value determined for $q(1-\gamma)$ is $-2.3a_0^{-3}$, where a_0 is the Bohr radius.

The spectra which were observed with the Te metal (hexagonal) source are interpreted as resulting from the simultaneous quadrupole splitting of source and absorber. These spectra are roughly twice as wide as those obtained with the ZnTe source.

According to the above interpretation, the peak on the right of Fig. 2 results from an unsplit line. The full width at half maximum of this line is approximately 0.1 cm/sec; the corresponding mean life of the state is 1.5×10^{-8} sec. Because of the possibility of line broadening (particularly in the source) this result is a lower limit. It is, however, of the order of the mean lives of the 24-keV state of Sn^{119} and the 35-keV state of Te^{125}, both of which also decay by $M1$ transition.

Using the Debye model, the Lamb-Mössbauer factor[1] of ZnTe at 78°K is 0.8. The Debye temperature of $NaI\cdot 2H_2O$ is not known, but it is probably less than that of NaI, whose Lamb-Mössbauer factor, f', is 0.4 at nitrogen temperature. We may use this to calculate an upper limit to the expected percentage resonant absorption. Taking $f'=0.4$ and a calculated L conversion coefficient of 4, the absorber thickness for $1/e$ transmission is 20 mg/cm² of I^{129}, before taking account of the quadrupole splitting. The peak on the right of Fig. 2 should, according to our previous interpretation, result from a single transition whose statistical weight is about 1/4 of the total. Thus, when this resolved line is on resonance, the thickness for $1/e$ transmission is about 80 mg/cm². The actual absorber thickness is 35 mg/cm² of I^{129} and thus about 0.35 of the resonant gammas should be absorbed. When account is taken of the estimated source recoilless fraction (0.8) and the dilution factor (0.2), the predicted fractional effect is 0.06. This figure, which is an upper limit, is to be compared with the observed fractional effect, which is 0.02 for the resolved line. The agreement is as good as could be expected, considering the roughness of the calculation and the doubtful utility of the Lamb-Mössbauer factor in the case of solids which are composed of chemical compounds.[6]

ACKNOWLEDGMENTS

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Ranges of Be^9 Ions in Gold and Aluminum*

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The ranges of Be^9 ions in gold and aluminum have been measured in the energy range 2 to 21 MeV. Pulse height measurements of Be^9 recoils, degraded by various thicknesses of gold or aluminum foil, served as the basis for construction of range-difference curves. These curves were extrapolated to zero energy and transformed into the more useful range-energy relationships.

INTRODUCTION

THE advent of accelerators which generate beams of heavy ions has produced a need for more complete information on the range-energy relationship in various materials for ions heavier than He^4. An increasing interest in heavy ions as products of nuclear reactions has amplified this need. Recently, Northcliffe[1] has determined range-energy relationships for He^4, B^{10}, B^{11}, C^{12}, N^{14}, O^{16}, F^{19}, and Ne^{20} ions in aluminum in the energy range 1 to 10 MeV per nucleon. A complementary study of the ranges of the same ions in oxygen and nickel has been made by Roll and Steigert.[2] Heckman *et al.*[3] have measured the range-energy relationship for C^{12}, N^{14}, O^{16}, Ne^{20}, and Ar^{40} ions in emulsions at energies up to 10 MeV per nucleon. Detailed information for the ranges of N^{14} ions in nickel and aluminum is available.[4] Other determinations of range-energy relationships for heavy ions include the work of Burcham[5] on C^{12} in aluminum; Oganesyan[6] on C^{12}, N^{14}, O^{16} in aluminum, copper, and gold; Barkas[7] on Li^8 and B^8 in emulsions; and Schambra, Rauth, and Northcliffe[8] on C^{12}, O^{16}, and

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Ne^{20} in Mylar and polyethylene. The purpose of this paper is to report some range-energy determinations that were made for Be^9 ions in connection with a study of (α, Be^7) reactions. The measurements were made for gold and aluminum in the energy range 2 to 21 MeV by a pulse-height method. The results are probably not as accurate as data obtained from magnetically-analyzed heavy ion beams but they should be adequate for many applications.

EXPERIMENTAL

The Be^9 ions were produced in the 60-in. scattering chamber of the University of Washington cyclotron by elastically scattering helium ions from a beryllium target. Pulse-height measurements of the Be^9 recoils, degraded by various thicknesses of gold or aluminum foil, served as the basis for determining range-difference curves. Extrapolation of these curves to zero energy permits transformation of the data into the more useful range-energy relationship.

