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Berkeley, California

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ABSTRACT

Using a silicon detector, the energy spectra of 415 MeV Ar^{40} ions after their passage through selected thicknesses of aluminum have been measured. The thickest absorber used was 29.2 mg/cm^2 after which the most probable energy was 40.8 MeV. By extrapolation the full range was determined to be 31.1 ± 0.2 mg/cm^2.

The energy distributions were very nearly equal to that of a Gaussian. The full width at half maximum in MeV, FWHM, of the energy straggling was found to fit the relationship:

$$(\mathrm{FWHM})^2 = 3.3\ d$$

where d is the thickness of aluminum in units of mg/cm^2.

I. INTRODUCTION

The Hilac of this Laboratory is capable of accelerating beams of ions as heavy as Ar^{40} to energies of 10.4 ± 0.2 MeV/nucleon. The most convenient way of obtaining lower energies is by inserting Al-foils in the beam path. Hence, in order to effectively utilize these beams, range-energy calibration data are required.

The energy degradation in Al have been measured[1] for ions up to Ne^{20}. For heavier ions calculated range-energy curves are available.[1,2] In experiments with Ar^{40} we found, however, that the values for the energy as estimated from these curves deviated significantly from those determined experimentally with a silicon-diode detector. It was, therefore, decided to measure as accurately as possible the energy of the Ar^{40} beam as it penetrates aluminum. In addition, it was found to be of importance to also measure the energy straggling of the argon ions. The knowledge of the latter is necessary in excitation function studies. In many cases, the cross section for a reaction product changes rapidly with the energy of the ion. The energy distribution of the incident ions, therefore, will have a marked influence on the slope of the function.

II. EXPERIMENTAL

The experiments were performed with the heavy ion beams from the Berkeley Hilac. The degraders consisted of 1/4, 1/2, 1, 2, 3, and 4 mil foils that had been carefully weighed. They were mounted on individual paddles that could be moved in and out of the beam. Before entering the degrader stack, the beam was purified by magnetic deflection through 30°. By the insertion of attenuators at the ground end of the Cockroft-Walton injector of the Hilac, the heavy ion flux was adjusted to such a low level that a detector, used to measure the energy, could be exposed directly to the beam.

Three collimators, each with a diameter of 0.16 cm, were placed before and after the degraders and in front of the detector. The distance between each collimator was about 30 cm. This arrangement assured that the ions entering the crystal had essentially all penetrated the same degrader thickness (ignoring inhomogeneities in the foil) and excluded the possibility of single nuclear scattering. Contribution from multiple nuclear scattering should be negligible.

The detector was a P-type (phosphorus doped) silicon diode crystal with a bias of about 500 volts. After proper linear amplification, the pulses were analyzed by the use of a 400 channel transistorized pulse height analyzer. A pulse from a pulse generator, triggered by a signal from the Hilac, was used to check gain stability and resolution of the system during the 2-sec beam burst.

The energy calibration of the crystal was crucial to the success of the measurements. This was achieved in the following way. First, it was properly shown, by pulse-height analysis, that the ions C^{12}, O^{16}, Ne^{20}, and Ar^{40}, alternately accelerated by the Hilac during the period of one day, had the same kinetic energy per nucleon. Second, the stopping power curves for C^{12} and O^{16} in Al were measured. These curves were in excellent agreement with those of Northcliffe when the initial energy of these ions were chosen as 10.38 MeV/nucleon.[3] Consequently, the most probable energy of Ar^{40} from the Hilac was taken as 415.2 MeV and those of C^{12}, O^{16}, and Ne^{20} as 124.6, 166.1, and 207.6 MeV, respectively. A perfect linear relationship was found between these energies and their respective pulse heights. The most probable pulse height of the 38.91 MeV Ar^{40} ions from the Prestripper cavity of the Hilac also fell on the same calibration curve. The latter must be regarded as an independent check since the energy of these ions can be rather accurately calculated from the RF frequency, the number of drift tubes of the Prestripper and the distances between them.

