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(d,p) Reactions with Kr^{78} and Kr^{80}†*

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Three targets of krypton gas, the first analyzing Kr^{78} 45%, Kr^{80} 51%, Kr^{82} 3.8%, the second Kr^{78} 28%, Kr^{80} 65%, Kr^{82} 6.3%, and the third Kr^{78} 14.2%, Kr^{80} 69.8%, Kr^{82} 14.4%, were produced by the thermal diffusion separation process. The (d,p) reactions for these samples were studied with the 4-Mev deuteron beam of the Yale cyclotron. The ground state and first excited state Q values of Kr^{79} are 5.98 ± 0.05 Mev and 5.52 ± 0.05 Mev, respectively. The ground state Q value of Kr^{81} is tentatively set at 5.63 ± 0.1 Mev. The masses of Kr^{79} and Kr^{81} are 78.94530 ± 11 and 80.94249 ± 14 amu.

ENRICHMENT OF THE ISOTOPES

IN 1953, Wheeler, Schwartz, and Watson were able to produce good targets highly enriched in Kr^{84} and Kr^{86} for deuteron bombardment.[1] By using the process of thermal diffusion, this work has been extended to include the two lightest isotopes, Kr^{78} and Kr^{80}. These are the rarest of the krypton isotopes, being only 0.35% and 2.3% respectively in the normal gas.

The concentration of the light fractions was accomplished by using a batch-wise recycling process of the product of several hot-wire thermal diffusion columns. Two batches of intermediate concentrations were needed to provide the final enrichment. For this purpose, three sets of two-stage, convectively-coupled systems were used. Each column was 3.7 meters long, making an effective total length of 7.4 meters per set. The cold wall was about 9 mm in diameter, maintained at 290°K by an enclosing water jacket. The hot surface in each column was a 20-mil tungsten wire at 1500°K requiring a power input of 1.2 kilowatts. Collecting reservoirs were provided at the top and bottom of each double column. The upper reservoir was 100 cc in volume, and the lower one 500 cc. Two of the three sets of columns were constructed of metal. The third set was made of glass, for which the construction details are described by Zucker and Watson.[2] To ascertain the optimum conditions for the column operation, a simple theory for multicomponent mixtures was developed, as outlined by Jones,[3] from the binary case treated by Jones and Furry.[4]

The final separation came from a single two-story column having the same effective length and characteristics as the two-stage sets. This long single-column apparatus had a longer relaxation time, but by elimination of the convective coupling volumes, a saving in partially enriched gas and total operating time was effected.

The first batch of the "light" krypton was made up of 1800 cc of gas at the column operating pressure of 65 cm of Hg with the isotopic analysis given in Table I. This gas was the accumulation of that taken from the top of the columns. Each time after the gas was extracted from the upper end-volume, the gas in the lower end-volume was replaced with enough normal krypton to bring the whole system back to the operating pressure. This procedure could be repeated about every 72 hours, during which time the columns had reached about 75% of their equilibrium concentrations.

The second batch of gas with further enrichment of the light krypton isotopes resulted from using about 1200 cc of the first batch to fill one of the sets of columns. The above procedure was repeated once, but instead of replacing the lower end-volume with normal gas, the remaining 600 cc of the first batch was used. Also, the column was allowed to reach 95% of equilibrium. Table II gives the analysis of the two samples of the second batch.

When enough of the gas of the type shown for the second batch was collected, it was used to fill the single 7-meter column. Successive extractions of the gas con-

TABLE I. Approximate concentrations in percent of the gas composing batch number one, starting with normal krypton at a pressure of 65 cm of Hg.

Isotope:	78	80	82	83	84	86
Concentration:	2.2	11.0	27.6	15.8	40.5	2.9

TABLE II. Approximate concentrations in percent of batch number two, starting with batch number one.

Isotope:	78	80	82	83	84	86
Concentration 1st	11.6	37.1	31.6	8.9	10.4	0.16
Concentration 2nd	10.9	38.6	32.5	8.6	9.3	0.11

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[1] Wheeler, Schwartz, and Watson, Phys. Rev. **92**, 121 (1953).
[2] A. Zucker and W. W. Watson, Phys. Rev. **80**, 966 (1950).
[3] R. C. Jones, Phys. Rev. **59**, 1019 (1941).
[4] R. C. Jones and W. H. Furry, Revs. Modern Phys. **18**, 151 (1946).

centrated in the top end-volume yielded samples *A*, *B*, and *C* of Table III.

In all, 92 liters of normal krypton gas were needed in this batch-wise procedure. The three final samples of the "light" krypton gas contain a total of 68 cc of Kr^{78}, which represents an extraction efficiency of 23%.

