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Chemically induced shifts of ²³⁵U and ²³⁴U neutron resonances

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<u>Abstract</u>:

Transmission spectra were measured with time-of-flight technique at the Dubna pulsed reactor for samples of metallic U, JO_2 , U_3O_8 , and UO_3 enriched in ²³⁵U, and were compared in the regions of nine low-energy resonances to observe chemically induced shifts. After elimination of contributions caused by different Doppler broadenings, the shifts are interpreted as changes of the mean-square charge radius for nuclei capturing neutrons. The $\langle r^2 \rangle$ of the compound nucleus states show on the average a weak diminution compared with the ground state value.

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1. Introduction

Neutron resonances of a nuclide inserted in different chemical compounds are very slightly shifted in dependence on the electric hyperfine interaction energy between the nucleus and the surrounding electrons. For two samples, I and II, the positions of a considered resonance differ approximatly by:

$$\Delta E_{o} = \frac{e^{2}}{6\epsilon_{o}} Z \Delta g_{e}(0) \Delta \langle r^{2} \rangle , \qquad (1)$$

with $\Delta g_e(0) = g_{eII}(0) - g_{eII}(0)$ being the difference of the electron densities in the nucleus region; Z is the proton number of the nucleus, and $\Delta \langle r^2 \rangle$ is the change of its mean-square charge radius due to neutron capture.

In ref.¹), the 6.67 eV resonance of ²³⁸U has been studied in several uranium compounds to search for this effect predicted by Ignatovich et al.²) in analogy to the Mössbauer isomer shift.

From the experimentally found resonance shifts, $\Delta \langle \mathbf{r}^2 \rangle$ has been derived using electron density differences at the nucleus determined from other experimental data on chemical X-ray shifts in uranium compounds and on Mössbauer isomer shifts in isovalent neptunium compounds, combined with computations in the frame of the free-ion model. The ground states of the nuclei are well investigated ($\langle \mathbf{r}^2 \rangle = 34 \text{ fm}^2$ for 238 U) so that with $\Delta \langle \mathbf{r}^2 \rangle$, the meansquare radius of the 239 U compound nucleus state could be estimated. Other experimental information on $\langle \mathbf{r}^2 \rangle$ at the relatively high excitation energy around the neutron binding energy is not available.

A theoretical approach to estimate $\langle r^2 \rangle$ has been performed by Bunatian ³) with a statistical model including strong particlehole and particle-particle interactions. He has found that in the actinide region at temperatures corresponding to the neutron binding energy, $\langle r^2 \rangle$ is diminished by the order of 0.1 fm² in comparison to its ground state value. In addition he has shown that the reduction is connected with the release of the pair correlation, whereas at higher nuclear temperatures, $\langle r^2 \rangle$ increases more and more as generally expected for higher excited fermion systems. This tendency of a diminution is in accordance with the experimental value found for ²³⁹U, but the amounts are different by one order of magnitude. However, the result of a statistical model represents the mean behaviour averaged over many compound nucleus states, and should not be compared with a single resonance value only.

To extend the measurements over more neighbouring states, 235 U is a suitable candidate with almost 10 low-energy resonances sufficiently separated. Moreover, samples enriched in 235 U contain often some 234 U which gives the advantage to study together with the resonances of the even-odd target nucleus an additional resonance of an even-even nucleus. Some of the 236 U compound nucleus states have large fission widths; at the others the gamma width is dominating, or both decay modes are in competition.

Unfortunately, the resonance shift values extracted from the measured spectra (ΔE_{exp}) are composed of two components - the wanted chemically induced shift (ΔE_o) , and a falsifying contribution arising from different Doppler broadenings in the compared polycrystalline

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samples. This requires a careful analysis of the differences in the resonance shapes. Applying the same method as used for the 6.67 eV resonance of 238U in several compounds ¹), the 235U resonances offer the possibility to vary by about one order the magnitude of parameters which determine the Doppler broadening substantially; namely the recoil energy and the total resonance width. In this sense, a consistent description of all observed differences is a proof of the used model too.

