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PHB-74-165-E
F 3781

#81
Phys. Rev. C

Recoil properties of ^{22}Na and ^{24}Na produced in the interaction of ^{27}Al with 3 to 300 GeV protons*

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Values of 2W(F+B) and F/B were determined for ^{22}Na and ^{24}Na in irradiations of Al targets with protons of 3, 6, 9, 11.5, 200, and 300 GeV. The values of 2W(F+B) were found to be constant within experimental error from 3 to 300 GeV for both ^{22}Na and ^{24}Na. The F/B values for both nuclides decreased about 20% over the same energy range.

[NUCLEAR REACTIONS ^{27}Al (p,spallation) ^{22}Na, ^{24}Na; E = 3, 6, 9, 11.5, 200, and 300 GeV; measured 2W(F+B) and F/B.]

I. INTRODUCTION

Recent measurements of the formation cross sections of a variety of spallation products from the proton bombardment of V,[1] Co,[1] Ag,[2] and U[3,4] targets indicate no appreciable changes as the beam energy increases from 11.5 to 300 GeV. Although this suggests that the deposition energy spectrum is not changing appreciably over this proton energy range, the cross-section data alone are not sensitive indicators of reaction mechanisms. Some thick-target recoil studies have been carried out on U[3,4] and the present investigation of Al extends these studies to the light-mass region.

The present studies involved measurement of the forward and backward recoil of ^{22}Na and ^{24}Na from ^{27}Al targets that were thick with respect to the range of the recoils. Experiments were carried out at proton energies of 3, 6, 9, 11.5, 200 and 300 GeV. Comparisons were made with similar studies of the ^{27}Al(p,3pn)^{24}Na reaction at proton energies below 3 GeV and at 28 GeV.[5]

Data were also obtained on the recoil properties of ^{18}F, but some anomalies were noted that have not yet been resolved.

II. EXPERIMENTAL PROCEDURE

Irradiations at proton energies from 3.0-11.5 GeV were carried out in the circulating beam of the Zero Gradient Synchroton (ZGS) at the Argonne National Laboratory. Irradiations at 200 and 300 GeV were performed with the primary proton beam in the meson area of the Fermi National Accelerator Laboratory (NAL).

The targets consisted of Al foils of approximately 1.8 mg/cm^2 surface density surrounded by several mylar foils of approximately 0.90 mg/cm^2. A typical target assembly is shown in Fig. 1. In the ZGS irradiations, which employed the internal, circulating beam, the Al foil was recessed approximately 0.5 mm behind the mylar catchers to ensure that no losses occurred at the leading edge of the target assembly.

After irradiation, a 1 cm x 2 cm area was cut around the exposed portion of the target and the various foils were separated and mounted for counting. The total beta activity of each foil was measured by means of gas-flow proportional counters. After about a week, the counting data were analyzed by the method of least squares into 20.4 m ^{11}C, 110 m ^{18}F, and 15 h ^{24}Na components.

The 2.60 y ^{22}Na component was determined after decay of the 15 h ^{24}Na by counting of the positron annihilation radiation in a coincidence apparatus consisting of two 3" x 3" NaI detectors. The coincidence background was approximately one count per minute.

Since most of the ^{11}C activity resulted from the interaction of the protons with the mylar foils, this component was disregarded in the evaluation of the data. Another set of experiments is in progress to determine the recoil properties of ^{11}C and to complete the measurements on ^{18}F.

III. RESULTS

The distribution of activity in the aluminum target foil and in the mylar catcher foils normalized to unity for the total activity, is given in Table I for ^{22}Na and in Table II for ^{24}Na. Only the

catcher foils nearest the target (foils 3 and 5 in Fig. 1) contained a measurable amount of ^{22}Na activity.

In the case of ^{24}Na the activity in foil 1 (approximately 0.1 percent of the total) was taken to be due to ^{24}Na production from impurities in the mylar foils and was subtracted from the ^{24}Na activity in all of the mylar foils.

The values in Tables I and II are the average of all of the results at each proton energy. Although the values are given to 4 decimal places, only the first 3 are significant for most entries. The fraction of the nuclei that recoil backward, that remain in the target, and that recoil forward are represented by the letters B, T, and F, and are found in foil 3, foil 4, and foil 5 (+ foil 6), respectively.

In the next to last column of Tables I and II is given the value of the ratio F/B of the fraction F of the recoils in the forward catchers to the same quantity B in the backward direction. The value of F/B is a measure of the average momentum that is transferred to the ^{22}Na or ^{24}Na nuclei in the forward direction. A large value indicates a relatively large momentum transfer.

