Recoil properties of nuclei produced in the interaction of protons with ^{27}Al

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(Received 5 June 1979)

Recoil properties of ^{7}Be, ^{11}C, and ^{18}F produced in the interaction of 1–11.5 GeV protons with ^{27}Al were measured in a stack of aluminum foils. A difference method was employed to determine the fraction of recoil loss in the forward (beam) and backward directions (F and B, respectively). The values of F/B and the recoil ranges were combined with previous data on ^{8}Li, ^{22}Na, and ^{24}Na and with counter-experiment measurements in a systematic analysis of the reaction mechanism, based on the two-velocity reaction model. The analysis indicates that the same processes occur in ^{27}Al as in heavier target nuclei. The mechanism of formation of the products from ^{27}Al, that were measured, appears to be independent of the energy of the incident proton in the GeV energy region.

[NUCLEAR REACTIONS ^{27}Al$(p,x)^{7}$Be to ^{24}Na, $E_p \leq 400$ GeV; analyzed recoil properties as evidence for reaction mechanism.]

The thick-target thick-catcher technique has been widely used in studies of the recoil properties of the products of nuclear reactions.[1-7] In this type of experiment, the incident particles pass through a foil assembly containing a target foil, which is thick compared to the recoil ranges being investigated and is sandwiched between two thick-catcher foils. The fraction of nuclei, which recoil into the forward and backward foils (with respect to the beam direction), are denoted by F and B, respectively. The remainder come to rest within the target foil.

Such experiments have been performed on ^{27}Al to measure the recoil properties of ^{22}Na at proton energies in the GeV range and ^{24}Na at energies above 20 MeV.[8-14] The present study extends the measurement of recoil products from ^{27}Al to include ^{7}Be, ^{11}C, and ^{18}F at proton energies of 1 to 11.5 GeV. The production of ^{8}Li has been studied at 2.2 GeV with nuclear emulsions as detectors.[15] Measurements of nuclear recoils from ^{27}Al have also been carried out with counters at 4.9 GeV.[16]

A systematic survey of nuclear reactions, induced by high-energy projectiles, has been made using a set of parameters based on simple reaction models.[1] In that study, recoil measurements on a variety of nuclear reactions are correlated with several of these parameters, and a test for distinguishing among spallation, fragmentation, and fission mechanisms is presented. In the present work we evaluate several of these parameters for the recoiling nuclei produced in the interaction of protons with ^{27}Al in order to determine the reaction mechanism and, in particular, to assess whether the processes that occur in a light nucleus like ^{27}Al are similar to those occurring in heavy nuclei. The analysis of the results obtained here is continued in the following papers.[1]

I. EXPERIMENTAL PROCEDURE

The catcher foils in the ^{22}Na and ^{24}Na experiments were Mylar, an organic plastic material.[13] This type of catcher foil could not be used for ^{7}Be and ^{11}C, because these nuclei are formed directly in Mylar by the incident protons. Although this problem should not occur in the case of ^{18}F, erratic results were obtained with Mylar catcher foils. This could have been due to the escape of gaseous compounds of fluorine from this type of foil.

In order to avoid these difficulties, no catcher foils were used other than the target foils themselves, and a difference method was used to determine F and B. A stack of aluminum foils was exposed to the circulating beam of the zero-gradient synchrotron (ZGS) at the Argonne National Laboratory. In the ^{11}C and ^{18}F experiments, the stack in effect consisted of five 6μm aluminum foils (see Fig. 1). Eight 25 μm foils were used for the ^{7}Be experiments.

After irradiation a 1×2 cm area was cut from

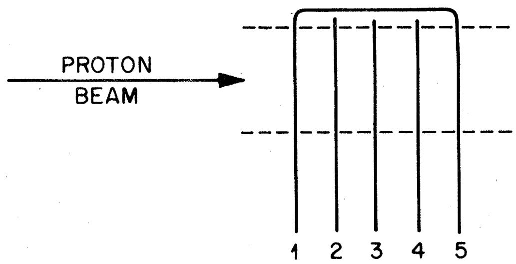

FIG. 1. Arrangement of aluminum foils in target assembly for the ^{11}C and ^{18}F experiments. The dotted lines indicate how the foils were cut for mounting after the proton irradiation.

the exposed portion of the target. The various foils were then separated and mounted for counting. The total beta activity of each foil in the ^{11}C and ^{18}F experiments was measured by means of two gas-flow proportional counters. In addition, the positron annihilation radiation was measured by two coincidence systems, each consisting of two 7.6×7.6 cm NaI detectors. The latter method suppressed the ^{24}Na activity by a factor of 10, thereby improving the resolution of the positron components. The five foils were rotated among the four detectors. After several days to 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.