In the following, the experiment and the determination of $\Delta \Box_{exp}$ are described. After that, the different resonance shapes are analysed, followed by a compilation of results and their discussion.

2. Experiment

Transmission spectra were observed with the time-of-flight technique at the Dubna fast pulsed reactor IBR-30 operated in booster mode with the linac LUE-40⁴). With a flight path of about 60 m and a time resolution of 4 μ s, the energy resolution lay between 2 and 80 meV in the energy region of interest from 1 to 12 eV. The used samples of metallic U, UO₂, U₃O₈, and UO₃ were enriched in ²³⁵U to about 90 %. They had 0.48, 0.51, and 1.10 x 10²² nuclei ²³⁵U per cm². The UO₃ was produced from a portion of the UO₂. It showed the typical colour of the <u>of</u>-modification. During the measurements, the samples were at room temperature.

Searching for differences, two or three samples were measured quasisimultaneously by dividing the time of about 400 h necessary for sufficient statistical accuracy, in short-time runs of about five minutes with automatic sample alternation.

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The minicomputer operated spectrometer ¹) allowed also to inspect after each short-time run the obtained spectrum and data from a neutron-beam monitor, a timer, and a reactor-pulse counter. Only those spectra were accumulated, of which the experimental conditions were equal within a few per cent compared with the preceding runs. A tantalum foil of about 0.1 mm thickness was permanently placed in the neutron beam in addition to the uranium samples. The Ta resonances observed in the transmission spectra of the different uranium compounds, were analysed in the same way as the U resonances, so that they reveal all eventual shifts and other differences between the measured spectra, with the exception of those attributed to the uranium samples. A typical spectrum is shown in fig. 1.

3. Determination of the resonance shifts

As in the preceding paper, the spectra of two samples ($N_{I}(t)$, $N_{II}(t)$) measured in the same period are compared for given channel ranges (t_{i}, t_{j}) located symmetrically with respect to the resonance dips, with the aid of chi-square fits with variation of the resonance positions Δt_{exp} , A, and N_{B} in N_{II} relatively to N_{I} .

$$N_{II}(t) = A \left[N_{II}(t + \Delta t_{exp}) + N_{B} \right]$$
(2a)

minimizing

$$\chi^{2} = \sum_{t=t_{i}}^{t_{j}} \frac{\left[N_{I}(t) - N_{II}(t)\right]^{2}}{N_{I}(t) + N_{II}(t)}$$
(2b)

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The parameters A and N_B take into account any minor differences in the transmitted beam and background intensities, respectively. To eliminate contributions in Δt_{exp} arising from different resonance shapes caused first of all by different Doppler broadenings, a hypothetical pair of transmission spectra, $C_I(t)$ and $C_{II}(t)$, is defined having the same shape differences as N_I and N_{II} but without chemical resonance shift. Then, the fit of eqs. (2a and b) carried out with C_I and C_{II} , yields a shift Δt_{1v} which, together with Δt_{exp} , gives the wanted chemically induced energy shift;

$$\Delta E_{o} = -2.77 \times 10^{-2} E_{o}^{3/2} (\Delta t_{exp} - \Delta t_{lv}) / L, \qquad (3)$$

with the resonance energy E_0 and $\underline{\Delta}E_0$ in eV, the flight path L in m, and $\underline{\Delta}t$ in $\underline{\mu}s$. The spectra C_I and C_{II} are calculated with equal E_0 and with the conditions that, within the statistical uncertainties of N_I and N_{II} , hold:

$$C_{I}(t) = N_{I}(t), \qquad (4a)$$

and

$$N_{I}(t) - N_{II}(t) = C_{I}(t) - C_{II}(t).$$
 (4b)

The calculation of Doppler broadened resonance shapes will be dealt with in the next section.

