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Energies and Yields of Prompt Neutrons from Individual Fragments in the Fission of U^{233} + n.

In the last few years considerable interest has centered on the prompt neutrons emitted during the fission process. These measurements are important to the understanding of the fission process since the neutrons carry off about 70% of the total excitation energy.

An experiment to study the prompt neutrons from thermal neutron fissionable nuclei has been set up at the NRU reactor. The apparatus is illustrated in slide one. A beam of neutrons from the reactor travels normal to the slide thru the source of fissionable material. The beam is filtered thru 6" of Bi to remove γ's from the reactor and thru 8" of crystalline quartz to improve the ratio of thermal-to-fast-neutrons. Even so background due to fast neutrons is a serious problem and a liquid N_2 cooler is being installed for the quartz filter to increase the transmission of thermal neutrons without changing that for the fast neutrons.

Both fragments are timed over nearly equal 140 cm flight paths. All three fission detectors are of the secondary electron type. The passage of one of the fragmants thru the "start" detector gives the zero for all 3 timing measurements. The neutron flight path is 1 meter. All 3 flight times, together with a code specifying which of the 4 neutron counters was responsible for the quadrupbe coincidence are punched on 5 channel paper tape. The data are subsequently converted thru cards to magnetic tape and all further data processing done on

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a Bendix G-20 computer.

A complete time calibration on all counters will be done automatically every 16,000 events by a motor driven helical delay line with a range of 100 nsec. The time calibration is known to an absolute accuracy of better than 1%. The efficiency of the neutron detectors was measured by comparing the time-of-flight spectrum with the known energy spectrum of the U^{235} neutrons. For this purpose the fission fragment time-of-flight system was replaced by 2π solid angle gas scintaillation counter. The efficiency measurements were not made with high precision and must be repeated. Consequently the results presented today should be considered as a progress report.

All data so far have been taken using a U^{233} source. In one month of continuous operation 300,000 events were recorded, over half of which were background. Because of the two problems, background and neutron efficiency, most of what I will say today has been deduced from the 10^{o} data only. In that counter we observed 150,000 events, of which 42,000 were neutrons and 29,000 prompt γ rays. The normal spectrum (fragments only, no neutron coincidence required) contained 73,000 events.

An extensive series of data reduction programs have been tested on the G-20. There is of course a great wealth of information in experiments of this type and one of the problems is how to present yourself with this information in a form ready for assimilation. Generally speaking our philosophy has been to calculate the moments of the velocity spectrum as a function of the mass and energy of the fission fragments. In particular we have calculated the 0, 1, 2 and 4 moments in both the lab, and center-of-mass co-ordinate systems. I will have time for only one illustration of how these moments can be used. Let us look at the center-of-mass moments in Slide two. The lower curve shows the zeroeth moment, or the number of neutrons ν, as a function of fragment mass. The middle curve shows essentially the second moment, or the average energy η. The fourth moment is used in finding the statistical errors in η. The upper curve is the "normal" mass yield shown for orientation. It has been shown, at least for Cf^{252}, that the assumption of isotropic emission from the fully accelerated fragments, an assumption necessary for the interpretation of this figure, is sufficiently well fulfilled.

This is the first direct measurement of ν for U^{233} with high precision. It is in excellent agreement with the indirect determination made by Terrell from the comparison of prompt and final mass yields, even down to the flat portion in the light fragment which is less prominent in the heavy. Notice that ν drops to zero in the neighborhood of mass 80 and 130. This suggests that the expected mass resolution of 1.8 mass units FWHM, has been achieved. The figure has not been corrected for any instrumental resolution.