In the last column of the tables is given the value 2W(F+B), where W is the thickness of the target foil. The value of 2W(F+B) is related to the recoil range of the ^{22}Na or ^{24}Na nucleus from the decay of some postulated intermediate excited nucleus. A more complete discussion of the significance of these recoil parameters is given in references 6 and 7.

The statistical counting errors were less than one percent for the ^{22}Na activity and less than 0.5 percent for the ^{24}Na activity in foils 3, 4, and 5 (see Fig. 1). The errors in the values of F/B and 2W(F+B) given in Tables I and II are the average deviations from the mean.

IV. DISCUSSION

The values of 2W(F+B) for ^{22}Na and ^{24}Na are plotted in Fig. 2. The F/B values are shown in Fig. 3. Results previously reported[5] for ^{24}Na are included in both figures.

The data indicate no change in 2W(F+B) within the experimental errors and about a 20% decrease in F/B over the range from 3 to 300 GeV. It is apparent that with increasing proton energy less forward momentum is transferred to the cascade residues leading to the products measured here. The essential constancy of the 2W(F+B) values indicates no significant change in reaction mechanism as a function of bombarding energy.

Similar results are observed for U targets[3,4] although there is perhaps some discrepancy between the observation of a decrease in 2W(F+B) and F/B from 11.5 to 300 GeV in the measurements of Chang and Sugarman[3] and the essential constancy in these values in the measurements of Yu and Porile,[4] who studied a much more limited range of products.

The energy dependence of the simple spallation reactions in Al and the deep spallation and fission reactions in U seems to be very similar and essentially asymptotic at 300 GeV. Further studies

of both integral and differential recoil properties for a broader range of targets and products will be required to establish these reaction mechanisms.

ACKNOWLEDGEMENTS

We wish to thank Dr. M. W. Weisfield for his assistance with the NAL irradiations, the operating crews of the ZGS for their cooperation, Mr. Dale Henderson for his invaluable aid in counting the many samples inolved in this study, and Dr. Sheldon Kaufman for his kind assistance with the computer processing of the data.

8/14/74/ljc

TABLE I. The distribution of ^{22}Na nuclei recoiling from an aluminum target.

Proton Energy (GeV)	No. of measure-ments	Thickness of Al Target (W) (mg/cm^2)	Fraction of Nuclei in Foils 3(B)	4(T)	5(F)	$\frac{F}{B}$	2W(F+B) (mg/cm^2)
3	2	1.78	.0478	.8177	.1345	2.81±.03	.649±.009
6	6	1.86_4	.0458	.8273	.1269	2.77±.08	.644±.012
9	3	1.84	.0473	.8251	.1276	2.70±.02	.644±.003
11.5	3	1.84	.0481	.8264	.1255	2.61±.02	.639±.010
200	1	1.80	.0583	.8254	.1163	2.00	.629
300	2	1.88	.0500	.8333	.1167	2.33±.05	.627±.001

TABLE II. The distribution of ^{24}Na nuclei recoiling from an aluminum target.

Proton Energy (GeV)	No. of measure-ments	Thickness of Al target (W) (mg/cm^2)	Fraction of Nuclei in Foils 3(B)	4(T)	5 (F)	6 (F)	$\frac{F}{B}$	2W(F+B) (mg/cm^2)
3	2	1.78	.0351	.8696	.0951	.0002	2.72±.08	.464±.033
6	6	1.86_4	.0360	.8707	.0930	.0003	2.59±.06	.482±.012
9	2	1.82	.0389	.8634	.0976	.0001	2.51±.05	.496±.005
11.5	4	1.85	.0370	.8715	.0914	.0001	2.47±.06	.475±.010
200	1	1.80	.0427	.8660	.0913	0	2.14	.482
300	3	1.88	.0398	.8753	.0848	0	2.13±.06	.469±.007

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*Work performed under the auspices of the U. S. Atomic Energy Commission.