4. Analysis of the different Doppler broadenings

The effective cross section $\underline{\sigma}_{LS}$ as a function of the neutron kinetic energy \underline{E}_n in the laboratory system is a convolution of the nuclear cross section $\underline{\sigma}$ with the function S, describing the energy exchange between the incident neutron and the crystal lattice vibrations of the sample atoms,

$$\widetilde{\mathbf{G}}_{\mathrm{LS}}(\mathbf{E}_{\mathrm{n}}) = \int S(\mathbf{E}_{\mathrm{t}}, \mathbf{E}_{\mathrm{n}}) \, \underline{\mathbf{6}}(\mathbf{E}_{\mathrm{n}} - \mathbf{E}_{\mathrm{t}}) \, \mathrm{d}\mathbf{E}_{\mathrm{t}} \, . \tag{5}$$

For the present purpose where differences between transmission spectra of the same nuclei inserted in different chemical compounds are analysed, the energy dependence of $\underline{6}$ may be formulated as a summation over Breit-Wigner terms $\underline{6}_{BW}$ of all resonances contributing in the considered range with inclusion of interference between potential and resonance scattering. Owing to the small resonance spacing and sometimes appreciable fission widths of ²³⁵U resonances, the interference between resonances must be taken into account too. As shown by Takano and Ishiguro ⁵), this may be done with an additional term $\underline{6}_{int}$. Finally, by adding the potential scattering $\underline{6}_{pot}$, the total (removal) cross section $\underline{6}$ can be written as:

$$\mathbf{G}(\mathbf{E}) = \sum_{j} (\mathbf{G}_{BW} + \mathbf{G}_{int})_{j} + \mathbf{G}_{pot}$$
(6a)

with

$$\underbrace{\mathbf{G}_{BW}(E)}_{(E)} = \frac{(\mathbf{T}\hbar^{2}/2m_{n}) g \Gamma_{n}/E_{0}^{1/2} (\Gamma - \Gamma_{n})/E^{1/2} + \Gamma_{n}/E_{0}^{1/2} + (4/\hbar)(2m_{n})^{1/2} R(E - E_{0})^{2}}{(E - E_{0})^{2} + 1/4(\Gamma)^{2}}$$
(6b)

$$\underline{\mathbf{\mathfrak{S}}_{int}}(E) = \frac{\underline{\mathbf{J}}\underline{\mathbf{h}}^{2}\underline{\mathbf{E}}}{2\underline{\mathbf{m}}_{n} E^{1/2}} \times \frac{\underline{\mathbf{u}} \ \underline{\Gamma} + \underline{\mathbf{v}}(\underline{\mathbf{E}} - \underline{\mathbf{E}}_{0})}{(\underline{\mathbf{E}} - \underline{\mathbf{E}}_{0})^{2} + \frac{1}{4} (\underline{\Gamma})^{2}}$$
(6c)

$$\underline{\mathfrak{G}}_{\text{pot}} = 4 \, \underline{\mathfrak{I}} \, \mathbb{R}^2 \tag{6d}$$

where \prod_n and \prod_r are the neutron and total widths, respectively, R is

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the potential scattering radius, m_n is the neutron mass, g is the statistical factor, and u and v are interference parameters. The energy transfer function S is expressed for the used polycrystalline samples in terms of the normalized distribution of the vibrational frequencies ⁶, ⁷). Taking into account the very different masses of the uranium and the ligand atoms, the normal-mode spectrum can be approximated by two terms ⁷),

$$\omega_{\rm U}(hv) = a_1 \, \delta(hv - hv_1) + a_2 \, \delta(hv - hv_2), \qquad (7a)$$

with

$$\mathbf{a}_1 + \mathbf{a}_2 = \mathbf{1}. \tag{75}$$

The index U at 49 indicates that the weighted spectrum must be used, not the total as observed for example in inelastic neutron scattering, because only the uranium atoms capture the considered resonance neutrons and excite vibration modes ⁸, ⁹).