III. RESULTS

The energy spectra of the Ar^{40} particles both before and after the foils were, to a good approximation, symmetric. The shapes of the distributions were very nearly equal to that of a normal distribution.

Values for the most probable and average energies, denoted E_{mp} and E_{av}, respectively, and the observed full width at half maximum, $FWHM_o$, of the energy distribution are given in Table I. The uncertainties in E_{mp} are less than 0.2 and 1 MeV in the experiments with the 38.9 MeV and 415 argon ions, respectively. As is seen from Table I, E_{mp} is systematically higher than E_{av} but never more than 0.8 MeV.

The stopping power data are presented graphically in Fig. 2. The result with the Prestripper ions is also included. This was done by setting the residual energy of the incident 415 MeV argon beam equal to 38.9 MeV after it had penetrated 29.3 mg Al/cm^2.

IV. DISCUSSION AND CONCLUSION

A. Range-Energy Relationship

None of the theoretical formulas that have been developed for the energy loss of a particle to an absorbing medium can be applied to the present system.

Semi-empirical expressions exist that relate experimental range-energy relations for heavy ions in emulsions to those in metals.[1,2] To compare with such calculations, we have to know the total range of argon particles at one energy. By extrapolation of the curve in Fig. 2, we find that 415 MeV Ar^{40} has a range of 31.1 ± 0.2 mg/cm^2 in aluminum. Semi-empirical values for the same quantity have been reported as 34.0[1] and 36.4.[2]

The differential energy loss of an ion is proportional to its charge. Near the end of the range the Ar^{40} ion has picked up most of its electrons and, hence, the extrapolated value probably represents a lower limit for the true range. Due to this uncertainty, no range-energy curve will be constructed from our data.

A more direct comparison can be made of the values for $\Delta E/\Delta d$. Here we find the semi-empirical values to differ significantly from the experimental ones. For instance, 400 MeV Ar^{40} will after 27.7 mg Al/cm^2 be reduced to 100 MeV according to the experimental stopping power curve in Fig. 1, and to 120 MeV according to calculated range-energy curves.[1,2]

B. Energy Straggling

Bohr's nonrelativistic expression predicts that the variance of the energy straggling is directly proportional to the thickness of the absorber.[4] Although we cannot expect this to hold in our case, it seemed appropriate to find the empirical relationship between these quantities. Contributing to the values for FWHM_o listed in Table I are 1) the true energy straggling, 2) effects due to nonuniform foil thickness, 3) the spread of the incident beam, and 4) instrumental effects (slit widths, electronic resolution, etc.). The latter contribution was negligible. The beam from the accelerator had a FWHM of 2.1 MeV. Then in the quantity FWHM_s, as estimated from the expression:

$$(\mathrm{FWHM}_s)^2 = (\mathrm{FWHM}_o)^2 - 4.4 \tag{1}$$

are included both factors 1) and 2).

Values for FWHM_s and $(\mathrm{FWHM}_s)^2/d$ are given in Table I. Values for the latter quantity have been listed in two columns. Column 5 consists of those from the experiments performed with the 1/4 mil foil included in the stack. They yield a value $6 \pm 1\ \mathrm{MeV}^2/\mathrm{mg/cm}^2$ for $(\mathrm{FWHM}_s)^2/d$. The corresponding value for those in column 6 is 3.3 ± 0.4. The stopping power experiments did not reveal any irregularities when the 1/4 mil foil was used, indicating its average thickness to be correct. Hence, we must conclude the higher value of $(\mathrm{FWHM}_s)^2/d$ to be due to inhomogeneities in the thickness of that particular foil. Similarly, the 1.2 $\mathrm{mg/cm}^2$ foil, used in the experiment with 38.9 MeV ions, probably has not a very uniform thickness. Consequently, the values obtained with these foils will not be considered further.

