and the elements in the Fe peak need temperatures well above 2×10^9 °K for their formation. It is reasonable to suppose that the elements Na to Ca are produced at intermediate temperatures. We have shown that the carbon burning reactions at temperatures between 5×10^8 and 10×10^8 °K produce large amounts of Na^{23} and of the Mg isotopes plus decreasing amounts of Al^{27} and Si, but very little of heavier nuclei. One striking feature of our results is the relatively large ratio of Na^{23} to Mg^{24} produced, 1:2 to 1:5 depending on temperature, compared with the Suess-Urey[37] "cosmic abundance" ratio of 1:15. Our ratio of Mg^{24}:Si^{28} of about 50:1 is also in contrast with the cosmic abundance ratio of 1:1. As outlined in Sec. 6, O^{16} burning and Ne^{20} photodisintegration will take place at slightly higher temperatures and result in the buildup of Si and heavier elements and, indirectly, in the depletion of Na^{23}. We hope to obtain detailed results for these reactions soon. At the moment we can only conclude that carbon burning produces plenty of sodium and magnesium.

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[37] See also A. G. W. Cameron (to be published).

ACKNOWLEDGMENTS

We are indebted to Dr. A. G. W. Cameron for many discussions and comments and to Dr. W. A. Fowler, Dr. J. H. Gibbons, Dr. T. H. Kruse, and Dr. J. G. Rutherglen for interesting communications. We want to thank Mr. W. A. Cartledge for a careful checking of the manuscript.

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Total Neutron Cross Section of Xenon and Krypton*†

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By the thermal diffusion method, using 12 meters of hot-wire columns, concentrations of the xenon isotopes in good quantity (about 57% Xe^{129} in the light fraction and 27% Xe^{136} in the heavy one) have been produced without recycling. A fair-sized sample of "light" krypton, analyzing better than 50% Kr^{80}, was available from earlier thermal diffusion separation with recycling by Blais and Watson. These samples together with the normal gases were concentrated to thicknesses of about 3.3 g/cm^2 in special gas target holders for use with the Brookhaven fast chopper. For krypton, neutron widths and isotopic identifications have been determined for the following levels: 27.9 ev in Kr^{83}, 39.8 ev in Kr^{82}, 106 ev in Kr^{80}, 233 ev in Kr^{83}, 519 ev in Kr^{84}, 580 ev in Kr^{84}, and 640 ev in either Kr^{78} or Kr^{80}. Total widths and radiation widths have been obtained for the 27.9- and 106-ev levels by thick-thin area analysis. For xenon, new resonances are observed at 5.2 ev in Xe^{124}, 9.5 ev in Xe^{129}, 14.1, 46.0, and 76.0 ev all in Xe^{131}, 92.0 ev in Xe^{129}, and 126 ev to be assigned to either the 128, 129, or 130 isotope.

INTRODUCTION

Although measurements on the total slow-neutron cross section of xenon[1] and krypton[2] had already been made, it was clear that, with the combination of the higher resolution of the Brookhaven fast chopper and time-of-flight apparatus and gas samples with good isotopic enrichments, these results could be improved. Since krypton has six isotopes and xenon has nine, it was obviously desirable to have usable amounts of these gases with the normal isotope abundance ratios sufficiently changed to make possible the isotopic identification of each of the resonances. For this purpose it was only necessary to have gas samples of a few hundred cm^3 in size and with isotope abundances changed by a factor of two or so. The thermal diffusion method, using hot-wire columns, is the preferred way to accomplish such isotope enrichments in these gases.

A difficulty to be overcome was the concentration of these gases into suitable holders that would go into the small, precisely limited, target area traversed by the collimated neutron beam in the Brookhaven fast chopper entrance stator. This was accomplished by freezing the gas within the proper pressure-temperature range into especially designed Armco iron holders to give sample thicknesses of about 3.3 g/cm^2.

PRODUCTION OF THE ENRICHED XENON AND KRYPTON SAMPLES

The thermal diffusion apparatus consisted of four, hot-wire, glass columns, each three meters in length, the

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[1] S. P. Harris, Phys. Rev. 89, 904(A) (1953).