To evaluate the three independent parameters of eqs. (7a and b), one has at hand the measured spectral differences $N_{I}(t) - N_{II}'(t)$, where metallic uranium with $a_2 = 0$ and $h\Psi_1 = 11 \text{ meV } ^7$) may be used as a reference. A more datailed description and illustrations of this approach to the interpretation of resonance shape differences are given in ref.¹). It has been shown too, that the amplitudes of the difference curve are mainly determined by the combination of the parameters to $\langle E \rangle_U$, the average energy per vibrational degree of freedom in the sample,

$$\langle \boldsymbol{\xi} \rangle_{U} = \frac{1}{2} \int h \boldsymbol{v} \, \boldsymbol{\omega}_{U}(h \boldsymbol{v}) \, \coth \, (h \boldsymbol{v}/2kT) \, d(h \boldsymbol{v}), \qquad (8)$$

whereas relatively crude approximations are sufficient for the independent parameters $(h\underline{v}_1, h\underline{v}_2, a_1)$.

So, hy may be estimated by fitting the specific heat data of the sample in the temperature region T 4 100 K where hyp - modes are practically not excited and assuming that all hy, vibrations are related to the uranium atoms. In the next step, the model differences, $C_T(t) - C_{TT}(t)$, are adjusted to the measured with variation of $\Delta \langle E \rangle_U = \langle E \rangle_{UI} - \langle E \rangle_{UII}$ and $\Delta h v_2 = h v_{2I} - h v_{2II}$. To test the reliability of the model, these fits are carried out for each resonance range, all measured sample combinations, and the several used sample thicknesses independently. The χ^2 -values of the 90 fits in consideration yielded a total of 100. The obtained hyp-values are plotted in fig. 2 versus the neutron resonance energy. The averages of hyperbolic sector $h_{\mathcal{D}}$ for the used samples are presented in table 1 together with the estimated hy, Finally, the $\Delta \langle \xi \rangle_{U}$ -values received with these vibration mode energies are shown in fig. 3 for the different resonances; the averages of $\langle \xi \rangle_U$ for the samples are included in table 1. Keeping in mind that the total widths of the considered resonances vary by a factor of about four, the recoil energies which also influence the Doppler broadening, increase by a factor of ten and the \prod_n which determine together with the sample thicknesses the part of the cross section differences displayed in the transmission spectra, differ by two orders of magnitude, the consistency of the obtained values for the model parameters seems to be sufficient. So far as available, comparisons with works of other authors on weighted frequency spectra calculated for UO_2 ¹⁰) and experimentally studied for U_30_8 ⁷), and on total phonon spectra measured by infrared spectroscopy ¹¹, ¹²) for all compounds, are qualitatively in accordance.

5. Results and discussion

The deduced values of ΔE_{exp} and ΔE_{lv} corresponding to Δt_{orp} and Δt_{lv} respectively, and the resulting chemical shifts ΔE_{o} are compiled in table 2 for all studied resonances and sample combinations. The errors include the statistical uncertainties of the measured spectra, the phonon spectra and resonance parameter uncortainties, and other quantities influencing the shifts (for example sample thickness differences).

The given ΔE_{exp} and ΔE_{lv} result from the largest analysed channel ranges around the resonances. In each case, they have been determined for three or four smaller ranges too. The obtained ΔE_o agree within the error intervals what is expected if the spectral differences are accurately described.

In principle, the resonance shifts may be affected also by hyperfine effects of higher multipolarity than the electric monopole interaction. The quadrupole interaction leads at 235 U to a sample dependent splitting of the levels. But an estimate reveals that the resonance centre of area is shifted not more than 1μ eV in any case, and the magnetic dipole splitting is symmetrical around the original state for unpolarized target and neutron beam. Thus, they may be neglected.

To determine the nuclear mean-square radius change $\Delta \langle r^2 \rangle$ from the chemical shifts ΔE_0 , the electron density differences $\Delta g_e(0)$ must be known. Values of $\Delta g_e(0)$ are evaluated in ref.¹) for all used compounds, with the exception of $U_3 O_8$. $U_3 O_8$ is assumed to be a mixed oxide consisting for 1/3 of the uranium in the valence state

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 4^+ and to 2/3 with oxidation number 6 ¹³). Under this assumption $\Delta g_e(0)$ of $U_3 O_8$ could be estimated. The obtained $\Delta g_e(0)$ values of the measured sample combinations are presented in table 3.

