tions of silver with 3- and 29-GeV protons indicated that the cross sections for the formation of light-mass products were as much as a factor of 2 higher at 29 GeV, while those for the formation of products in the $A = 70-90$ region were some 20% lower than at 3 GeV. These results showed that reactions which require very high excitation become somewhat more probable at 29 GeV, at the expense of reactions involving more moderate excitation. Evidently, this trend does not continue between 10–30 and 300 GeV, and the excitation energy spectrum for a silver target reaches a point of saturation at bombarding energies of 10–30 GeV.

Although our overall impression is that the interaction of high-energy protons with silver changes very little between 10–30 and 300 GeV, it is well to remember that activation cross sections do not provide a complete picture of this interaction. A more definite conclusion must await the results of recoil studies, energy spectra, and other measurements.

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Subthreshold Fission Induced by Neutrons on ^{238}U†

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Subthreshold fission is observed in ^{238}U(n,f) at 0.720, 1.210, 2.5, 7.5, 11, 15, 27, and 35 keV. Fission widths are obtained for the resonances at 720 and 1210 eV. The average fission cross section is 87 ± 26 μb for $10 \leq E_n \leq 30$ keV and 40 ± 12 μb for $30 \leq E_n \leq 100$ keV. The second potential minimum is deduced to lie ≈ 2.2 MeV above the first minimum.

A recent lead slowing-down spectrometer measurement of neutron-induced fission in a ^{238}U fission chamber indicated a large fission component near 800 eV, whereas no effect was observed in a blank chamber of identical construction. One plausible interpretation of this measurement was subthreshold fission in ^{238}U, although measurements by Silbert and Bergen[1] seemed to indicate that ^{238}U would have too small a fission cross section in this energy region to account for the large fission counting rate. In order to test for subthreshold fission in ^{238}U, it was decided to carry out a high-resolution time-of-flight beam experiment and see if the large fission component near 800 eV could be resolved into the fine structure characteristic of ^{238}U resonances in the first potential well.

The experiment was conducted at the Rensselaer LINAC laboratory with a 10.1-m flight path, the standard 2.54-cm-thick CH_2 moderator geometry,[2] an accelerator electron pulse width of 66 nsec, a repetition rate of 550 pulses/sec, and an electron beam power of 9 kW. Five fission ionization chambers, each 2.54 cm diam by 12.5 cm long, were coated with a total of 0.66 g of ^{238}U. The only significant impurity in the ^{238}U was 27 ± 6 ppm of ^{235}U, with less than 0.3 ppm of ^{233}U, ^{234}U, and ^{236}U. The ionization chambers were shielded with 0.75-mm-thick Cd, and a 0.75-mm-thick Cd overlap filter was placed in the beam at approximately 5 m; this resulted in a very low-background experiment with the counting rate below the ~0.5-eV Cd cutoff being less than 1% of that observed above the cutoff. The data were collected over the energy range from 0.2 eV to over 100 keV.

An auxiliary measurement was also carried out with a ^{235}U (93% enriched) fission chamber in the same geometry to normalize the ^{238}U subthreshold fission cross section to the known ^{235}U fission cross section.

In this measurement the following were observed: (1) distinct fission resonances below ~60 eV which correspond to ^{235}U resonances, (2) a smoothly varying fission rate above ~100 eV attributed to ^{235}U fission, and (3) several prominent clusters of fission resonances attributed to subthreshold fission in ^{238}U. Two strong clusters were observed near 720 and 1210 eV and weaker groups were observed near 2.5, 7.5, 11, 15, 27, and 35 keV. The data near the two strong clusters are shown in the upper half of Fig. 1 as counts (per channel) versus neutron time of flight, and the higher energy data are