[2] S. J. Cocking, J. Nuclear Energy 6, 113 (1957).

interconnections being a single capillary of 1.5 mm i.d. from the top of each column to the bottom of the one next in line. The glass columns were 9 mm i.d., each surrounded by a water jacket and carrying a tungsten wire heated to 1500°K well-centered along the axis of the column. The end volumes were each a 200 cm^3 cylindrical flask wrapped with a nichrome-wire heater. A timing mechanism supplied electrical power to these two heaters alternately for a five-minute period so that about 30 cm^3 of gas was continuously "rocked" back and forth through the system by the driving pressure from the expansion of the gas in the heated flask. Our experience with this "gasschaukel" method of operation first used by Clusius and Buhler[3] is good, and we therefore recommend it rather than the scheme of interconnecting columns with pairs of larger-bore convective couplers.

Using xenon, the optimum gas pressure was found empirically to be 40 cm of Hg. With the column wires cold, this pressure dropped to about $\frac{1}{3}$ atmos, and hence each 200 cm^3 end reservoir contained about 60 cm^3 of gas NTP. At or near equilibrium (7 to 10 days) we extracted the contents of both reservoirs and also the gas in the columns, recharged the system with normal xenon gas, and repeated the cycle. Several hundred cm^3 of both "light" and "heavy" xenon were so produced. A typical analysis of this product as used for the neutron cross-section measurements is given in Table I.

A sufficient amount of "light" krypton analyzing better than 50% Kr^{80} to fill two of the target holders described below to a pressure of about 2000 lb/in.^{2} was available at Yale from the earlier thermal diffusion concentrations produced by Blais and Watson.[4] The important single odd isotope Kr^{83} was reduced in this sample from its normal abundance of 11.5% to less than 1%. Reference 4 should be consulted for details of the batch-wise recycling procedure that effected this excellent concentration of the light krypton isotopes.

GAS TARGET HOLDERS

The two sample-container regions in the BNL fast chopper are just 0.385 in.±0.001 in. wide by $2\frac{1}{2}$ in. high (maximum) by 1 in. (maximum) in the neutron beam direction. This is more than enough to accomodate target samples in powder form or of metal foil, but never before the present work had gas samples been concentrated into holders in these tiny spaces. It was clear from the start that to obtain xenon or krypton targets of maximum thickness, consistent with the amount of separated material available, pressures of about 100 atmos would be necessary. Only pure aluminum or pure iron could be used to contain the gas, then, for only these of all structural materials could both provide the requisite strength and also have low constant neutron cross section in the energy range of interest. After our first model of aluminum ruptured on test at 1000 psi we adopted Armco iron for fabrication of the holders. Iron has a total neutron cross section nine times greater than that of Al, but still the transmission of one such holder is 65% for the $\frac{3}{32}$ in. thickness in the beam direction.

TABLE I. Equilibrium concentrations in percent of the xenon isotopes from operation of 12 meters of thermal diffusion columns.

Isotope	Normal Xe	"Light" end	"Heavy" end	Light/Heavy ratio
124	0.094	0.55	<0.008	>700
126	0.092	0.49	<0.004	>60
128	1.92	5.13	0.20	25.7
129	26.4	57.2	6.07	9.41
130	4.1	6.0	1.46	4.11
131	21.2	19.3	14.8	1.30
132	26.9	13.5	29.1	0.462
134	10.4	1.7	21.6	0.078
136	8.9	0.20	27.2	0.008

Target holders of Armco iron were completely successful. The construction was accomplished by starting with a block 0.385 in.×1 in.×$2\frac{1}{4}$ in., milling into the 1 in.×$2\frac{1}{4}$ in. face to form a cavity deep enough so that by proper insertion of a shaped plug a volume of thickness 0.040 in. was left. The maximum width of the neutron beam at the target position is 0.030 in. The plug was Heliarc-welded into position, and a filling line in the form of a Cu capillary tube of 0.024 in. i.d. was attached. Ten of these were fabricated, pressure tested at 2200 psi, and x-rayed for detection of any residual internal imperfections. All the holders seemed to be sound and regular.