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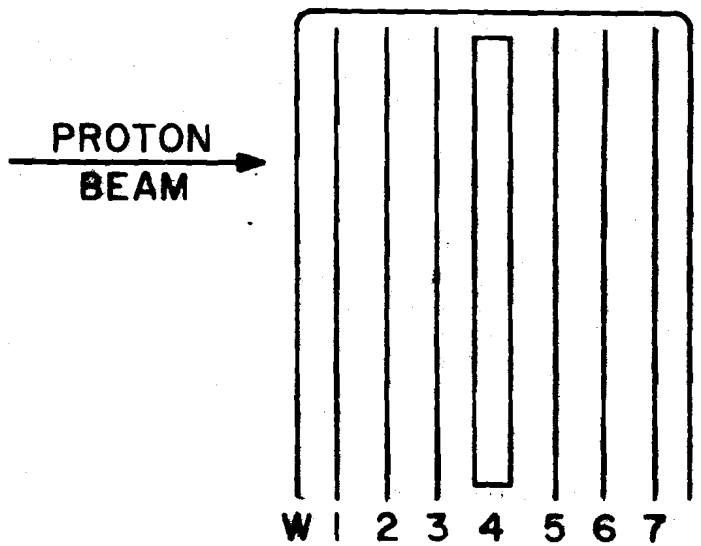
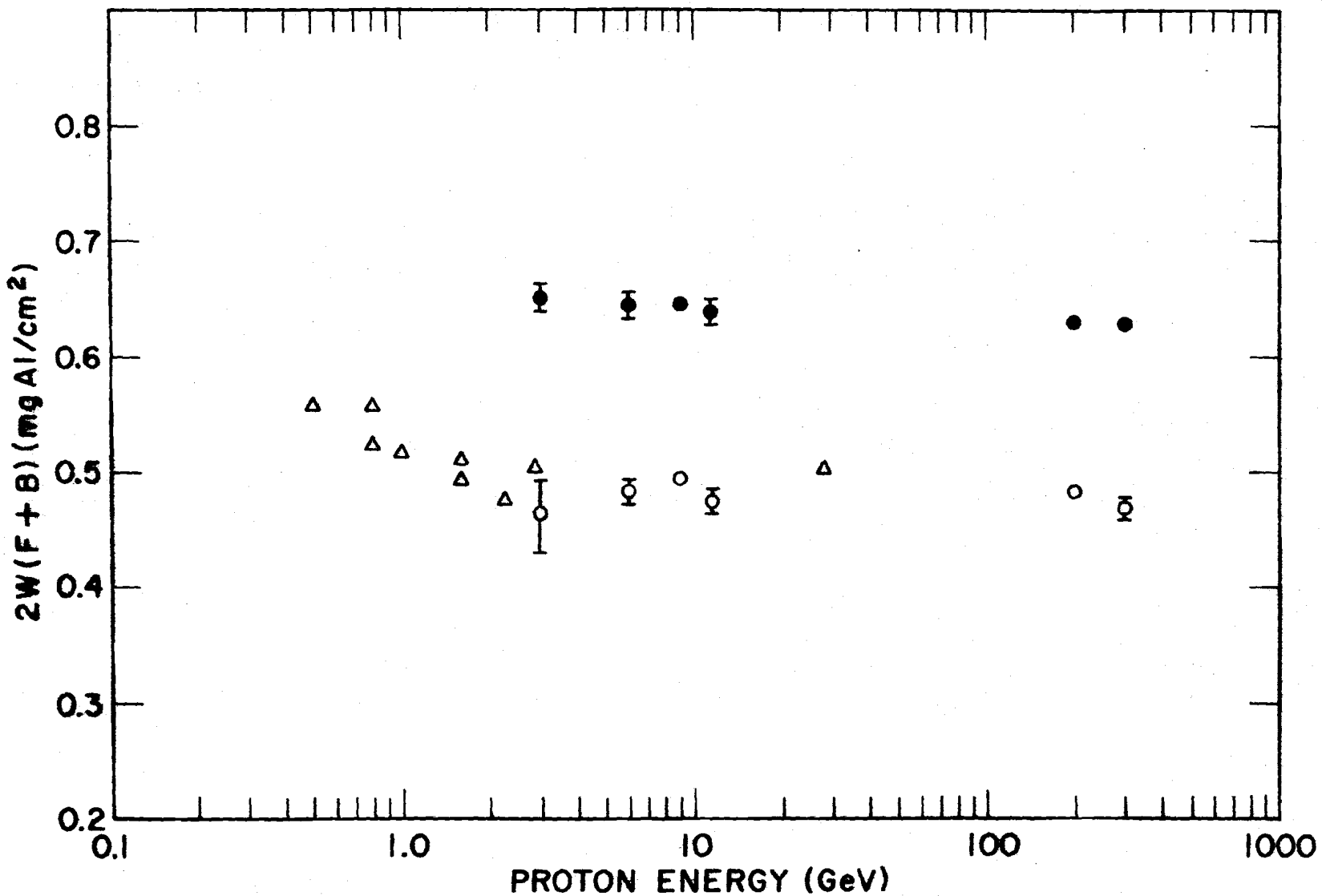
FIGURE CAPTIONS