According to eq. (1), the next step is a plot for each resonance with all determined ΔE_0 values versus $\Delta g_e(0)$ followed by a chisquare fit of a straight line through this points and the origin. Taking into account the weak radius-dependence of $\Delta g_e(r)$ within the nucleus by a factor of 0.9¹), the line slope represents 0.9 $\Delta \langle r^2 \rangle$. The so obtained values of $\Delta \langle r^2 \rangle$ are given in table 4.

For comparisons with theoretical calculations on the change of the mean-square charge radius with the excitation for a particular nuclide n $\langle \underline{4} \langle \mathbf{r}^2 \rangle_n \rangle$, the experimental $\underline{4} \langle \mathbf{r}^2 \rangle$ must be reduced by the differences of the mean-square charge radius between the ground states of the neighbouring isotopes $\langle \underline{4} \langle \mathbf{r}^2 \rangle_i \rangle$. These have been deduced from optical isotope shifts ¹⁶) and amount to $(\pm 0.05 \pm 0.02)$ fm² when adding a neutron to ²³⁴U and $(\pm 0.10 \pm 0.03)$ fm² in the case of the ²³⁵U target nucleus. At first, the mean behaviour of $\langle \mathbf{r}^2 \rangle_n$ at excitations corresponding to the neutron binding energy should be regarded. The mean-square radius of the ²³⁶U ground state is about 33.8 fm² ¹⁶). The average of the eight values of table 4 for ²³⁶U compound nucleus states results in

$$\underline{\Delta \langle r^2 \rangle_n} = \underline{\Delta \langle r^2 \rangle} - \underline{\Delta \langle r^2 \rangle_i} = (-0.18 \pm 0.10) \text{ fm}^2,$$

in agreement with the statistical model predictions of Bunatian 3) in sign as well as in the order of magnitude. Also the fluctuation

of the mean-square radius between the resonance states j may be of interest, that is

$$\delta\langle \mathbf{r}^2 \rangle_n = \overline{\langle \langle \mathbf{r}^2 \rangle_j - \langle \mathbf{r}^2 \rangle \rangle^2}. \tag{9}$$

The dispersion of the experimental data compared with their statistical uncertainties (after elimination of systematical contributions to the given errors) yields a crude estimate of $\delta \langle r^2 \rangle_n = (+0.1 \ +0.2 \ -0.1) \ fm^2$.

A weak correlation of the mean-square radius change with the fission width seems to be apparent. For the 236U states with $\int_{f} \Delta \frac{1}{2} \int_{V} \left(\sqrt{s^{2}} 35 \text{ meV} \right)$ for example, the average is $\Delta \left\langle \frac{r^{2}}{nf\Delta} \right\rangle_{nf\Delta} =$ (-0.02 ± 0.12) fm² whereas for those with $\Gamma_{f} 4 \frac{1}{2} \sqrt{\Lambda (r^{2})_{mT}}$ is found to be (-0.38 \pm 0.14) fm². The quoted uncertainties include a systematical contribution of about 0.06 fm² in both cases. In principle such a tendency could be expected: The fission probability is higher if $\langle r^2 \rangle_n$ is larger. But in comparison to the $\langle r^2 \rangle_n$ change during the fission pictured as crossing of a double-humped barrier ¹⁷) where $\underline{A} \langle r^2 \rangle_n$ is at deformations corresponding to the second well, +4 to +5 fm² (assuming a rotational ellipsoid with $\beta \approx 0.6$ or using the data of ref.¹⁸)) and at the outer saddle point in the order of +10 fm², the deduced $\langle r^2 \rangle_n$ of the compound nucleus states are very close to the ground-state value. For even-even U targets bombarded with neutrons, intermediate structures are observed in the fission cross-section which are interpreted in terms of the double-humped fission barrier as coupling between the states of the two potential wells 15, 19-21)

where the class 2 configurations are very different from those

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of class 1 and are dominating in the fission channel. If for the higher excited and therefore stronger mixed ²³⁶U compound nucleus states the wave functions are partitioned in these groups of configurations, $\Upsilon = \alpha_1 \Upsilon_1 + \alpha_2 \Upsilon_2$, and the admixture $\alpha_2 \Upsilon_2$ would be determining for the fission probability, the difference between the $\Delta \langle r^2 \rangle_n$ - average of the resonances with $\Gamma_f \geq \frac{1}{2} \Gamma_r$ and that of the resonances with $\Gamma_f \leq \frac{1}{2} \Gamma_r$ results in