DEUTERON BOMBARDMENT

All three samples, *A*, *B*, and *C*, have been bombarded with 3.80-Mev deuterons from the Yale cyclotron. Protons from the (d,p) reaction were detected at 90° to the deuteron beam, using Ilford C2 emulsions 50 μ thick. Preliminary runs indicated that the yields of the ground-state proton groups were extremely low, and that the nuclear energy levels at higher excitations were closely spaced. An absorber consisting of 57.9 mg/cm² of aluminum was later inserted between the gas target and the emulsion to eliminate all protons of energy less than 5.2 Mev. This allowed longer exposures of the photographic plates without obscuring the proton tracks of the ground-state groups from the great density of shorter range tracks. The deuteron beam entered the target chamber through a 1.8-cm air-equivalent Mylar foil, degrading the energy by 270 kev at 4.1 Mev. When the gas pressure was 20 cm of Hg, the effective target "thickness" was 110 kev.

TABLE III. Concentrations (%) of the samples obtained from successive withdrawals of gas starting with batch number two.

Isotope:	78	80	82	83	84	86
Sample *A*	44.9	50.1	3.78	0.66	0.83	0.01
Sample *B*	28.3	65.0	6.25	0.43	0.16	0.02
Sample *C*	14.2	69.8	14.4	1.13	0.37	···

An exposure to an average beam of 0.25 μa for a total integrated charge of 3000 microcoulombs for each sample was found to be sufficient for a convenient track density in the emulsions. These tracks were measured on a microscope projection apparatus described by Plendl and Steigert[5] using an ordinary centimeter scale. With a Bausch and Lomb 43× objective plus 5× eyepiece, the magnification was such that tracks 300 μ long in the plate measured 26.5 cm on the screen.

RESULTS

A histogram of the proton tracks from sample *A* is shown in Fig. 1. Figure 2 consists of histograms from samples *B* and *C*. Some 3000 to 3500 tracks were measured for each histogram by one observer. Superposed on these are Gaussian curves drawn to represent the proton groups. These curves are Gaussian only on an energy scale. However, the histograms cover a small energy interval at high energies, so that there is a nearly linear dependence between range and energy in the emulsions. The symmetry of the peaks is confirmed by the shape of the N^{15} ground-state proton group (Fig. 1) which is not overlapped by any other proton group.

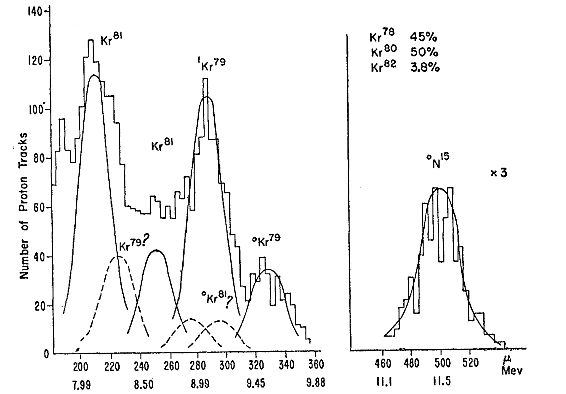

FIG. 1. Histogram and proton spectrum from the deuteron bombardment of sample *A* containing Kr^{78} 45%, Kr^{80} 50%, and Kr^{82} 3.8%.

This same N^{15} peak furnishes an ideal calibration for the deuteron beam, and as a measure of the energy spread. Since the N^{14} was a small impurity in the target gas, exactly the same conditions of beam energy, absorber thickness and proton detection prevailed. At the same time, the N^{15} first-excited-state proton group lies far below the energy region covered by the histograms. The Q value of 8.609 Mev is used for the calibration peak.

Initially, only samples *A* and *B* were available for bombardment. A comparison of Figs. 1 and 2 revealed that the relative intensities of the peaks as marked (neglecting the dotted curves) changed very closely with the relative abundance of Kr^{78} and K^8r^0. Any prominent peak can be used as the standard of com-

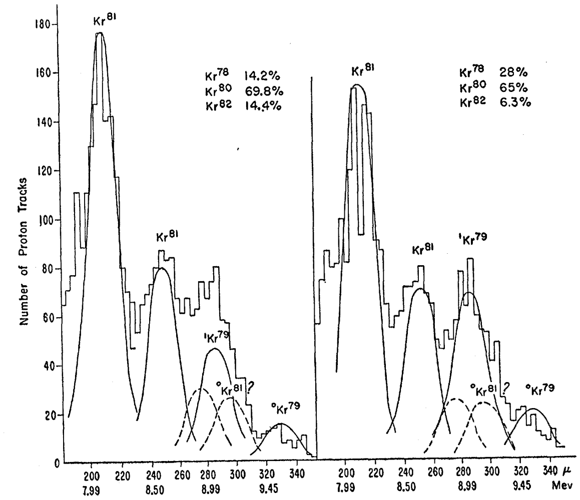

FIG. 2. Histograms and proton spectra from the deuteron bombardment of samples *B* and *C*. Sample *B*, on the right, has Kr^{78} 28%, Kr^{80} 65%, Kr^{82} 6.3%. Sample *C*, on the left, has Kr^{78} 14.2%, Kr^{80} 69.8%, Kr^{82} 14.4%.

[5] H. Plendl and F. Steigert, Rev. Sci. Instr. 27, 239 (1956).

TABLE IV. Level assignment, proton energies, and Q values for Kr^{79} and Kr^{81}. The (?) indicates that the excitation of the level is not clear because of the uncertainty of the 9.16- and 8.9-Mev groups.

