Range of 1–3 MeV Ne^{22} Ions in Al and the Analysis of Some Na^{24} Recoil Data*

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Beams of Ne^{22} ions from a Van de Graaff accelerator were stopped in stacks of aluminum leaf which were then analyzed for Ne content with a high-sensitivity mass spectrometer. The mean ranges projected along the beam direction for 1.0-, 2.0-, and 2.8-MeV Ne^{22} ions were found to be (0.35, 0.54, and 0.67) ± 0.02 mg/cm^2 of Al, respectively. The half-widths of the range curves were 0.20 ± 0.05 mg/cm^2.

By interpolation with other data a range-energy curve for Na^{24} in Al was constructed. Existing data on the thick-target ranges of Na^{24} produced from Al by medium-energy protons, deuterons, and alpha particles were compared with the range-energy curve. The comparison indicated that partial momentum transfer for reactions leading to Na^{24} begins to occur for protons and alpha particles of bombarding energies of about 60 MeV.

IN the preceding paper[1] the recoil ranges of Na^{24} produced from aluminum targets with GeV protons was studied. In order to interpret the data, a relationship between the range and the energy of the Na^{24} recoils was needed. The average recoil range of about one-half mg/cm^2 of Al indicated that the velocities of interest were a few times the Bohr velocity and were not amenable to accurate theoretical treatment at the present time. A range-energy curve for a similar species, Ne^{22}, was determined. The 3-MeV Van de Graaff generator at Brookhaven was used to accelerate the Ne^{22} ions. These were stopped in stacks of Al leaf about 150 μg/cm^2 thick and each foil was analyzed on a mass spectrometer to determine its Ne^{22} content. The efficiency of the spectrometer was determined with Ne^{20} spike samples also prepared at the Van de Graaff generator with the help of a Faraday cup. A range-energy curve for Na^{24} in Al was constructed by interpolation with other data. This curve, in addition to being used in the preceding paper, is also used to reanalyze existing data on the fraction of Na^{24} activity recoiling out of Al targets which were thick with respect to the range of the Na^{24} recoils. These reactions were induced by medium-energy protons, deuterons, and alpha particles.

RANGE-ENERGY EXPERIMENT

A mixture of 5% natural Ne in He was let into the ion source of the Van de Graaff generator. After acceleration the singly charged beam was mass-analyzed by a bending magnet. Further downstream was placed a $\frac{3}{8}$-in. collimator, an insulated section of beam pipe, and a Faraday cup one foot deep. The foils were irradiated at the end of the Faraday cup. A special valve and pump attached to the Faraday cup made sample changing very rapid. The system resolved the Ne^{20} and Ne^{22} mass peaks. Three stacked-foil irradiations were done with 1.0-, 2.0-, and 2.8-MeV Ne^{22} beams. The beam currents were about 0.1 μA and the irradiations lasted 1 to 3 h. Isotopic spike samples to determine the efficiency of the mass spectrometer to be used later were prepared by bombardment of 0.00025-in. Al (thick compared to the range of the ions) with the Ne^{20} beam while the integrated current from the Faraday cup was measured. About 25 spike samples were prepared in 1-min irradiations with beam currents of about 1 μA.

In the bombardments of stacked Al leaves each foil was mounted on a separate Al frame. After bombardment the thickness of each foil was determined with an alpha-particle thickness gauge.[2] This device consists of a Po^{210} alpha source collimated to give a $\frac{1}{8}$-in.-diam beam and mounted on a micrometer screw. The micrometer is positioned in front of a thin-window counter so that the alpha particles just penetrate the window. The quantity measured is the thickness of air equivalent to the thickness of each foil. The device was calibrated absolutely by the determination, on a microbalance, of the weights of several foils. The uniformity of the Al leaf used was determined with the thickness gauge. It was found that a measurement within a 1-in.-diam circle was within 5% of the average two-thirds of the time. To minimize the effect of this nonuniformity on the range measurements, the thickness of each foil was determined at the point where the $\frac{3}{8}$-in.-diam Ne beam passed through it.

To determine the Ne^{22} content of each leaf, the leaf was melted, together with a Ne^{20} spike in 0.00025-in. Al, in the vacuum line of a high-sensitivity rare-gas mass spectrometer.[3] The ratio Ne^{22}/Ne^{20} was determined and multiplied by the Faraday cup reading for the spike sample. In Fig. 1 the amount of Ne^{22} (in relative units) divided by foil thickness is plotted against the depth of penetration of the beam. A small variable spectrometer blank caused some difficulty and thus the measurements of foils with low Ne^{22} content (wings of the histograms) are not as accurate as those near the peaks of the histograms. The average depths of penetration, which are equal to the mean ranges projected along the beam

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[1] A. M. Poskanzer, J. B. Cumming, and R. Wolfgang, preceding paper [Phys. Rev. **129**, 374 (1963)].

[2] K. Ramavataram and D. I. Porat, Nucl. Instr. and Methods 4, 239 (1959).