About two months after the proton irradiation, counting began on foils from the ^7Be experiments. The intensities of the 478-keV gamma ray were measured for two to three months on a Ge(Li) spectrometer. The peaks were checked for proper shape, width, and energy and the peak areas were determined.[17] The intensities as a function of time were least-squares analyzed to obtain the relative ^7Be intensities in the various foils. The final analysis was made on data which fit the known half-life.

In analyzing the activity measurements, we assumed that the foil with the largest specific activity contained the full radioactivity with nuclei lost by recoil replaced by recoiling nuclei from other foils. This assumption is correct, if the total thickness W of the foil stack is larger than the maximum recoil range.

The maximum specific activity was found in the third or fourth foil for the ^{11}C and ^{18}F experiments and in the fifth or sixth foil for the ^7Be experiments. These adjacent foils had the same specific activity within 1 or 2%. The value of F was calculated from the difference of the specific activities of the upstream foils from the maximum value and B from the same comparison for the downstream foils.

In order for this difference method to succeed, it is necessary that the target assembly be located in a large evacuated region during the irradiation. Otherwise, the outer foils can be contaminated by extraneous activity. A facility of this type was available at the ZGS but not at the Fermilab accelerator, where some of the ^{22}Na and ^{24}Na measurements had been made.[13]

Data were obtained on ^{24}Na by the difference method and compared with those obtained previously, as a test of the validity of the technique. The F/B data agreed within a few percent, while the range values obtained by the difference method were about 10% higher than those obtained by the conventional thick-catcher technique. It is expected that the accuracy of the difference method will increase with increasing range of the recoiling nucleus and thus be more accurate for ^7Be, ^{11}C, and ^{18}F than for ^{24}Na. The ^{24}Na results reported here are those from the previous study.[13]

II. RECOIL PARAMETERS

The analysis of the recoil-range results is based on the V_0 approximation of the two-velocity model.[1,7] The velocity of the observed recoil nucleus is assumed to be the vector sum of an initial velocity v, which is constant and in the forward direction, from the first step of the reaction, and a velocity V, which has a distribution of values and is isotropic, from the second step. The range of a recoiling nucleus with the energy $T=\frac{1}{2}M_{REC}V^2$, where M_{REC} and A_{REC} are the mass and mass number of this nucleus, is taken to be

$$R=kT^{N/2}\,. \tag{1}$$

The constants k and N for stopping in aluminum were derived from range-energy data.[18-21] (The mass number of the target nucleus is designated A.)

Values of the fractional momentum transfer p/p_{CN} from the first step and $\langle T\rangle$ from the second step are given by this analysis of the measurements. The parameter p/p_{CN} is the ratio of the momentum of the excited nucleus from the initial interaction to the value it would have in a compound-nucleus reaction.

Additional parameters can be obtained from the recoil measurements by assuming the nature of the initial interaction. The single-collision (SC) model has been used in this way to systematize the recoil results of many reactions.[1] The incident nucleus is assumed to collide with a nucleon inside the nucleus and escape. The target nucleon remains behind with its kinetic energy becoming E_0^* = excitation energy plus kinetic energy (usually small) and its momentum becoming the recoil

TABLE I. Recoil data for ^{7}Be, ^{11}C, and ^{18}F from ^{27}Al.

E_p (GeV)	Number of experiments	W (mg/cm^2)	F/B	$2W(F+B)$ (mg/cm^2)	$\langle R\rangle$ (mg/cm^2)
		^{7}Be			
1	1	54.21	4.11	7.10	6.06
3	1	51.25	2.79	7.51	6.88
11.5	1	43.28	2.48	5.90	5.50
		^{11}C			
1	1	9.44	2.92	1.99	1.82
3	3	9.04	2.93	1.90	1.73
6	3	9.13	2.72	2.10	1.94
11.5	3	8.97	3.06	1.93	1.75
		^{18}F			
1	1	9.44	3.23	1.15	1.04
3	3	9.04	2.88	1.08	0.99
6	3	9.13	2.67	1.12	1.04
11.5	3	8.97	3.11	1.16	1.05

momentum of the nucleus. In this model, the value of E_0^* is given by

$$E_0^* = \frac{p}{p_{CN}} E_{CN}, \tag{2}$$

where E_{CN} is the excitation energy (plus a small kinetic energy) in a compound-nucleus reaction. The number of nucleons ΔA which are emitted in the second step of the reaction depends on the value of E_0^*. A convenient parameter to describe the reaction is the quantity $E_0^*/\Delta A$.