In Fig. 2, $(\mathrm{FWHM}_s)^2$ is plotted versus d for the measurements where the 1/2, 1, 2, 3, and 4 mils foils were used. We see that the points are well represented by a straight line given by the expression:

$$(\mathrm{FWHM}_s)^2 = 3.3\ d \tag{2}$$

The fact that the line intercepts origo strongly suggests a negligible contribution to the energy spread from imperfections in the thicknesses of the foils. Hence, here $FWHM_s$ should represent the true energy straggling.

Bohr's formula predicts $(FWHM_s)^2/d$ to be 0.25 $MeV^2/mg/cm^2$ for fully stripped Ar^{40} ions.[4]

$\frac{d\epsilon}{d\rho} = k\epsilon^{a}$; $\int_0^{\epsilon} \epsilon^{-a} d\epsilon = k \int_0^{\rho} d\rho$; $\frac{\epsilon^{1-a}}{1-a} = k\rho$; $\rho = \frac{\epsilon^{1-a}}{k(1-a)}$

Table I. Results of the analysis of the energy spectra of argon-40 ions after the penetration of selected thicknesses of aluminum. Here d is the thickness, E_{mp} and E_{av} are the most probable and average kinetic energy, respectively, and $FWHM_o$ and $FWHM_s$ are the observed and corrected full widths at half maximum, respectively.

Program	d (mg/cm^2)		E_{mp} (MeV)		E_{av} (MeV)	$FWHM_o$ (MeV)	$FWHM_s$ (MeV)	$(FWHM_s)^2/d$	
								With the 1/4 mil foil	Without the 1/4 mil foil
31,94	0	31,94 86	415.2	10,4	415.0	2.1	0	---	---
~30.2	1.71	30.23	396.5	9,9	395.7	4.8	4.3	10.9	
	3.43	29,51	383.7	9,6	383.0	4.0	3.4		3.4
~26,3	5.14	26,80	365.2	9,12	364.5	6.3	5.9	6.9	
	6.83	25,11	347.4	8,68	346.7	5.5	5.1		3.7
	8.54	23,40	328.3	8,2	327.5	7.8	7.5	6.6	
~22.5	10.26	21,68	314.0	7,85	313.5	5.9	5.5		3.0
	11.97	19,97	294.0	7,35	293.3	8.4	8.1	5.5	
~19,0	13.76	18,18	270.9	6,78	270.5	7.1	6.8		3.3
~15.7	15.41	16,53	250.4	6,25	249.7	9.8	9.6	5.9	
	17.19	14,75	233.1	5,93	232.3	7.1	6.8		2.7
~12,7	18.90	13,04	209.3	5,22	208.5	9.0	8.8	4.1	
	20.67	11,27	181.9	4,80	181.4	9.1	8.9		3.8
~9.9	22.38	9,56	156.8	3,92	156.3	11.2	11.0	5.4	
	24.10	7,84	132.9	3,32	132.2	9.2	9.0		3.3
~7,5	25.81	6,76	103.8	2.40	103.3	11.4	11.2	4.9	
~4,7	27.50	4,44	72.5	1,81	72.1	10.0	9.8		3.5
~3.0	29.21	2,73	40.8	1,02	40.5	10.0	9.8	3.3	
	0		38.91		38.9	0.59	0	---	---
	1.21		16.0		15.9	4.4	4.36	15.7	