[3] O. A. Schaeffer, Brookhaven National Laboratory Report BNL-581, 1959 (unpublished).

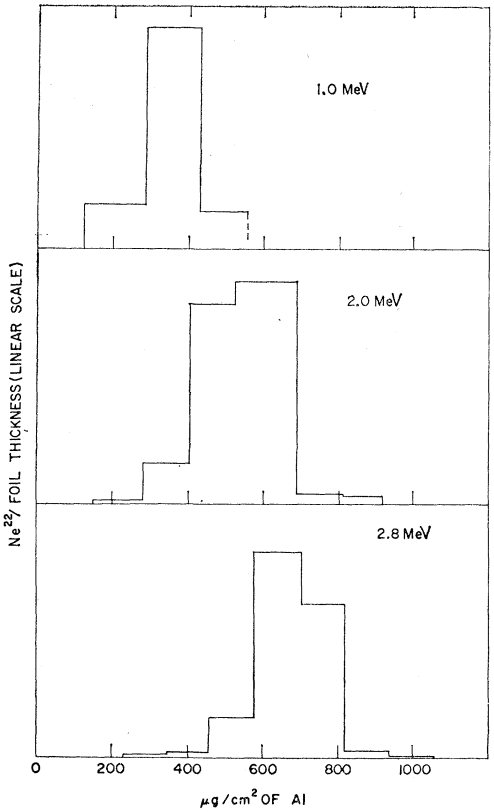

FIG. 1. Differential range curves for monoenergetic Ne^{22} ions stopping in Al. The abscissa is the depth penetrated along the beam direction.

direction, are shown in Table I. The errors are estimated to be a combination of a contribution of 3% for the calibration of the thickness gauge and a random contribution of 15 $\mu g/cm^2$. The half-widths of the curves were obtained by the probability plot method[4] so as not to include the effect of finite foil thickness. The half-widths, determined with less accuracy than the mean ranges, appear to be about 200 ± 50 $\mu g/cm^2$ at all three energies. The Na^{24} ranges shown in Table I were obtained by interpolation with the Ar^{41} ranges in Al of Davies.[5] The present data, together with the low-energy Na^{24} data of Davies and Sims,[6] are shown in Fig. 2. In the region of the present measurements the data can be fitted to an equation of the form $R = kV^N$ with $N = 1.2$.

TABLE I. Mean ranges in Al projected along the beam direction, in $\mu g/cm^2$.

E (MeV)	Ne^{22}	Na^{24}
1.0	350	340
2.0	540	520
2.8	670	640

[4] L. Winsberg and J. M. Alexander, Phys. Rev. **121**, 518 (1961).
[5] J. A. Davies (private communication, 1961).
[6] J. A. Davies and G. A. Sims, Can. J. Chem. **39**, 601 (1961).

ANALYSIS OF RECOIL DATA

Now that a range-energy curve for Na^{24} is available it is of interest to reanalyze the data on recoil ranges of Na^{24} produced by medium-energy reactions to test consistancy with a full-momentum-transfer (compound nucleus) mechanism[7] and to see at what bombarding energy the constant-deposition-energy mechanism discussed in the previous paper becomes important. The production of Na^{24} from Al with protons, deuterons, and alpha particles will be considered. The measurements discussed here were made by Hintz,[8] Fung and Perlman,[9] Porile,[10] and Crespo,[11] and are analyzed in terms of the product FW, where F is the fraction of activity recoiling out of a thick target oriented perpendicular to the beam, and W is the thickness of the target.

At low bombarding energies there are essentially no recoils in the backward direction and FW is a measure of $v_{||}$, the velocity along the beam direction imparted to the recoil by the bombarding particle. The energy that the recoil product would have after full momentum transfer is

$$E_{CN} = E_B(A_R/A_{CN}^2)[A_B + (E_B/2m_0c^2)], \quad (1)$$

where E_B is the energy of the bombarding particle, and A_B, A_R, and A_{CN} are the mass numbers, respectively, of the bombarding particle, recoil product, and compound nucleus. Winsberg and Alexander[4] have pointed out that there is a correction which slightly alters the dependence of FW on $v_{||}$. It is due to the distribution imposed on the recoil velocity by the momentum from particle evaporation and is important only when range is not proportional to velocity. With the exponent of velocity in the range-velocity relation obtained above ($N = 1.2$), their equation becomes

$$FW = R_0(1 + 0.12E_E/E_{CN}), \quad (2)$$

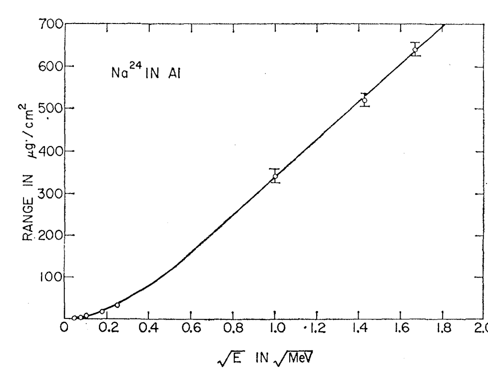

FIG. 2. Range-energy curve for Na^{24} in Al. The low-energy points are from reference 6.