From the recent *PV vs P* measurements by Michels one calculates that at 130 atmos the density of xenon is 1.94 g/cm^3, which means for our chamber volume of 0.590 cm^3 about 1.14 g of gas or about 200 cm^3 NTP. Thus about 400 cm^3 of each enriched sample was needed to fill two holders. When one of the holders was immersed in liquid nitrogen, however, it was found to be impossible to deposit more than 30 to 40 cm^3 of xenon gas into the chamber, probably because the small thermal conductivity of the layer of solid xenon prevented further freezing, with the heat leaking down the Cu capillary balancing the evaporation from the frozen film. Liquefying, not freezing, the gas into the chamber was then the indicated procedure, and construction of a phase diagram for xenon showed that at about 2 atmos the temperature range for the liquid region is from about −111°C to −96°C. After some practice with ordinary xenon it was found possible by alternately cooling the chamber and then warming the filling line with a flame to condense the desired amount of gas into a holder. The chamber was then immersed completely into the liquid nitrogen to solidify the xenon, the Cu capillary was pressure-welded, and the cut end of the tubing was quickly dipped into molten solder as a precautionary measure.

Weighing the holders both before and after com-

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[3] K. Clusius and H. H. Buhler, Z. Naturforsch. **9a**, 775 (1954).

[4] N. C. Blais and W. W. Watson, Phys. Rev. **104**, 202 (1956).

TABLE II. Composition of krypton samples, in percent.

	Normal krypton $n=0.00912\times10^{24}$ atmos/cm^2	Light enrichment 0.0102×10^{24} atmos/cm^2	Intermediate enrichment 0.00924×10^{24} atmos/cm^2
78	0.35%	29.5%	0.13%
80	2.27	62.1	3.30
82	11.6	7.88	23.0
83	11.4	0.50	15.5
84	56	0.14	52.2
86	17.2	<0.05	6.15

pletely filling them with water indicated a ±5% variation in volume around the design value of 0.590 cm^3. This is the dominant error since for the six holders filled with xenon (two each of heavy, light, and normal gas) the measured gas deposited in each chamber was 185±1 cm^3. The target thickness in each case, then, was 3.3 g/cm^2±5%.

By a similar procedure six target holders were filled with krypton, giving target thicknesses of 1.4 g/cm^2, or about $0.01\times10^{+24}$ atoms/cm^2. Two of these krypton target holders contained the gas highly enriched in the light Kr isotopes, two were filled with krypton somewhat enriched in Kr^{83}, and the remaining two with normal krypton.

NEUTRON TRANSMISSION OF KRYPTON AND XENON

The samples of krypton and xenon gas, prepared according to the above descrption, were examined with the Brookhaven fast-chopper facility. Neutron transmissions were measured in the energy region from about 10 ev to about 1 kev, for the various isotopic mixtures prepared by the Yale hot-wire thermal diffusion apparatus.

The neutron velocity spectrometer consists of the BNL fast chopper[5] operating with a 20-meter flight path. The data are timed and recorded with the aid of a 1024 channel time delay analyzer utilizing an electrostatic memory storage system, designed by M. Graham at Brookhaven National Laboratory. A bank consisting of 128 BF$_3$ counters in a common BF$_3$ atmosphere is used for neutron detection. The chopper is thoroughly described in reference 5. At the maximum rotational speed, 10 000 rpm, a resolution of 0.07 μsec/meter is realized with the 20-meter flight path.

With the gas sample inserted into the sample carrier in the chopper entrance stator, the neutron spectrum as recorded by the detector and time analyzer was observed and compared to the spectrum observed with a similar, but empty, holder in position. The transmission thus obtained, after a small (5 to 10%) background correction, was accurate to about 2% per 0.5-μsec channel, excluding normalization errors due to possible differences between the dummy and actual gas sample holders.