III. RESULTS

The results of the recoil measurements for ^{7}Be, ^{11}C, and ^{18}F are given in Table I. The incident-proton energy E_p is given in the first column, the number of replicate runs in the second column, the target thickness W in the third, the values of F/B in the fourth, and the values of $2W(F+B)$, which is a measure of the recoil range, in the fifth column. Values of the average range $\langle R\rangle$, determined from these results,[7] are given in

TABLE II. Results of analysis of data.

E_p (GeV)	$P(V<v)$	v $\left(\frac{\text{MeV}}{\text{nucleon}}\right)^{1/2}$	$\frac{p}{p_{CN}}$	E_0^* (MeV)	$\langle T\rangle$ (MeV)
		^{7}Be ($N=1.92$, $k=0.416$ mg/cm^2, $\langle v/V\rangle=0.28$)			
1	0.0115	0.612	0.3091	297	16.4
3	0.0034	0.477	0.1067	308	18.8
11.5	0.0022	0.377	0.0260	288	14.9
Average		0.489		298 ± 7	16.7 ± 1.4
		^{11}C ($N=1.69$, $k=0.323$ mg/cm^2, $\langle v/V\rangle=0.28$)			
1	0.0046	0.268	0.1354	130	8.00
3	0.0046	0.261	0.0583	169	7.56
6	0.0033	0.261	0.0324	188	8.64
11.5	0.0054	0.274	0.0188	209	7.65
Average		0.266		174 ± 25	7.96 ± 0.36
		^{18}F ($N=1.36$, $k=0.325$ mg/cm^2, $\langle v/V\rangle=0.30$)			
1	0.0079	0.209	0.1052	101	5.95
3	0.0053	0.182	0.0407	118	5.58
6	0.0040	0.176	0.0218	127	6.00
11.5	0.0069	0.203	0.0140	155	6.05
Average		0.192		125 ± 16	5.90 ± 0.16

TABLE III. Results of analysis of data.

E_p (GeV)	$P(V< v)$	v $\left(\frac{\text{MeV}}{\text{nucleon}}\right)^{1/2}$	$\frac{p}{p_{CN}}$	E_0^* (MeV)	$\langle T\rangle$ (MeV)
		^{22}Na (N=1.28, k=0.320 mg/cm^2, $\langle v/V\rangle$=0.28 [a])			
3	0.0051	0.118	0.0264	76	2.91
6	0.0049	0.115	0.0144	83	2.88
9	0.0044	0.113	0.0098	85	2.90
11.5	0.0039	0.109	0.0075	83	2.88
200	0.0011	0.080	0.0003	66	2.95
300	0.0024	0.096	0.0003	79	2.86
Average		0.114 [a]		79 ± 5	2.90 ± 0.02

[a]Average of values at E_p = 3.0 to 11.5 GeV.

the last column.

The results of the data analysis for these nuclei and for ^{22}Na and ^{24}Na are given in Tables II, III, and IV. This analysis is based on the distribution in T, given by Eq. (3), and is valid for all values of v/V.[7]

$$P(T)=\frac{4T\exp(-2T/\langle T\rangle)}{\langle T\rangle^2}\,. \tag{3}$$

The quantity $P(V<v)$, given in the second column of the tables, represents the probability that V is less than v. When this value is small, the pre-

TABLE IV. Results of analysis of data.