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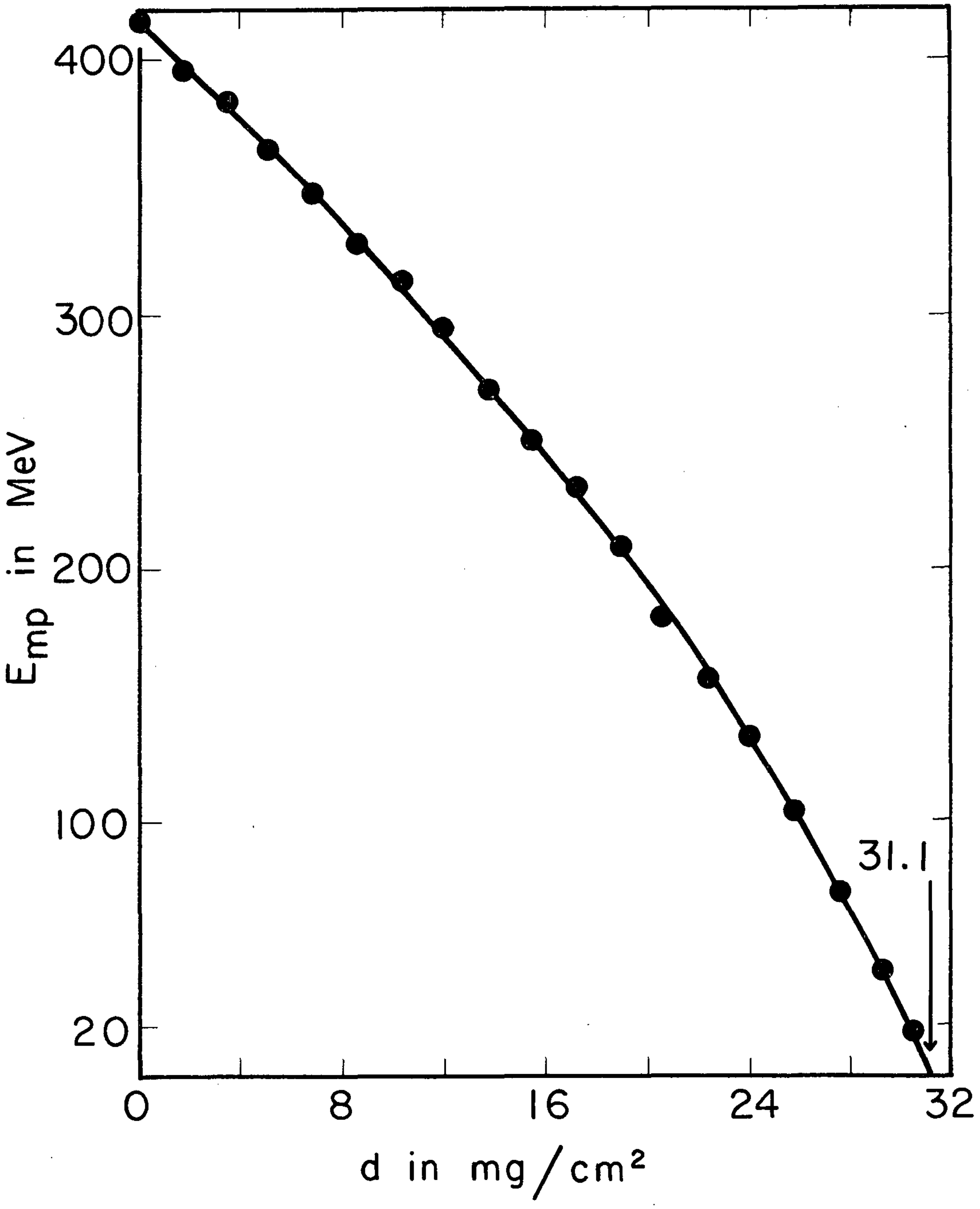

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Fig. 1. Energy loss of argon-40 in aluminum. The line has been drawn through the experimental points.