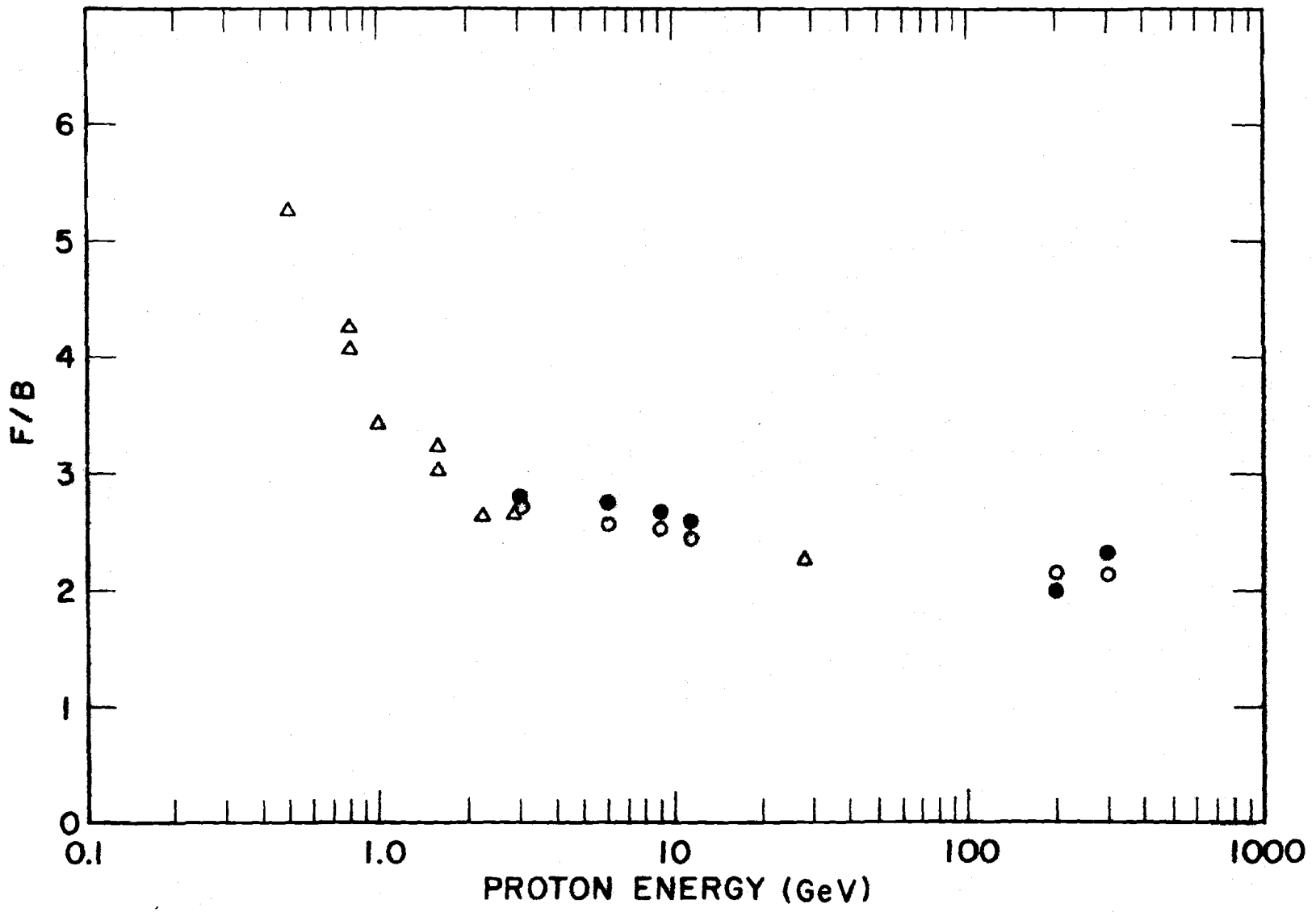
FIG. 1. Arrangement of Al and mylar foils in target assembly. The foils are numbered for identification. Foils 1-3 and 5-7 are mylar, foil 4 is the Al target, and W is a mylar wrapper foil.

FIG. 2. The values of 2W(F+B) as a function of proton energy for ^{22}Na and ^{24}Na from the proton irradiation of aluminum. Values from this work: ● ^{22}Na, o ^{24}Na. From reference 5: Δ ^{24}Na.

FIG. 3. The values of F/B as a function of proton energy for ^{22}Na and ^{24}Na from the proton irradiation of aluminum. Values from this work: ● ^{22}Na, o ^{24}Na. From reference 5: Δ ^{24}Na.


PROTON
BEAM
W
1
2
3
4
5
6
7


0.8
0.7
0.6
0.5
0.4
0.3
0.2
2W(F+B) (mg Al/cm²)
0.1
1.0
10
100
1000
PROTON ENERGY (GeV)


F/B
0
1
2
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0.1
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PROTON ENERGY (GeV)