E_p (GeV)	$P(V< v)$	v $\left(\frac{\text{MeV}}{\text{nucleon}}\right)^{1/2}$	$\frac{p}{p_{CN}}$	E_0^* (MeV)	$\langle T\rangle$ (MeV)	Ref.
		^{24}Na (N=1.28, k=0.330 mg/cm^2, $\langle v/V\rangle$=0.28 [a])				
0.024	0.089	0.127	0.511	12	0.78	8,12
0.039	0.137	0.172	0.538	20	1.10	8,12
0.052	0.225	0.259	0.701	35	1.80	8,12
0.060	0.263	0.299	0.752	43	2.15	9
0.070	0.274	0.312	0.724	49	2.27	9
0.080	0.256	0.291	0.631	49	2.08	9
0.090	0.250	0.285	0.581	50	2.03	9
0.14	0.151	0.227	0.366	49	1.80	9
0.18	0.1055	0.205	0.289	50	1.84	9
0.22	0.0801	0.196	0.247	52	1.97	9
0.28	0.0529	0.177	0.195	53	2.04	9
0.34	0.0308	0.150	0.148	48	1.98	9
0.50	0.0296	0.142	0.112	54	1.84	12
0.80	0.0172	0.125	0.0730	56	1.88	12
1.0	0.0100	0.107	0.0541	52	1.85	12
1.6	0.0074	0.098	0.0355	55	1.81	12
2.25	0.0041	0.082	0.0231	50	1.73	12
2.9	0.0042	0.086	0.0199	55	1.89	12
3.0	0.0045	0.082	0.0184	53	1.65	13
6.0	0.0038	0.081	0.0101	58	1.77	13
9.0	0.0033	0.081	0.00697	61	1.87	13
11.5	0.0031	0.077	0.00529	59	1.75	13
28	0.0020	0.072	0.00213	57	1.94	12
200	0.0016	0.066	0.00028	54	1.84	13
300	0.0015	0.064	0.00018	53	1.76	13
400	0.0014	0.065	0.00014	54	1.88	14
Average		0.087 [a]		54 ± 2 [b]	1.85 ± 0.07 [b]	

[a]Average of values at E_p = 1 to 11.5 GeV.
[b]Average of values at $E_p \geq 0.18$ GeV.

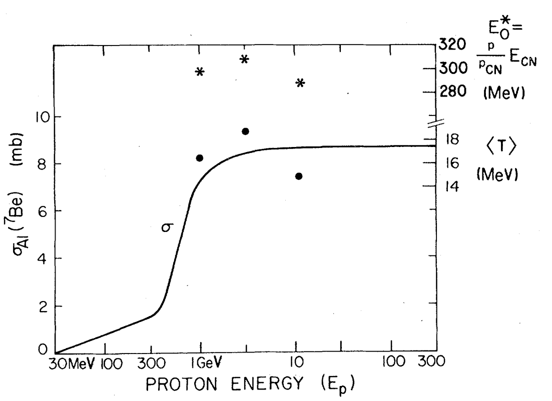

FIG. 2. The excitation function for the reaction $p + {}^{27}Al \rightarrow {}^{7}Be$ is given by the line. The values of E_0^* are indicated by the symbol * and $\langle T \rangle$ by ●.

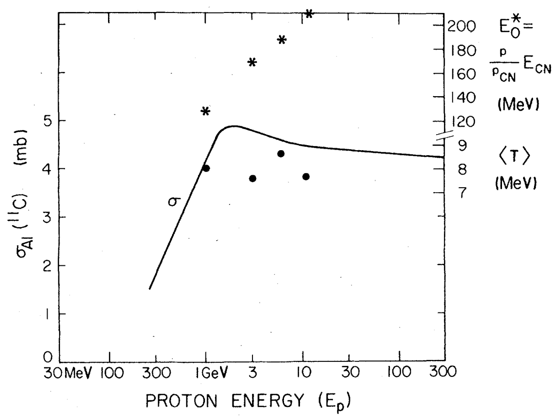

FIG. 3. The excitation function for the reaction $p + {}^{27}Al \rightarrow {}^{11}C$ is given by the line. The values of E_0^* are indicated by the symbol * and $\langle T \rangle$ by ●.

vious calculations, which assume the v/V is small, are valid.[2-6] The numbers in the last column of Table IV identify the references for the input data at each value of E_p. The input data for Table III are from Ref. 13. The values of all quantities in Table IV at $E_p \leq 0.14$ GeV and at $E_p = 0.22$ and 0.28 GeV are approximate, since the values of B were not given for these cases and were approximated by linear extrapolation of the measured values. The values of E_0^* and $\langle T \rangle$ from these tables are compared with the excitation function[22-24] for each reaction in Figs. 2 to 6.