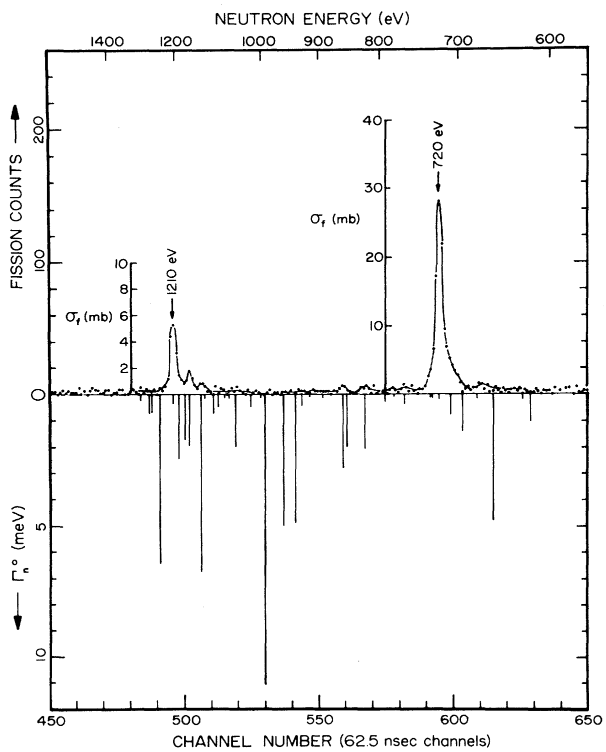

FIG. 1. Neutron-induced ^{238}U fission in the 600- to 1200-eV region. The upper curve is the ^{238}U fission chamber counts versus time-of-flight channel. The lines in the lower half of this figure represent the positions (in channels) and the reduced neutron widths of the ^{238}U resonances obtained from Ref. 3.

shown in Fig. 2. Also plotted in the lower half of Fig. 1 are the positions and reduced neutron widths (strengths) of the neutron-induced resonances observed in ^{238}U.[3] The contribution from ^{235}U fission in Fig. 1 is only ~1.5 counts per channel, about 1% of the counts at the 720-eV peak. The resolution in this experiment varies from 7.5 eV [full width at half-maximum (FWHM)] near the 700-eV region to about 14 eV (FWHM) near 1200 eV.

The results in Fig. 1 show two characteristic groups of fission resonances, with the fine structure occurring at the same position as the ^{238}U resonances. This is interpreted via the Strutinsky model[4] as subthreshold fission with the fine structure corresponding to levels in the first well and the gross structure to levels in the secone well. The average spacing of the groups in the second well, based on the observation of three fission clusters in the first ≈3000 eV, is $D_{\rm II} = 1000 \pm 400$ eV, compared to a spacing of $D_{\rm I}$ of about 14 eV in the first well. The level spacing $D_{\rm II}$ corresponds to an excitation energy of about 2.6 MeV, implying that the second minimum discussed by Strutinsky[4] and Lynn[5] lies about 2.2 MeV above the first minimum in the double-humped potential barrier. It is interesting to note in Fig. 1 that the fission strengths appear anticorrelated to the neutron strengths; i.e., when Γ_n^0 is small the fission peak is large. This anticorrelation behavior has been observed in subthreshold fission in other nuclei[6,7] and is predicted by Lynn.[5,8]

The ^{238}U fission cross section is deduced from this experiment by normalizing to the fission occurring in the 27 ± 6 ppm of ^{235}U in the fission chamber. For a thin sample (such as for this measurement), the ratio of the observed ^{238}U to

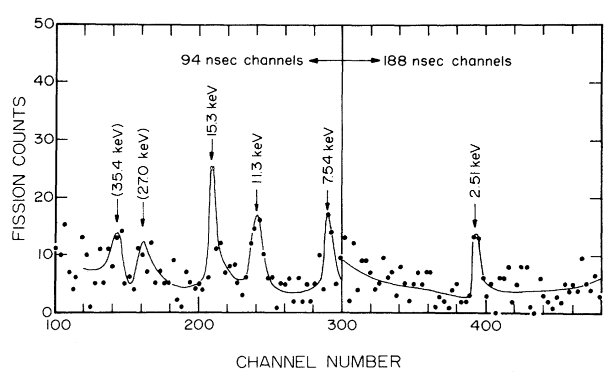

FIG. 2. Neutron-induced ^{238}U fission from approximately 1.5 to 40 keV.