Product nucleus	Level	Proton energy (Mev)	Q value (Mev)
Kr^{79}	0	9.56 ± 0.04	5.98 ± 0.05
Kr^{79}	1	9.11 ± 0.05	5.52 ± 0.05
Kr^{81}	0?	9.16 ± 0.1	5.63 ± 0.1
Kr^{81} or Kr^{83}?		8.9	5.4
Kr^{81}	1?	8.65 ± 0.05	5.04 ± 0.06
Kr^{81}	2?	8.18 ± 0.05	4.57 ± 0.06

parison. In this way, the assignment of a group to the proper isotope has been made. The question of the excitation was also easily resolved for the case of the ground and first excited-states of Kr^{79}. There was some doubt as to whether the ground-state proton group of Kr^{81} was superposed on the group representing the first excited state of Kr^{79}. To begin with, the evident proton group of highest energy (at 290 μ) from Kr^{81} is more intense than that of the ground state of Kr^{79} in Fig. 1 for which the concentrations of Kr^{78} and Kr^{80} are equal. In the simplified picture of the single-particle model, the relative cross section for a deuteron stripping reaction on isotopes depends primarily on the binding energy of the neutron, as well as the angular momentum it must carry into the nucleus. The binding energies for Kr^{79} and Kr^{81} are nearly equal. However, the neutron must have four units of angular momentum in the case of Kr^{81} as compared to one unit for Kr^{79}. One would expect the cross section for the formation of the ground-state of Kr^{81} to be less than that of Kr^{79}. To clarify this picture, sample C was bombarded.

By comparing the histograms of samples B and C, considering the change in the relative abundance of Kr^{78} and Kr^{80} between the two samples, it is obvious that other groups are present near the energy region of the first excited state of Kr^{79}. From Fig. 1, the energy of this group and its relative intensity were measured and then drawn at the proper position in the histogram of sample C. The process of subtraction revealed that at least two proton groups were necessary to reproduce the histogram points. These groups are indicated by dotted curves. Evidence for the existence of the group marked $°Kr^{81}$? also appears in the sample B histogram, but the validity of the proton group adjacent to this is perhaps questionable in B.

Table IV summarizes the assignment, proton energies, and Q values for these levels. In view of the uncertainty in excitation of Kr^{81}, only the isotopic assignment is made. All energies are corrected for target loss and the angle of incidence into the emulsions.

Using the mass of Kr^{78} obtained from mass-spectroscopic data,[6] and the Q value for the ground state of the $Kr^{78}(d,p)Kr^{79}$ reaction, we get 78.94530 amu for the mass of Kr^{79}. This is in excellent agreement with the value of 78.94539 amu obtained from the Br^{79} mass[6] and the decay energy of 1.620 Mev measured by Thulin[7] and Bergström.[8] The decay energy of Kr^{81} has not been measured, being a K capture with a half-life of 2.1×10^5 years. If we use the Q of the peak marked $°Kr^{81}$? (appearing at 300 μ) and calculate the mass of Kr^{81}, we get 80.94249 amu. Comparison with the mass of Br^{81} gives a decay energy of 0.2 ± 0.1 Mev. On the other hand, using the peak at 250 μ gives a decay energy of 0.75 Mev. Both of these are consistent with the 100% K-capture decay scheme. A calculation from the expression

$$\log(W_0^2 ft)\sim 10$$

indicates that the decay energy might be only 160 ±160 kev.[9] Also, the Kr to Br β-decay systematics[10] would lead one to expect a decay of 0.3 Mev. Our assignment of the peak at 300μ to $°Kr^{81}$ seems more credible in view of this information.

It is difficult to assign the dotted group at 280 μ. It could be composed of a multiplicity of small proton groups belonging to Kr^{81} and/or Kr^{83}. There is a known metastable state of Kr^{81} 190 kev above the ground state. This one is about 230 kev above the dotted group at 300 μ. Similarly, the ground state of Kr^{83} and many low-lying levels (3 levels$<$90 kev above ground level) fall very close to this energy region. The dotted group at 220 μ in Fig. 1 was drawn only to explain the asymmetry of the peak at 210 μ.

TABLE V. Masses of Kr^{79} and Kr^{81}; neutron binding energies. The last column uses mass spectrometer data and β-decay schemes.

Mass (amu)	Neutron number	Binding energy (Mev)	Binding energy, other data (Mev)
$Kr^{79}=78.94530\pm11$	43	8.00 ± 0.06	8.2 ± 0.1
$Kr^{81}=80.94249\pm14$?	44	11.5 ± 0.1	11.60 ± 0.08
	45	7.6 ± 0.1	7.7 ± 0.1
	46	11.0 ± 0.1	11.2 ± 0.1

Table V is a summary of the calculated masses and the binding energies of the 43rd, 44th, 45th, and 46th neutrons. The last column is a compilation of these binding energies obtained when mass-spectrometer data and β-decay schemes are used.[10]

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[10] *Nuclear Level Schemes*, U. S. Atomic Energy Commission Report TID-5300 (National Academy of Sciences—National Research Council, Washington, D. C., 1955).