Two counters were used. The Be^9 recoil detector was a 5000 Ω-cm silicon, diffused type, solid-state counter with a reverse-bias of 20 V. It was used in conjunction with a low-noise Tennelec preamplifier. The elastically scattered helium ions were detected with a CsI(Tl) crystal and photomultiplier assembly. Coincident pulses from both counters were displayed on two 20-channel pulse-height analyzers. The solid-state counter was calibrated on Be^9 recoils, the energy being calculated from kinematic considerations. The energy of the recoils was changed by varying the angle of observation. The absolute energy scale of the calibration was checked by looking at the 6.05 and 8.78 MeV α particles from a Pb^{212} source. The α-particle points were 400 keV above the Be^9 calibration curve. Since the average energy loss

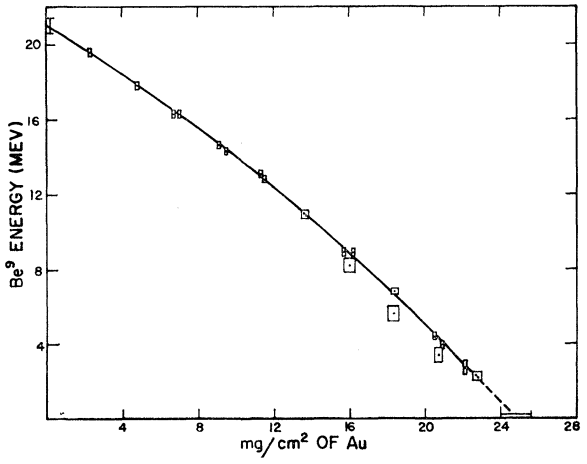

FIG. 1. The range-difference curve for Be^9 ions in gold. The error limits on the data points are composites of uncertainties in the calibration curve, the centers of pulse-height distributions, and the thickness of degraders. The error limit on the energy axis indicates the uncertainty in the absolute values of the energy. The error limit on the range axis is the estimated uncertainty in extrapolation of the curve to zero energy.

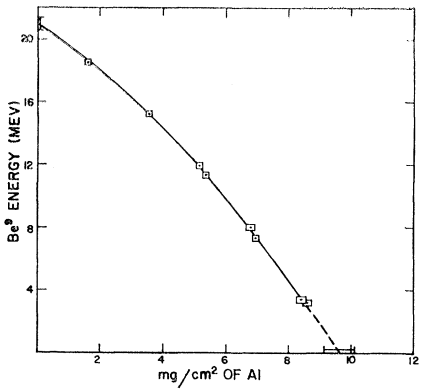

FIG. 2. The range-difference curve for Be^9 ions in aluminum. The error limits have the same interpretations as in Fig. 1.

of Be^9 recoils in the 0.3 mg/cm² beryllium target was estimated to be about 400 keV, the agreement was considered satisfactory. A true calibration curve was obtained by shifting the measured curve upward to coincide with the α-particle points.

Gold and aluminum foils were interposed between the target and the solid-state counter by means of a remotely operated degrader wheel. The unit thickness of the foils was 2.28±0.07 mg/cm² for gold and 1.60±0.04 mg/cm² for aluminum. The degraders consisted of stacks of these unit foils from 1 to 8 foils thick. The thickness of each foil was determined by weighing, but no investigation was made of thickness uniformity within a foil. However, the practice of using foils in stacks tended to average out any nonuniformities.

The energy of the recoil fragment emerging from the target was calculated from the kinematics of the scattering process and corrected for energy loss in the target. The energy of the degraded Be^9 recoil was determined by taking the center of the pulse height distribution, in channels, and converting to energy units by means of the calibration curve. Range-difference curves were obtained simply by plotting the energy of the degraded recoil against the thickness of the degrader. As the thickness of the degraders was increased, the width of the pulse-height distributions increased rapidly. This was undoubtedly due in part to straggling. A scattering effect may have been another contributing factor. The degrader foils were a short distance in front of the recoil detector and subtended a larger solid angle than the detector. Thus, it was possible for the degraders to scatter recoils into the detector which would not otherwise be admitted. These scattered recoils would be of different energy owing to their somewhat different initial angles with respect to the helium-ion beam.