TABLE I. ^{238}U fission parameters.

E_0 (eV)	A_f^G (b eV)	A_f (b eV)	Γ_n (meV)	Γ_f (meV) [$\Gamma_\gamma = 23$ meV]	Γ_f (meV) [$\Gamma_\gamma = 4.9$ meV]
720	0.45 ± 0.12	0.31 ± 0.08	1.2[a]	1.2 ± 0.3	0.29 ± 0.07
1210	0.19 ± 0.05	0.11 ± 0.03	9.0[a]	0.12 ± 0.03	0.051 ± 0.013

[a]Ref. 3.

^{235}U fission counts is

$$C_8/C_5 = N_8\sigma_8/N_5\sigma_5, \tag{1}$$

where C is the number of fission counts in a time-of-flight channel, N is the sample thickness, σ is the fission cross section at the neutron energy corresponding to the time-of-flight channel, and the subscripts 8 and 5 refer to ^{238}U and ^{235}U, respectively. In comparing the ^{235}U fission counts in the (27 ± 6)-ppm chamber with the enriched ^{235}U chamber, Eq. (2) results in

$$C_5/A_5 = C_5'/A_5', \tag{2}$$

where A is the integrated number of counts over the low energy ^{235}U fission resonances (taken from 8 to 40 eV) and the primed quantities refer to the enriched ^{235}U chamber. Combining Eqs. (1) and (2), and solving for the ^{238}U fission cross section, results in

$$\sigma_8 = \frac{N_5}{N_8}\frac{C_8}{C_5'}\frac{A_5'}{A_5}\sigma_5. \tag{3}$$

The ratio N_5/N_8 is taken as $(27 \pm 6) \times 10^{-6}$, and σ_5 was taken from the recent work of Perez *et al.*[9] The two fission cross-section scales shown in Fig. 1 were determined from Eq. (3) and they represent the cross section in the vicinity of the peaks.

The data in Fig. 1 have been analyzed for fission parameters, and the results are listed in Table I. In column 1 is listed the energy of the most prominent resonance in each subthreshold fission group. In column 2 are listed the group fission areas A_f^G obtained by integrating the fission cross section over all the resonances comprising the subthreshold group. Column 3 lists the fission area A_f for the prominent resonance in each fission group. Columns 4 and 5 list the neutron and radiative widths taken from Ref. 3. The fission widths of the 720- and 1210-eV resonances can be obtained from the data listed in Table I from the following expression for the fission area:

$$A_f = \int \sigma_f \, dE = \tfrac{1}{2}\pi\sigma_0\Gamma_f = 2\pi^2\lambda\!\!\!^{-}{}_0^2 g\Gamma_n\Gamma_f/(\Gamma_n + \Gamma_f + \Gamma_\gamma), \tag{4}$$

where the thin-sample approximation is used for the integration of a Breit-Wigner single-level resonance, σ_0 is the peak total cross section at resonance, $\lambda\!\!\!^{-}{}_0$ is the reduced neutron wavelength at the resonance energy E_0, and Γ_n, Γ_f, and Γ_γ are the neutron, fission, and radiation widths, respectively.

There exists some confusion about what value of Γ_γ should be used in Eq. (4). The average Γ_γ for the low-energy s-wave resonances in ^{238}U is 23 meV,[3] and if this value is used in Eq. (4), we obtain the fission widths listed in column 5 of Table I. This 23 meV represents the radiation width in well I of the double-humped fission barrier. On the other hand, it may be argued that the strong fission resonances at 720 and 1210 eV are almost pure class II levels[5,8] and that the radiation width for a level in well II should be used in Eq. (4).