The dips observed in the transmission, when plotted as a function of neutron energy, are indications of the excitation of compound nuclear states in the target nucleus plus neutron. The Breit-Wigner, Doppler-broadened, single-level formula is assumed to describe exactly the energy variation of the cross section over these resonance dips,

$$\sigma_T(E)=4\pi\lambda\!\!\!^{-}{}_0{}^2g\left|\frac{\Gamma_n}{(E-E_0)+i\Gamma/2}+\frac{R'}{\lambda\!\!\!^{-}{}_0}\right|^2+4\pi(1-g)R'^2$$

$$+\pi\lambda\!\!\!^{-}{}_0{}^2g\left(\frac{E_0}{E}\right)^{\frac{1}{2}}\left(\frac{\Gamma_n\Gamma_\gamma}{(E-E_0)^2+(\Gamma/2)^2}\right),$$

$$\sigma_\Delta(E)=\frac{1}{\Delta\pi^{\frac{1}{2}}}\int_0^\infty\sigma_T(E')\exp\left[-\left(\frac{E'-E}{\Delta}\right)^2\right]dE',$$

where the notation is the same as in reference 5. The method of analysis most suitable for the resonances observed in krypton and xenon with the resolution available is the so-called "area" analysis as developed by Hughes and his co-workers[6,7] in which the area under a transmission dip,

$$A=\int_{-\infty}^{\infty}\{1-\exp[-n\sigma_\Delta(E)]\}dE,$$

is related to some combination of the widths Γ_n and Γ: For details of the application of the "area" technique references 6 and 7 may be consulted. Here it is sufficient to note that in the limiting cases of thin ($n\sigma_0\ll1$) and thick ($n\sigma_0\gg1$) samples, the transmission dip area is proportional to $g\Gamma_n$ and $(g\Gamma_n\Gamma)^{\frac{1}{2}}$, respectively. In practical analysis no sample completely approaches these asymptotic limits, and graphs giving transmission area as a function of sample thickness for various values of Γ are employed as described in references 6 and 7. In many cases a knowledge of the radiation width Γ_γ, as

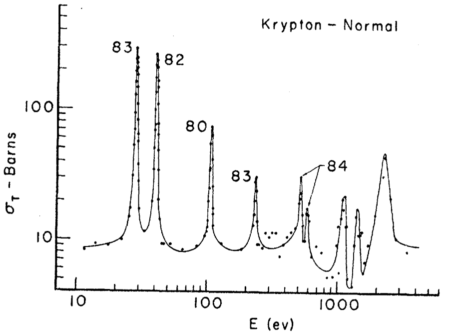

FIG. 1. Total neutron cross section of normal krypton with isotopic identification of the resonance peaks. These cross sections are uncorrected for resolution, Doppler effects, or isotopic abundances.

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[5] F. G. P. Seidl *et al.*, Phys. Rev. **95**, 476 (1954).

[6] D. J. Hughes, J. Nuclear Energy **1**, 237 (1955).

[7] Pilcher, Harvey, and Hughes, Phys. Rev. **103**, 1342 (1956).

measured by other experiments, allows a determination of $g\Gamma_n$ for intermediate and thick samples.

KRYPTON

The total neutron cross sections of normal krypton gas had been previously measured by Cocking,[2] who observed three resonances below about 100 ev without being able to make isotopic identifications. Three samples of krypton were available for examination. Table II specifies the composition and thickness of these samples.

Figure 1 shows the observed sample cross sections for normal krypton, uncorrected for resolution or Doppler effects or isotopic abundances. They are obtained directly from transmission measurements by the relation

$$\sigma = -(1/n)\ln T.$$

The other two enrichments give similar plots except that the resonance peaks are enchanced or diminished. Because of the relative thinness of the sample, a normalization error of ±3 barns must be assigned to the cross sections of Fig. 1. From the known chopper resolution and the observed level spacing at low energies for krypton (~30 ev), it may be calculated that resonant structure observed above about 600 ev results most likely from the effects of several levels. Resonance analysis was therefore not extended above that energy.