Because of the increase in the width of the pulse-height distributions with increasing degrader thickness it was not feasible to degrade a 21-MeV recoil all the way down to 2 MeV, the useful threshold of the detection system. Instead, the energy of the undegraded recoil was decreased in several steps by changing the

angle of observation. The result was a series of overlapping range-difference curves, typified by the following sequence of energy limits: 21–5.6 MeV, 17.9–3.4 MeV, 14.8–2.3 MeV, 8.9–2.2 MeV, 5.2–2.7 MeV. This series of curves was then fitted together to form a single range-difference curve in the energy interval 21–2.2 MeV.

RESULTS

The range-difference curves for Be^9 ions in gold and aluminum are given in Figs. 1 and 2, respectively. The error limits on the data points are composites of uncertainties in the calibration curve, the centers of pulse-height distributions, and the thickness of degraders. The error limit on the energy axis indicates the uncertainty in the absolute values of the energy. It is composed of an uncertainty of ± 200 keV in the helium ion beam energy and $\pm 0.3°$ in the angle of the Be^9 counter. The error limit on the range axis is the estimated uncertainty in extrapolation of the curve to zero energy.

There are three points on the range-difference curve for gold which are too low. Each of these points represents Be^9 recoils degraded by seven or more thicknesses of gold foil. The pulse-height distributions for these recoils was very broad and it is felt that there was some systematic error involved in their interpretation.

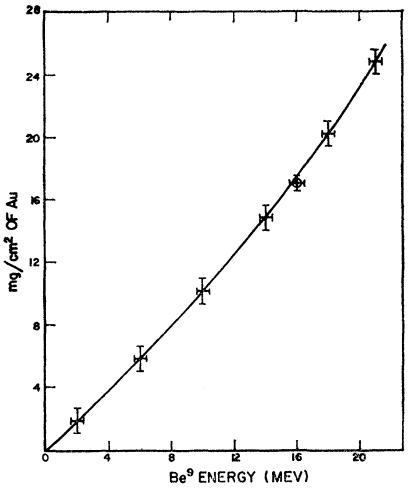

FIG. 3. The range-energy relation for Be^9 ions in gold. The error limits represent uncertainties in the absolute values of the energy and extrapolation of the range-difference curve. The circled point is from a radiochemical measurement of the range distribution of monoenergetic Be^7 ions from the $He^3(\alpha,\gamma)Be^7$ reaction.

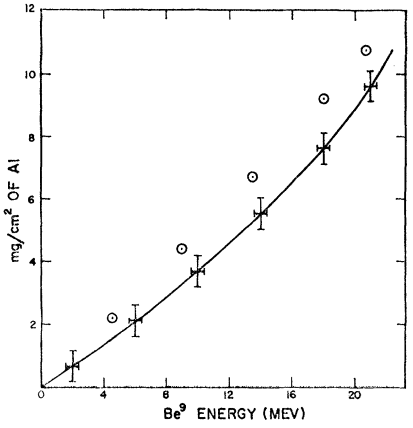

FIG. 4. The range-energy relation for Be^9 ions in aluminum. The error limits represent uncertainties in the absolute values of the energy and extrapolation of the range-difference curve. The circled points are taken from an estimate of Be^9 ranges in aluminum by Northcliffe. (See reference 9.)

The corresponding range-energy curves are shown in Figs. 3 and 4 for gold and aluminum, respectively. The error limits shown represent uncertainties in the absolute values of the energy and in the extrapolation of the range-difference curves. Errors due to the uncertainties imposed upon the individual data points in the range-difference curves are believed to be smaller and are not included. The circled points in the figure for aluminum are the estimates of Northcliffe[9] included here for comparison. Northcliffe's work is most accurate for much greater ion energies, and with this in mind, the agreement is considered to be satisfactory. The single circled point on the range-energy curve for gold is from a radiochemical measurement of the range distribution in thin gold foils of monoenergetic Be^7 ions from the $He^3(\alpha,\gamma)Be^7$ reaction. Northcliffe's work[1] on B^{10} and B^{11} ranges indicates that Be^7 may be expected to have a range about 3% greater than that of Be^9 in this energy region. Thus, for purposes of comparison the point for Be^7 should be displaced downward by 3% relative to the range-energy curve for Be^9. The agreement is still satisfactory.

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