The values of $\langle R \rangle$, $\langle V \rangle$, and $\langle v/V \rangle$ can be calculated from the entries in the tables by means of the following equations[7]:

$$\langle R \rangle = k\left(\frac{\langle T \rangle}{2}\right)^{N/2} \Gamma\left(2 + \frac{N}{2}\right), \tag{4}$$

where Γ is the gamma function,

$$\langle V \rangle = \frac{3}{4}\left(\frac{\pi \langle T \rangle}{M_{\mathrm{REC}}}\right)^{1/2} \tag{5}$$

and

$$\left\langle \frac{v}{V} \right\rangle = \frac{1}{2}\left(\frac{\pi M_{\mathrm{REC}}}{\langle T \rangle}\right)^{1/2} v\,. \tag{6}$$

TABLE V. Values of reaction parameters.

Recoil nucleus	E_0^* (MeV)	$E_0^*/\Delta A$ (MeV/nucleon)	$\frac{\Delta A}{A}$	$\langle T \rangle$ (MeV)	References (P=present work)
^{24}Na	54	18	0.111	1.85	P
^{22}Na	79	16	0.185	2.9	P
Ne			0.259	5	16
^{18}F	125	14	0.333	5.9	P
F			0.296	6	16
O			0.407	9	16
N			0.481	9	16
^{11}C	174	11	0.593	8.0	P
C			0.556	10	16
B			0.593	11	16
$^{9,10}Be$			0.648	11	16
^{8}Li	270 [a]	14	0.704	18.6	1,15
Li			0.741	14	16
^{7}Be	298	15	0.741	16.7	P
^{7}Be			0.741	15	16
^{4}He			0.852	12	16
^{3}H			0.889	14	16
^{2}H			0.926	12	16
^{1}H			0.963	9	16

[a]Value of E_0^* was obtained by interpolation of values for ^{11}C and ^{7}Be.

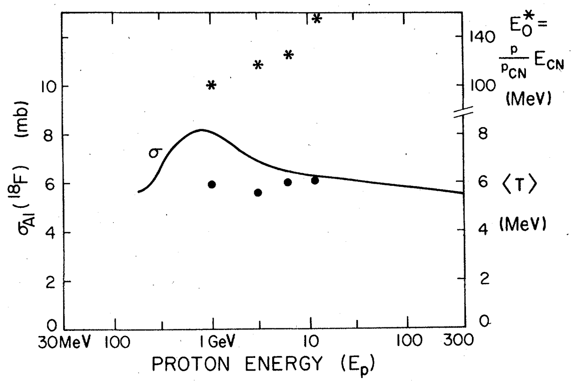

FIG. 4. The excitation function for the reaction $p+{}^{27}Al \rightarrow {}^{18}F$ is given by the line. The values of E_0^* are indicated by the symbol * and ⟨T⟩ by ●.

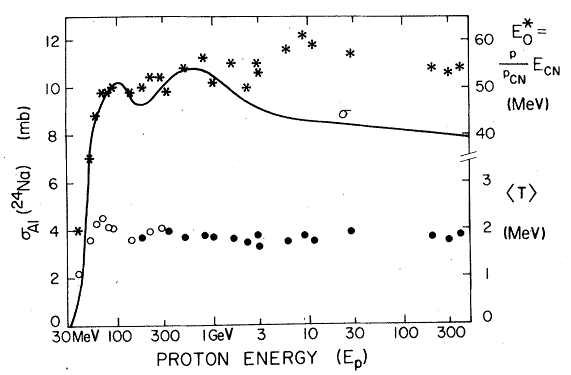

FIG. 6. The excitation function for the reaction $p+{}^{27}Al \rightarrow {}^{24}Na$ is given by the line. The values of E_0^* are indicated by the symbol * and ⟨T⟩ by O for the experiments in which the value of B was not given and had to be estimated or by ● for the experiments where B was measured. The * point closest to the left side of the graph is for a 39-MeV incident proton; $E_0^* = 20$ MeV.