$$\underline{\Delta\langle \mathbf{r}^2\rangle_{\mathrm{nf}}} - \underline{\Delta\langle \mathbf{r}^2\rangle_{\mathrm{nf}}} \approx (\underline{\boldsymbol{\alpha}}_{\mathrm{2f}}^2 - \underline{\boldsymbol{\alpha}}_{\mathrm{2f}}^2) (\langle \mathbf{r}^2\rangle_2 - \langle \mathbf{r}^2\rangle_1), \qquad (10)$$

where mixed terms as $\langle \Psi_1 | r^2 | \Psi_2 \rangle$ are neglected. Using in relation (10) the mean-square radius difference between second and first well states of (5.1 ± 0.2) fm² as found for ²⁴⁰Am ¹⁸), the admixture difference may be estimated to be $\langle \chi_{2f_{\Delta}}^2 - \chi_{2f_{\Delta}}^2 \rangle \approx$ $\approx 0.07 \pm 0.04$.

The even-even target resonance states of 234 U and 238 U with energies lower than the fission barrier and therefore weaker coupling through the barrier reveal $\langle r^2 \rangle_n$ which are apparently smaller than the 236 U values (fig. 4).

A plot of the $\underline{\Delta} \langle r^2 \rangle_n$ of all studied ²³⁵U resonances versus $\ln \int_{\hat{r}}$ and approximated by a straight line is followed also by the two investigated ²³⁴U and ²³⁸U resonances.

Though the precision of the presented experimental data on $\langle r^2 \rangle_n$ is not sufficient for a detailed analysis, a weak dependence of the fission widths of the discussed compound nucleus states on their mean-square radii is suggested to be significant.

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Fig. 1: Experimental time-of-flight spectrum obtained with a sample thickness of 0.51 x 10^{22} nuclei 235 J per cm². The widths of the time channels t are 2 µs for t $\angle 256$ and 4 µs for t ≥ 256 , respectively.







Fig. 3: Differences of the averaged energy per U vibrational degree of freedom between the indicated samples obtained from fits of measured spectral differences, plotted versus the energies of the analysed resonances (T is the sample temperature, k the Boltzmann constant).



Fig. 4: Change of the mean-square charge radius of uranium isotopes between ground states and excited states near the neutron binding energy plotted versus the fission width of the resonances.

TABLE 1

Sample		h¥2 [meV]	$\frac{\langle \mathbf{E} \rangle_{U} / \mathbf{k} \cdot \mathbf{T}}{\text{at } \mathbf{T} = 293 \text{ K}}$
υ	11, <u>+</u> 2		1.016
U0 ₂	12 <u>+</u> 3	46 <u>+</u> 4	1.037 <u>+</u> 0.003
^U 3 ⁰ 8	10 <u>+</u> 3	45 <u>+</u> 4	1.051 <u>+</u> 0.003
UO3	10 <u>+</u> 3	69 <u>+</u> 5	1.066 <u>+</u> 0.003

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Parameter values for the weighted normal-mode vibration spectra

