from the first two. Differences were $\geq 10\%$ for 7 irradiations, $\geq 20\%$ for 2. These were traced to problems in reproducibly positioning the samples close to the detector at lab3 in a geometry which

was intended to minimize statistical errors. Sample-to-detector distances of 5 and 10 cm had been used at lab1 and lab2. Results from lab3 were discarded; those from lab1 and lab2 were combined as weighted averages. Errors on the means were increased in the two cases where differences were larger than expected.

The relative energy dependence the $\text{Cu}(p, X)^{24}\text{Na}$ cross section can be inferred from the overlapping set of cross section ratios determined in the seven runs. Many systematic effects will cancel in such an analysis. No absolute calibration of a toroid is needed; only that it remain stable over the ≤ 28 min time span of a doublet or triplet of irradiations and be independent of beam energy. Beam intensities from the abort toroids were used to calculate cross section ratios where possible. However, output from the abort toroids was not available in runs 2, 3, and 5, necessitating the use of intensities from the ring toroids.

Results from a weighted least-squares adjustment of the cross-section ratios are shown in Fig. 2. In essence, this is a three-parameter fit which determines most probable values for the cross sections at 30, 150, and 400 GeV relative to the mean at 800 GeV fixed at 1.00. The overall sum of the variances of the 15 points from the four means is minimized. As indicated, points for each energy in this figure are displaced from left to right in temporal sequence about the true energy for display purposes. The run number is shown below each point to facilitate identification of the associated irradiations. For example, run 7 was a 30–150 GeV comparison while run 8 compared 150, 400, and 800 GeV. Mean cross sections are 1.012 ± 0.018 , 0.995 ± 0.012 , and 0.993 ± 0.011 at 30, 150, and 400 GeV, respectively, relative to 800 GeV equal to 1.000. This extremely flat excitation function supports the hypothesis of limiting fragmentation.

Some comments are appropriate concerning the measurements at 30 GeV where differences between lab1 and lab2 results were greater than two standard deviations for two early runs. Problems with beam control, size, and position were encountered in extracting at this low energy. Larger than expected differences in the disintegration rates measured by lab1 and lab2 may be due to the large and poorly centered beams in the first two irradiations. While the spot size and position were improved and the counting data were in agreement for the third

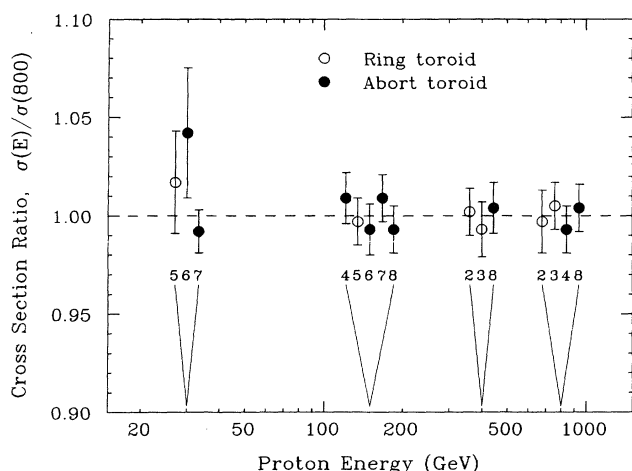


FIG. 2. Relative cross sections for the $\text{Cu}(p, X)^{24}\text{Na}$ reaction as a function of proton energy. Data are normalized to a mean of 1.00 at 800 GeV. Beam intensities were determined by the circulating beam (ring) toroid for the open points, and by the external beam (abort) toroid for the filled ones. Points are displaced in temporal sequence from left to right about the true energy for display purposes. Run numbers are shown below each point to facilitate identification of associated irradiations.

irradiation, there was evidence for a significant loss in extraction, see Table I.

Beam intensities were monitored with both ring and abort toroids in six of the irradiations. As seen in Table I, the abort toroid indicated a *higher* beam than that circulating in the accelerator in 5 of these irradiations. The mean difference, +2.4% and spread from +0.7% to +3.9% suggest calibration problems at the few percent level. The one low abort/ring ratio observed in run 7 may indicate beam losses in the extraction process at 30 GeV. Abort toroids were under our experimental control. The gate for integrating their signals was triggered by the

TABLE I. Comparison of beam intensity measurements with ring and abort toroids.

E (GeV)	Run ^a	Ratio Abort/Ring
30	7M	0.939 ^b
	7M	1.007
150	8T	1.039
	8T	1.039
400	8T	1.039
	8T	1.024
800	4T	1.024
	8T	1.024
Mean		1.024

^aM or T denote main-ring or Tevatron modes, respectively.

^bMay indicate beam loss during extraction, not included in the mean.

abort pulse and remained open for 50 μsec which is substantially longer than the 21 μsec single turn extraction time. Calibration data for the abort toroids were collected during each run to assure proper operation. These entailed passing a known current in a pulse of equivalent time length to the aborted beam pulse through the toroid *in situ*. Calibrations of the ring toroids were performed by accelerator personnel.