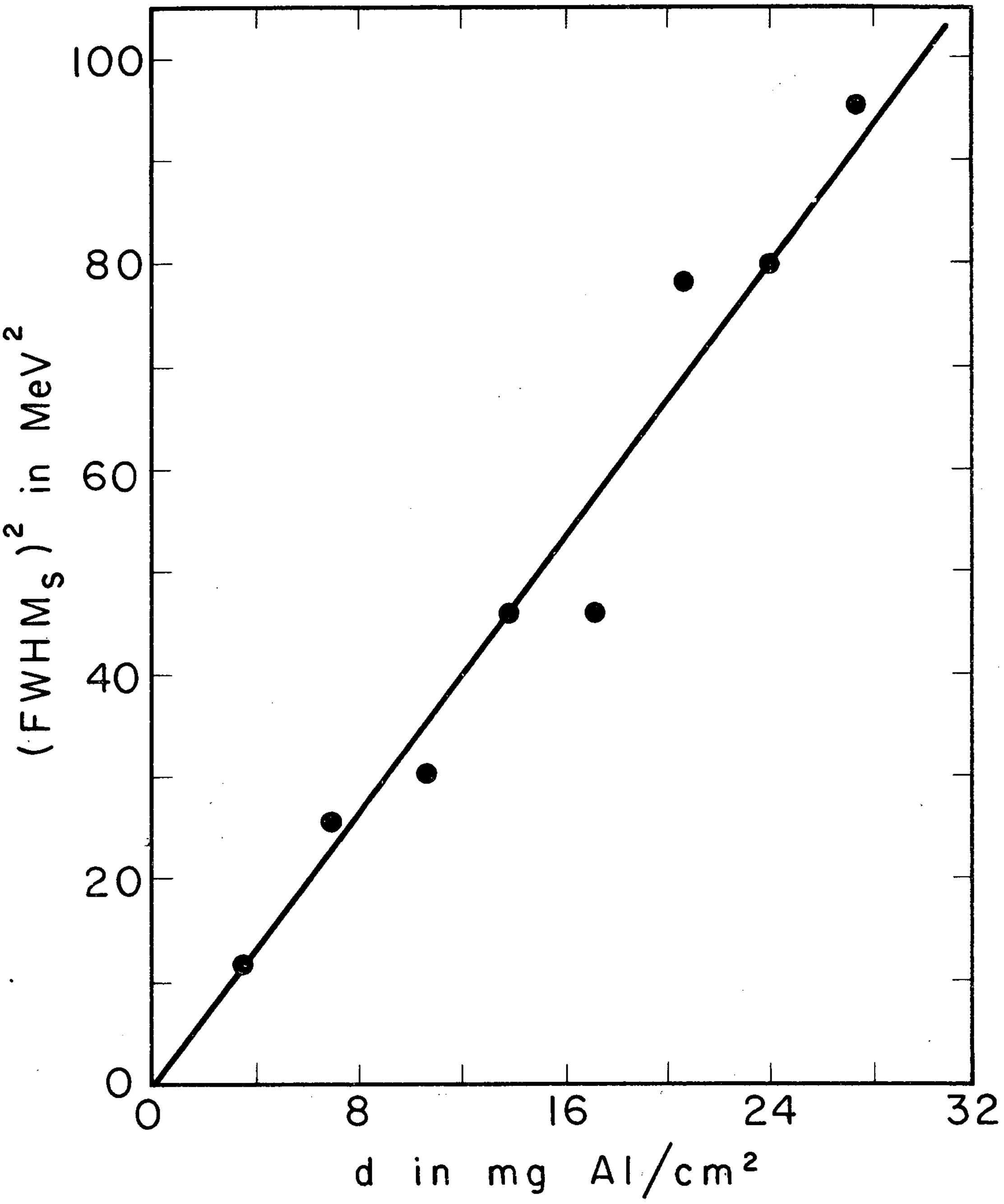

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Fig. 2. Relationship between $(\mathrm{FWHM_S})^2$ of the energy spectrum of argon-40 ions and the thickness of the aluminum. The line corresponds to $(\mathrm{FWHM_S})^2 = 3.3d$. The points represent experiments with 1/2, 1, 2, 3, and 4 mil foils.