Table III lists the energies, isotopic identification, and resonance parameters for the levels seen in krypton. The 640-ev level could not be definitely assigned to a single isotope, and so two possibilities are listed in the table.

For the 27.9-ev level in Kr^{83} and the 106-ev level in Kr^{80}, the sample thicknesses were sufficiently dissimilar to permit a determination of Γ by a comparison of the thin sample area (proportional to $g\Gamma_n$) and thick sample area [proportional to $(g\Gamma_n\Gamma)^{\frac{1}{2}}$]. From Γ, and the assumption $g=\frac{1}{2}$, Γ_γ, the radiation width, is determined from

$$\Gamma_\gamma \cong \Gamma - 2g\Gamma_n.$$

The results, 220±60 millielectron volts for Kr^{83} and 400±90 millielectron volts for Kr^{80}, can be compared to the predictions of Cameron[8] who devised a formula for radiation widths based on a modified level spacing formula due to Newton. The predictions of this formula are 220 millielectron volts for Kr^{83} and 200 for Kr^{80}.

TABLE III. Resonance parameters of krypton. Where Γ_γ is given in parentheses, it has been assumed, not measured. The reduced neutron width, $\Gamma_n{}^0$ is the neutron width evaluated at 1 ev. $\Gamma_n{}^0=\Gamma_n/(E_0)^{\frac{1}{2}}$.

E_0 (ev)	Target isotope	Γ_n (millielectron volts)	$\Gamma_n{}^0$ (millielectron volts)	Γ_γ (millielectron volts)
27.9±0.3	83	67±10	13±2	220±60
39.8±0.5	82	88±12	14±2	(200)
106±2	80	336±30	33±3	400±90
233±6	83	290±40	19±3	(200)
519±20	84	345±70	15±3	(200)
580±20	84	87±20	3.6±0.8	(200)
640±25	78	1500±300	59±12	(200)
	80	1000±200	40±8	

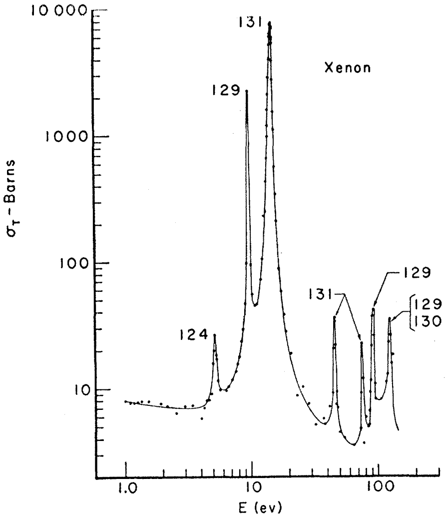

FIG. 2. Total neutron cross section for normal xenon, with isotopic identification of the resonance peaks. The points are uncorrected for resolution or Doppler broadening.

Another parameter of interest is the neutron strength function, $\langle\Gamma_n{}^0\rangle/D$, a measure of the probability of compound nucleus formation. The strength function is obtained from the ratio of the reduced neutron width to the level spacing per spin state.

This ratio is predictable from the "cloudy crystal ball" calculations of Feshbach, Porter, and Weisskopf,[9] and those of Chase, Wilets, and Edmonds.[10] In krypton there is a paucity of levels in the energy range available to chopper measurements, and so one calculates $\langle\Gamma_n{}^0\rangle/D$ averaged over all isotopes and spin states. From the seven levels analyzed up to 600 electron volts, a value for $\langle\Gamma_n{}^0\rangle/D$ of $(0.21\pm0.10)\times10^{-4}$ is obtained. This is somewhat lower than theory would predict in this range of nuclear masses. It would be desirable to extend resonance analysis to higher energies to improve the statistical accuracy of the above result, but present resolution does not permit this extension at Brookhaven.