Absolute cross sections from the nine irradiations which were monitored by the abort toroids are given in Table II. Means are included at each energy. While these absolute values do not set as stringent a limit on the energy independence as that inferred from the ratio measurements, they are consistent with a constant value. Measurements at 150 GeV were made both in the Tevatron abort line and in the main-ring abort line using separate toroids but only one set of calibration and integration electronics that was switched back and forth as needed. As can be seen in Fig. 1, the toroid was located upstream of the target in one line but downstream of both the target and SWIC in the other. The mean cross section for the Tevatron mode is $(2.5 \pm 1.3)\%$ greater than that for the main-ring mode, providing evidence that the configurations are nominally identical. Differences between the ring toroids and the abort toroids at the level of several percent have been noted in Table I. It is apparent that the accuracy of absolute cross-section measurements at high energies is determined by systematic effects which are difficult to estimate. We believe that 4% is a realistic estimate for the present experiment.

The most probable cross section for the 30–800 GeV region, 3.59 ± 0.14 mb, is in good agreement with the 3.56 ± 0.09 mb derived from the $\text{Cu}(p, X)^{24}\text{Na}/^{27}\text{Al}(p, 3pn)^{24}\text{Na}$ ratio¹⁰ and an absolute measurement of the

TABLE II. Cross sections for the $\text{Cu}(p, X)^{24}\text{Na}$ reaction.

E (GeV)	Run ^a	σ_{exp} (mb) ^b	σ_{mean} (mb) ^{b,c}
30	6M	3.75 ± 0.12	3.56 ± 0.07
	7M	3.53 ± 0.04	
150	4T	3.62 ± 0.05	3.57 ± 0.03
	6M	3.52 ± 0.05	
	7M	3.53 ± 0.04	
	8T	3.61 ± 0.04	
400	8T	3.64 ± 0.05	3.64 ± 0.05
	8T	3.64 ± 0.05	
800	4T	3.58 ± 0.04	3.62 ± 0.04
	8T	3.66 ± 0.04	
All			3.59 ± 0.02

^aM or T denote main-ring or Tevatron modes, respectively.

^bStatistical errors only.

^cWeighted means. The error of the mean has been increased in those cases where deviations of individual values from the mean exceeded those expected from their errors.

$^{27}\text{Al}(p, 3pn)^{24}\text{Na}$ cross section⁹ at 28 GeV. However, it is $\sim 8\%$ lower than the 3.90 ± 0.11 mb which was previously reported at 400 GeV.¹¹ Assay of ^{24}Na in all of these measurements involved comparisons with ^{60}Co standard sources which are typically reported to have an accuracy of 1–2%. Intercomparison⁹ of several standards indicated consistency at better than that level. It does not then appear that the difference between the old and new cross sections at 400 GeV can be ascribed to problems in the ^{24}Na assay. Both experiments used toroids for the determination of proton fluences. A significant difference, however, was in the temporal structure of the beam. The previous measurement was performed in a semifast spill beam which necessitated that the integrator gate be open for 1 msec to encompass the entire proton pulse. A number of effects related to the motion of ions or electrons through the toroids were noted on that time scale which could either increase or decrease the apparent fluence. While care was taken to suppress these effects, it is possible that some remain as the source of the discrepancy. The signal to noise ratio is markedly improved and other spurious effects should be reduced in the single turn extracted beam used for the present work. It had been noted during the previous experiment¹¹ that the beam intensity measured by the toroid at the target location was consistently $\sim 5\%$ lower than that seen by the ring toroid. This difference was ascribed to losses in the 600

m between the extraction and target positions. However, if this were not the case, it would account for part of the discrepancy between the new and previous cross section at 400 GeV.

It is apparent that to achieve significantly better than an $\sim 5\%$ uncertainty on an absolute cross section is a difficult task. The present measurements establish that the $\text{Cu}(p, X)^{24}\text{Na}$ cross section is constant to a few percent over the range from 30 to 800 GeV and they set the absolute scale at 3.59 mb with an estimated accuracy of $\pm 4\%$. The behavior of this relatively complex reaction is now consistent with that of the simpler $^{12}\text{C}(p, pn)^{11}\text{C}$ and $^{27}\text{Al}(p, 3pn)^{24}\text{Na}$ reactions and the observed energy independence is strong support for the hypothesis of limiting fragmentation.

This work was performed at the Fermi National Accelerator Laboratory under Contract DE-AC02-76CH03000 and at Brookhaven National Laboratory under Contract DE-AC02-76CH00016 with the U.S. Department of Energy. The authors wish to thank J. Baldwin, T. Johnson, and R. Oudt for their contributions to this experiment. That portion of the work at CERN was supported by the Proton Synchrotron Division. One of us (V.A.) would like to thank the Directorate of that Division and, in particular, R. Billinge for continued support and encouragement.

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