The average value of the latter for $E_p = 1$ to 11.5 GeV is given in Tables II to IV. These values are essentially the same for all observed recoil nuclei at these proton energies. The value of v for ^{24}Na has a maximum value of 0.312 (MeV/nucleon)$^{1/2}$ at $E_p = 70$ MeV (see Table IV). At this energy, ⟨v/V⟩ = 0.90 has its maximum value. The values of E_0^* and ⟨T⟩ in Table V are the overall average values from Tables II to IV and include ⟨T⟩ at $E_p = 2.2$ GeV (measured)[1,15] and E_0^* (estimated) for ^8Li and ⟨T⟩ from counter experiments at $E_p = 4.9$ GeV.[16]

IV. DISCUSSION

The reaction parameters discussed here are divided into two groups, according to the two steps in the Serber and related models.[1] Although this division may not be valid for all reactions of protons with ^{27}Al, it does provide a convenient way to systematize the measurements from diverse types of reaction. A survey of values of ⟨T⟩ and related parameters for various combinations of target and recoil nuclei has provided a test for distinguishing between spallation, fragmentation, and fission processes.[1] In this report, we will evaluate the significance of the parameters described here for reactions induced in ^{27}Al.

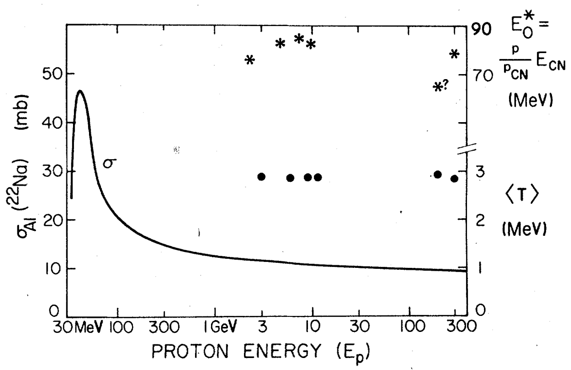

FIG. 5. The excitation function for the reaction $p+{}^{27}Al \rightarrow {}^{22}Na$ is given by the line. The values of E_0^* are indicated by the symbol * and ⟨T⟩ by ●.

First step of the reaction: the parameters p/p_{CN}, E_0^*, and $E_0^*/\Delta A$

The first step of the V_0 approximation ends with the struck nucleus moving in the forward direction with the velocity v. In the SC model this nucleus is the excited target nucleus. In reality, the target nucleus may lose one or more nucleons in the initial interaction.

The parameter p/p_{CN} is a test for a compound-nucleus reaction. If its value is unity, there is complete momentum transfer, and a compound-nucleus mechanism is indicated. The value of this parameter is relatively large at the lowest incident-proton energies for the recoil nucleus ^{24}Na, but is not unity at any energy (see Table IV). Its value drops sharply with increasing values of E_p above 1 GeV for all recoil nuclei (Tables II to IV). Values of $p/p_{CN} \ll 1.0$ are characteristic of high-energy reactions.

The values of E_0^* are compared with the excitation functions for each reaction in Figs. 2 to 6. The values of this quantity are remarkably constant for ^{24}Na, despite the large range in values of E_p and p/p_{CN}. The fact that values of E_0^* and the excitation function rise at about the same value of 50 MeV suggests that this quantity is related to

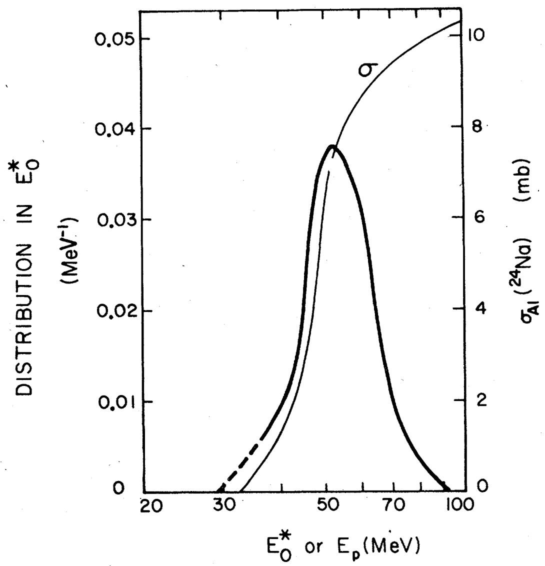

FIG. 7. The distribution in the values of E_0^* for ^{24}Na is given by the thick line. The excitation function is given by the thin line.

the true excitation energy. The relation between these two quantities is discussed in Ref. 1.