XENON

The only previously published work on xenon is that of Harris[1] who reported the existence of prominent levels at 9 and 14 electron volts, observed with a resolution of 1.0 μsec/meter. Samples of xenon gas of 3.3 grams/cm² or 0.016×10^{-24} atoms/cm² thickness were examined by us. The isotopic enrichments for these samples are described in Table I. In addition to these three samples, a fourth sample of normal xenon, of thickness 0.056 gram/cm² or $0.00026\times10^{+24}$ atoms/cm², was run for the purpose of examining the very large level at 14.1 ev in

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[8] A. G. W. Cameron, Can. J. Phys. **35**, 1021 (1957).

[9] Feshbach, Porter, and Weisskopf, Phys. Rev. **96**, 448 (1954).

[10] Chase, Wilets, and Edmonds, Phys. Rev. **110**, 1080 (1958).

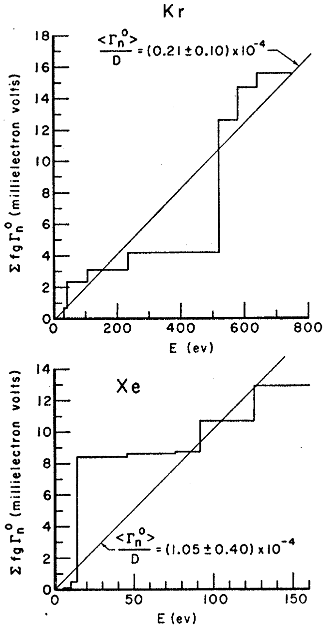

FIG. 3. Strength function determinations for krypton and xenon.

Xe^{131}. This level exhibited an observed peak cross section of 40 000±2000 barns, after correction for isotopic abundance, a rather large value at this energy.

Figure 2 shows the uncorrected, observed, cross section in normal xenon as a function of energy. Because of the more dense level structure of xenon relative to krypton, it was decided to limit resonance analysis to levels appearing below 200 ev. The two prominent resonances seen by Harris appear, as well as 5 others below 200 ev.

Table IV lists the resonance parameters of the xenon levels up to 130 ev. The 126-ev level could not definitely be assigned to a single isotope, and two possibilities are listed in the table. For the resonance analysis in xenon, a radiation width of 90±20 millielectron volts is assumed. This value was obtained from a study of the 0.082-ev level in Xe^{135}.[11]

From these parameters a plot of the cumulative sum $\sum fg\Gamma_n{}^0$, where f is the isotopic abundance fraction in normal xenon, *vs* energy can be made. The slope of this staircase plot gives the strength function, averaged over isotopes and spin states, directly. Figure 3 shows these plots for both krypton and zenon. From this plot $\langle\Gamma_n{}^0\rangle/D$ for xenon is $(1.05\pm0.40)\times10^{-4}$, obtained from seven levels. This value is slightly lower than the predictions of Chase, Wilets, and Edmonds for this region of mass number.

The small number of levels investigated in krypton and xenon indicate the advisability of extending the analysis of resonances to higher energies through the use of higher resolving power, such as would be available with a longer neutron flight path. The increase in the number of levels would greatly increase the statistical accuracy of $\langle\Gamma_n{}^0\rangle/D$ quoted for xenon and krypton.

TABLE IV. Resonance parameters of xenon. A radiation width of 90±20 millielectron volts is assumed.

E_0 (ev)	Isotope	Γ_n (10^{-3} ev)	$\Gamma_n{}^0$ (10^{-3} ev)
5.16±0.06	124	7.6±0.8	3.3±0.3
9.47±0.20	129	11.0±1.0	3.6±0.4
14.1±0.4	131	280±40	75±11
46.0±0.7	131	13±3	2.0±0.5
76.0±1.0	131	9.3±2.8	1.1±0.3
92.0±1.5	129	140±40	15±4
126±3	129	190±60	35±11
	130	400±100	17±5

ACKNOWLEDGMENTS

The authors are grateful to Mrs. Jean Domish, and to Miss Barbara Kane, who performed much of the computational work involved in the neutron resonance analysis.

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[11] Unpublished data from Oak Ridge National Laboratory as quoted in *Neutron Cross Sections*, compiled by D. J. Hughes and R. Schwartz, Brookhaven National Laboratory Report BNL-325 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1958), second edition.