[7] Full momentum transfer as deduced from recoil data corresponds to symmetry about 90° of the angular distributions of the outgoing particles in the center-of-mass system.
[8] N. M. Hintz, Phys. Rev. **86**, 1042 (1952).
[9] S. C. Fung and I. Perlman, Phys. Rev. **87**, 622 (1952).
[10] N. Porile, Phys. Rev. **127**, 224 (1962).
[11] V. Crespo (private communication, 1962).

where E_E is the average kinetic energy imparted to the recoil in the evaporating system due to evaporation. The quantity R_0 is defined as the range which corresponds to $v_\parallel$ only. The value of E_E was estimated from the following equation which is similar to that given by Winsberg and Alexander[4]:

$$E_E = [(E_B A_T / A_{CN}) + Q]\bar{A}_E / A_R. \qquad (3)$$

The quantity A_T is the mass number of the target and $\bar{A}_E$ is the average number of nucleons per evaporated particle.[12] These corrections lowered the values of R_0 calculated from the data by not more than 5, 10, and 20% for the alpha, proton, and deuteron reactions, respectively. The values of R_0 are plotted against E_{CN} in Fig. 3. Also plotted is the range-energy curve from Fig. 2. As long as the assumption of full momentum transfer is correct the points should fall on the range-energy curve. This appears to be true for bombarding deuterons from 12 to 20 MeV. For bombarding protons and alpha particles up to about 60 MeV, the data are close to the curve. This could be an indication that the range-energy curve is about 10% too high or that the exponent N in the range-velocity relation is closer to unity than the value 1.2 used, so that the above-mentioned corrections should not have been applied to the recoil data. However, the discrepancies are not considered large enough to warrant a change in the range-energy curve. It can be seen that the deuteron data above 40-MeV bombarding energy and one alpha-particle point at 60 MeV are far below the curve and inconsistent with adjacent experimental data. The alpha-particle point is probably low because of deuteron contamination in the alpha beam, which Fung and Perlman[9] point out was a problem. The deuteron data above 40 MeV are probably low because of neutron contamination initiating the (n,α) reaction in the Al target.

It may be concluded from the proton and alpha-particle curves that Na^{24} cannot be produced exclusively in a compound-nucleus reaction at bombarding energies greater than about 60 MeV. This is understandable in terms of the large excitation energy that has to be removed by just a few particles. Thus at higher bombarding energies the main process becomes one of partial energy and momentum deposition. In the case of the proton reaction the deposition energy calculated at the higher bombarding energies of the previous paper by means of the Turkevich mechanism is consistent with this limit of 60 MeV for the compound-nucleus reaction.

[12] The reactions assumed for the calculations were $(p,3pn)$, $(d,\alpha p)$, and $(\alpha,\alpha 2pn)$. At the lowest p and α bombarding energies it was assumed that a He^3 was emitted.

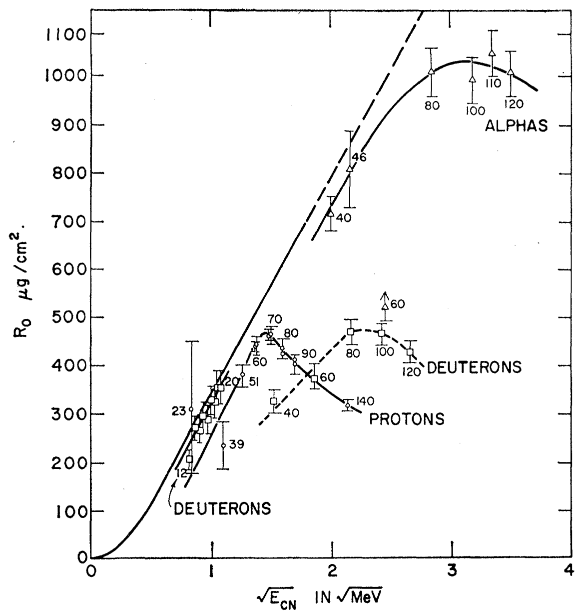

FIG. 3. Ranges of Na^{24} recoils produced by bombardment of Al with protons, deuterons, and alpha particles. The quantity R_0 is the average range in Al projected along the beam direction after correction for the effect of the recoil caused by evaporation. The quantity E_{CN} is the kinetic energy which the recoil product would have for full momentum transfer. The numbers adjacent to the points are the bombarding energies in MeV. The alpha-particle point at 40 MeV is from reference 10. The alpha-particle point at 46 MeV and the deuteron data from 12 to 20 MeV are from reference 11. The proton data from 23 to 90 MeV are from reference 8. The remainder of the data (including proton data down to 60 MeV) are from reference 9. The curve through the origin is from Fig. 2.

ACKNOWLEDGMENTS

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