TABLE 2 Results for the resonance shifts

Resonance	Samp	les		$\underline{\mathbb{E}}_{lv_{-}}$	_ 120
·	I	II		[//eV]	
	UO3	U ₃ 08 ^{°E})	-146 <u>+</u> 31	-76 <u>+</u> 112	-70 <u>+</u> 116
5.2 eV	^U 308	v ^a)	-382 <u>+</u> 52	-346 <u>+</u> 81	-36 <u>+</u> 96
	υ ₃ 0 ₈	υο ₂ ^b)	-299 <u>+</u> 31	-254 <u>+</u> 41	-45 ± 51
234 _U	vo ₃	^{U0} 2	-239 <u>*</u> 33	- 81 <u>+</u> 93	- 158 <u>+</u> 99
	U03	υο ₂ ^b)	-441 <u>+</u> 30	-418 <u>+</u> 111	-23 <u>+</u> 115
1.1 eV	U	UO2	-42 <u>+</u> 36	- 55 <u>+</u> 26	13 <u>+</u> 44
	UO3	U ₃ 08 ^b)	- 398 <u>+</u> 34	- 404 <u>+</u> 59	6 <u>+</u> 63
235 _U	υ ₃ 08	υ ^a)	163 <u>+</u> 56	226 <u>+</u> 61	-63 <u>+</u> 83
	υ ₃ 08	uo ₂ b)	282 <u>+</u> 34	283 <u>+</u> 57	-1 <u>+</u> 66
	UO3	U0 ₂ ^b)	- 120 <u>+</u> 34	-121 <u>+</u> 44	1 <u>+</u> 56
	U	UO2	263 <u>+</u> 22	274 <u>+</u> 19	-11 <u>+</u> 29
2.0 eV	UO3	0 ₃ 0 ₈ 0 ₆ 0	-65 <u>+</u> 41	-7 5 <u>+</u> 77	10 <u>+</u> 87
	υ ₃ 0 ₈	u ^a)	-441 <u>+</u> 53	-338 <u>+</u> 70	-103 <u>+</u> 88
235 _U	^U 308	002 b)	-1 32 <u>+</u> 41	- 74 <u>+</u> 40	-53 <u>+</u> 58
	UO3	U	-462 <u>+</u> 36	- 472 <u>+</u> 68	10 <u>+</u> 77
	vo ₃	UO2	- 208 <u>+</u> 34	- 228 <u>+</u> 68	20 <u>+</u> 76
	UO3	00 ₂ °)	-197 <u>+</u> 41	-1 84 <u>+</u> 80	-13 ± 90
	U	UO2	112 <u>+</u> 53	135 <u>+</u> 68	-23 <u>+</u> 86
3.1 eV	^{UO} 3	U308 ^b)	-253 <u>+</u> 101	-195 <u>+</u> 193	-58 <u>+</u> 218
	υ ₃ 08	v ^a)	-89 <u>+</u> 166	313 <u>+</u> 154	-402 <u>+</u> 226
235 _U	υ ₃ 08	uo ₂ b)	81 <u>+</u> 103	-41 <u>+</u> 90	122 <u>+</u> 136
	vo ₃	υ	-250 <u>+</u> 75	- 113 <u>+</u> 132	-1 37 <u>+</u> 152
	UO3	UO2	-180 <u>+</u> 72	89 <u>+</u> 153	-2 69 <u>+</u> 169
	UO3	uo ₂ b)	-175 <u>+</u> 102	-237 <u>+</u> 250	62 <u>+</u> 270