The distribution of E_0^* (heavy line in Fig. 7) was derived from a smooth curve drawn through the values of E_0^*. This distribution peaks at $E_0^* \cong 50$ MeV and has a width at half-height of approximately 20 MeV. The distribution of excitation energies may also be determined from the excitation function.[25]

Recoil measurements for ^{7}Be, ^{11}C, ^{18}F, and ^{22}Na are needed below 1 GeV to determine whether the correlation of E_0^* and the excitation function, noted for ^{24}Na, also applies to these nuclides. The available data are insufficient to justify any definite conclusion at present.

A relationship between E_0^* and the true excitation energy is also suggested by the correlation between the average value of E_0^* and the number of nucleons emitted, ΔA. The value of E_0^* increases with ΔA almost linearly with $E_0^*/\Delta A \cong 14$ MeV/nucleon: see Table V. This is the type of relationship expected for the excitation energy, which is the source of energy for the second step of the reaction.

Second step of the reaction: the parameter $\langle T \rangle$

The quantity $\langle T \rangle$ results from processes which occur in the second step of the reaction. The values of this parameter are compared with the excitation function of each reaction in Figs. 2 to 6. They are constant at proton energies above 50 MeV for ^{24}Na and at energies in the GeV range, where measurements were made, for ^{18}F and ^{22}Na. The values for ^{11}C appear to be constant, although here the results scatter more. The results for ^{7}Be are not of sufficient quality to determine the variation of $\langle T \rangle$ with energy.

These observations and those for E_0^* suggest that the mechanism of the ^{24}Na reaction does not change up to 400 GeV. For the other cases, the mechanism is observed to be essentially constant in the GeV range of proton energies. Measurements below 1 GeV for these cases are clearly desirable.

The values of $\langle T \rangle$ are listed in Table V. The value for the recoil nucleus ^{8}Li was determined from range measurements in emulsions.[1,15] The other values are from counter-experiment measurements of reactions induced in aluminum by 4.9-GeV protons.[16] These values were estimated from parameters, obtained by fitting curves based on evaporation theory to the energy spectra. The value for ^{4}He was also determined directly from its spectrum. In some of these measurements the combined spectrum for all the recoil nuclei of a given element was presented. These cases are identified by element, but not by mass number, in the first column of Table V. The value of $\Delta A/A$ for these entries is based on the mass number of the most abundant stable isotope of the element.

The values of $\langle T \rangle$ peak in the region of mass numbers 7 and 8. The significance of these results can be seen in a comparison of these values with those for other reactions.[1] The parameter $\langle T \rangle$ for many target nuclei varies in a systematic way with $\Delta A/A$. Since the results for the target ^{27}Al agree with the general picture presented there, we can conclude that the same processes occur in this light nucleus as in heavier nuclei. These observations attest to the usefulness of parameters derived from simple models.

The values in Table V give further evidence for the mechanism of the reactions. These observations can be summarized as follows:

(1) The values of E_0^* increase with ΔA, whereas $E_0^*/\Delta A$ is fairly constant. There may be a downward trend in the values of $E_0^*/\Delta A$ with ΔA, which stops at ^{11}C. If this trend were to continue, ^{7}Be would have a value that is approximately one-half of the observed value. More accurate values of E_0^* are needed to determine whether this effect is real.

(2) The peak in the value of $\langle T \rangle$ for $A_{\mathrm{REC}} \cong 7$ to 8 occurs in the same region as the change in $E_0^*/\Delta A$ noted above. This increase in $\langle T \rangle$ at $\Delta A/A = 0.67$, corresponding to $\Delta A/A_{\mathrm{REC}} = 2$, appears to be a

general characteristic of nonfission reactions.[1] These results suggest that lighter particles accompany the formation of recoil nuclei with mass numbers greater than 8 and heavier particles, or fragments, are emitted during the formation of ^{7}Be and ^{8}Li, when the target nucleus is ^{27}Al.

(3) The hydrogen nuclei, ^{4}He, and possibly ^{7}Be and ^{8}Li appear to be evaporation particles. Their energies are consistent with values calculated for the spallation partners of the heavier recoiling nuclei.[1] These topics are discussed further in Ref. 1.

ACKNOWLEDGMENTS

We wish to thank John M. Alexander for a critical reading of this manuscript. This work was supported in part by the Division of Nuclear Physics of the U. S. Department of Energy at the University of Illinois and at the Argonne National Laboratory and in part by the National Science Foundation (PHY76-83685) at Cal Tech.

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