The relationship between the radiation widths in wells I and II is given by Eq. (15) of Ref. 8 as

$$\frac{\Gamma_\gamma^{\rm I}}{\Gamma_\gamma^{\rm II}} \approx \left[\frac{E - \delta^{\rm I}}{E - \epsilon_0 - \delta^{\rm II}}\,\frac{a_{\rm II}^{1/2}}{a_{\rm I}^{1/2}}\right], \tag{5}$$

where E is the excitation energy above the bottom of the first well, a refers to the coefficient in the exponential level density formula, δ is the pairing energy gap, and ϵ_0 is the energy difference between wells I and II. Assuming $a_{\rm I} \approx a_{\rm II}$ and $\delta^{\rm I} \approx \delta^{\rm II} \approx 0.7$ MeV, and taking the value of $E_0 \approx 2.2$ MeV deduced from this experiment, and setting E equal to the binding energy of 4.78 MeV, the radiation width in well II is 4.9 meV. The fission widths based on this lower radiation width are listed in column 6 of Table I. Thus the fission widths range from a maximum value in column 5 assuming the class I radiation width to the minimum value in column 6 assuming the class II radiation width. The quoted error of about 25% in

TABLE II. ^{238}U average fission cross section.

Energy range (keV)	Average fission cross section This experiment (μb)	Ref. 1 (μb)
10–30	87 ± 26	61 ± 24
30–100	40 ± 12	36 ± 14

columns 5 and 6 results primarily from the uncertainty in the ^{235}U content of the ^{238}U fission chambers.

These results can be compared to the keV energy measurements of Silbert and Bergen[1] by summing the ^{238}U fission counts over the two neutron energy intervals $10 \leq E_n \leq 30$ keV and $30 \leq E_n \leq 100$ keV. Using Eq. (3) and the average σ_f values taken from data in Ref. 3 over these energy intervals, the average fission cross section for ^{238}U is obtained. These results are presented in Table II along with the results of Silbert and Bergen; within the experimental errors both measurements are in good agreement in this energy range. It is thus interesting that we agree with Silbert and Bergen in the average ^{238}U fission cross section, but that they did not report the observation of these fission clusters near 720 and 1210 eV.

In conclusion, this is the first observation (to our knowledge) of well-resolved and well-defined neutron-induced subthreshold fission in ^{238}U, and thus is a confirmation of the existence of a double-humped barrier in ^{239}U.

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(^{10}B, ^{7}Li) and (^{10}B, ^{7}Be) Analog Reactions on ^{12}C†

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The reactions ^{12}C(^{10}B, ^{7}Li)^{15}O and ^{12}C(^{10}B, ^{7}Be)^{15}N were investigated at 100 MeV incident energy. These analog reactions show almost identical features, as expected, because the incident energy is much higher than the Coulomb barriers. Therefore, these reactions represent a powerful reaction-mechanism–independent method of finding corresponding analog states in the residual nuclei. Furthermore, the data are consistent with the assumption that the processes are direct three-nucleon transfers populating high-spin states. We identify the states having two-particle, three-hole and three-particle, four-hole configurations coupled to high spins.

Despite the potential interest in and importance of heavy-ion–induced reactions, inherent difficulties involved in understanding their reaction mechanisms often hinder the extraction of quantitative structure information. In this Letter, it is demonstrated that analog states in mirror nuclei may be identified from the experimental results regardless of the reaction mechanism. It is also proposed that certain types of heavy-ion reactions are very powerful tools for obtaining structure information. The reactions ^{12}C(^{10}B, ^{7}Li)^{15}O and ^{12}C(^{10}B, ^{7}Be)^{15}N were studied to obtain such information. Several states in mass-15 systems were identified and their analog correspondence established. There are also indications that these reactions are direct three-nu-