Resonance	Samp	les			<u></u>
	I	II	[Lue V]	TueV	
	U	UO2	376 <u>+</u> 25	304 <u>+</u> 51	72 <u>÷</u> 57
4.8 eV	003	∪ ₃ 0 ₈ ^b)	-223 <u>+</u> 38	-203 <u>+</u> 87	- 20 <u>+</u> 94
	U308	υ ^a)	- 672 <u>+</u> 77	-453 <u>+</u> 109	-219 ± 133
235 _U	υ ₃ 0 ₈	υο ₂ ^b)	-1 31 <u>+</u> 37	-145 <u>+</u> 106	14 <u>+</u> 112
	JO3	U	-701 <u>+</u> 36	-514 <u>+</u> 74	-187 <u>+</u> 82
	Ψο ₃	UO2	-304 <u>+</u> 34	-1 66 <u>+</u> 49	-1 38 <u>+</u> 60
	UO3	υο ₂ ^b)	-357 <u>+</u> 37	-415 <u>+</u> 88	58 ± 95
- 	U	UO2	-201 <u>+</u> 102	52 <u>+</u> 340	- 253 <u>+</u> 355
8.8 eV	υο ₃	υ ₃ 08 ^b)	-1 60 <u>+</u> 49	-1 30 <u>+</u> 60	- 30 <u>+</u> 78
	U308	υ ^a)	370 <u>+</u> 101	1 92 <u>+</u> 67	178 <u>+</u> 122
235 ₀	U308	υο ₂ ου	245 <u>+</u> 48	258 <u>+</u> 42	-13 <u>+</u> 63
	UO3	U	774 <u>+</u> 89	456 <u>+</u> 209	318 <u>+</u> 227
	UO3	UO2	539 <u>+</u> 100	521 <u>+</u> 227	18 <u>÷</u> 248
	UO3	U0 ₂ b)	136 <u>+</u> 48	128 <u>+</u> 56	8 <u>÷</u> 74
	U	^{U0} 2	-414 <u>+</u> 54	-405 <u>+</u> 114	-9 <u>*</u> 126
1.7 eV	υο ₃	υ ₃ 08 ^b)	-75 <u>+</u> 59	7 ± 84	- 82 <u>+</u> 103
	U308	U ^a)	194 <u>+</u> 120	242 <u>+</u> 35	- 48 <u>+</u> 126
235 _U	υ ₃ 0 ₈	UO ₂ b)	96 <u>+</u> 57	92 <u>+</u> 30	4 🔬 64
	UO3	U	1513 <u>+</u> 77	1 454 <u>±</u> 194	59 <u>+</u> 209
	vo ₃	UO2	898 <u>+</u> 74	927 <u>+</u> 175	-29 <u>+</u> 190
	UO3	UO2 ^b)	21 <u>+</u> 57	139 <u>+</u> 94	-118 <u>+</u> 110
	U	UO2	-384 <u>+</u> 63	-513 <u>+</u> 126	129 <u>+</u> 141
12.4 eV	UO3	U ₃ 08 ^b)	420 <u>+</u> 60	313 <u>+</u> 74	1 07 <u>+</u> 96
	υ ₃ 0 ₈	v ^a)	311 <u>+</u> 123	288 <u>+</u> 88	23 <u>+</u> 151
235 _U	ບ _ວ 0 _ຂ	υο ₂ ^b)	163 + 58	133 + 92	30 + 109

TABLE 3

.

Electron density differences

Samp	les	$\Delta \mathbf{Q}_{e}^{(0)}$
·I	IT	$\begin{bmatrix} 10^{26} \text{ cm} -3 \end{bmatrix}$
U	UO2	2.8 <u>+</u> 2.5
vo ₃	U ₃ 08	3.1 <u>+</u> 1.2
^U 3 ⁰ 8	U	3.5 <u>+</u> 2.2
^U 308	UO2	6.3 <u>+</u> 1.6
UO3	U	6.6 <u>+</u> 3.0
uo ₃	UO2	9.4 <u>+</u> 2.0

111	57.5P	-21
سلاله معد −	يتبلغان	
-		

Target nuclide	Lev_	$\begin{bmatrix} \Gamma_{f} & 14 \\ meV \end{bmatrix}$	$\underline{\underline{A}} \langle r^2 \rangle$ [m^2]	$\frac{4}{\left[\frac{r^2}{m^2} \right]^n}$
234 _U	5.16	0.02 15) -0.41 <u>+</u> 0.25	-0.46 <u>+</u> 0.25
235 _U	1.14	107	+0.01 <u>+</u> 0.22	-0.09 <u>+</u> 0.22
235 _U	2.03	11	-0.13 <u>+</u> 0.21	-0.23 <u>+</u> 0.21
235 _U	3.15	103	+0.20 <u>+</u> 0.48	+0.10 <u>+</u> 0.48
235 _U	3.61	53	+0.02 <u>+</u> 0.25	-0. 08 <u>+</u> 0.25
235 _Ū	4.85	4	-0.52 <u>+</u> 0.25	-0.62 <u>+</u> 0.25
235 _U	8.77	98	+0.09 <u>+</u> 0.26	-0.01 <u>+</u> 0.26
235 _U	11.67	6	-0.24 <u>+</u> 0.29	-0. 34 <u>+</u> 0.29
235 _U	12.39	23	+0.25 <u>+</u> 0.31	+0.15 <u>+</u> 0.31

Results for the mean-square radius change