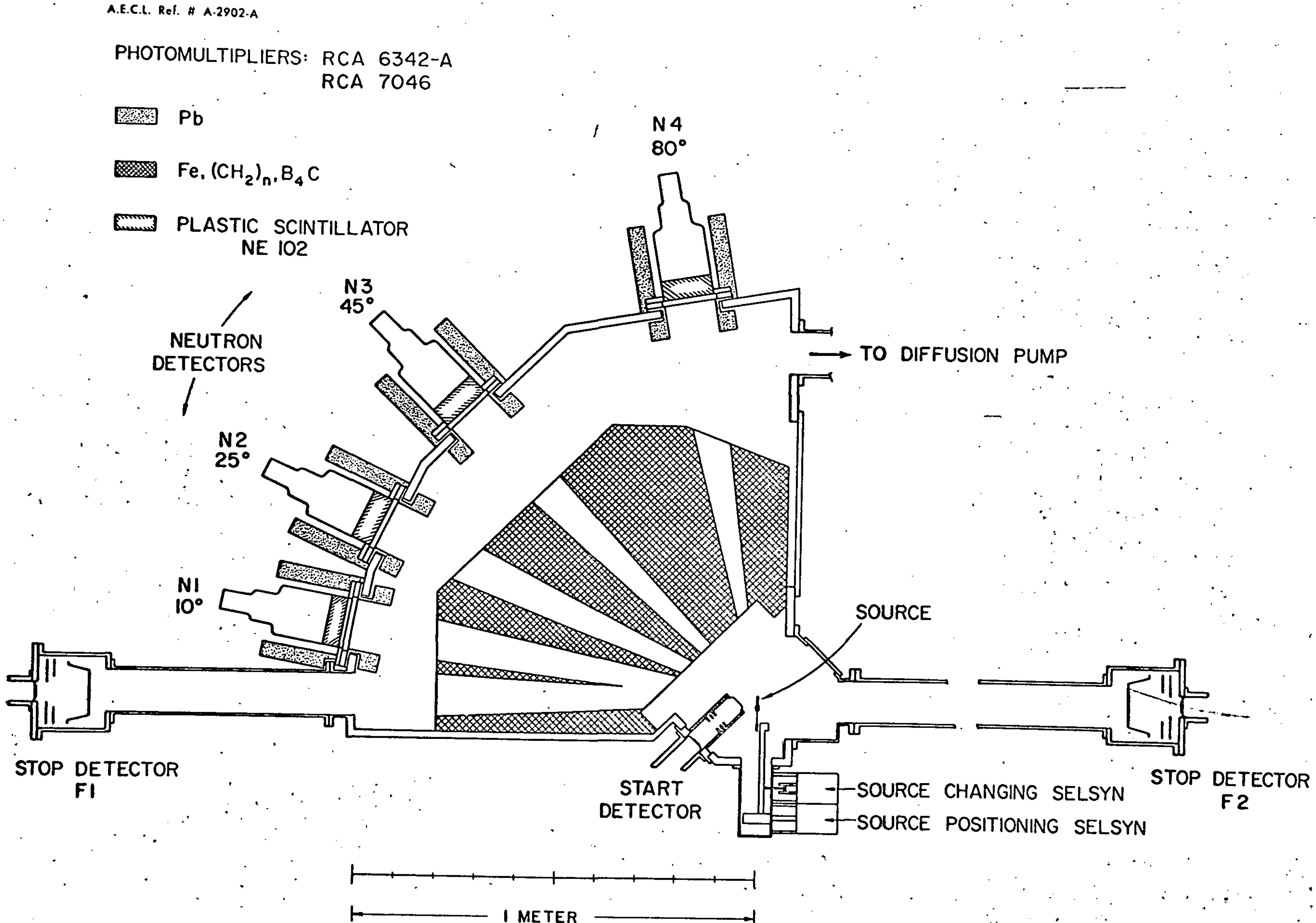
This slide also illustrates an interesing feature and one that was observed in the Cf experiment. Despite the saw tooth variation of ν, the average neutron energy η is symmetric about the symmetric mass point, so that even tho there are very few neutrons emitted b a mass 132 fragment, the neutron energy is nevertheless high. Or in other words the temperature of a mass 132 fragment in the neighborhood of the neutron binding energy is the same as the temperature in a mass 102 fragment at an excitation energy some 10's of Mev higher.

There are two rather different models which can explain both of these observations. These models differ mainly in their description of the fragments at the time of scission, i.e. as the two fragments are just separating. In the statistical model the fragments are thought of as nearly spherical, hot with little or no energy tied up in deformation and in thermal equilibrium. This model automatically ensures that the two fragments in a pair will be at the same temperature and so the appearance of the middle curve falls out immediately. The saw tooth ν curve Comes ~~covers~~ about as a consequence of the wide level spacing at low excitation energies in the near magic nuclei. The point is illustrated in SLIDE 3. This slide shows the excitation energy on the specified fragment when the two fragments have 10, 20, 30 and 40 MeV to share between them. Notice the saw tooth behavior at low excitation energies. Without too much difficulty this model can be made to fit the observed ν curve very well.

Nevertheless there are reasons for doubting the validity of such a model. Briefly there are two such reasons. First, the model does not give reasonable values for the kinetic energies of the fragments unless one tampers rather arbitrarily with the separation of the centre of the spheres. Second, if two nuclei in such proximity are to remain spherical in spite of the very strong polarizing forces present, they must be rather stiffer than ordinary nuclei. To meet these objections an opposing model has been developed which pictures the fragments at scission as completely cold, all the energy which subsequently appears as excitation energy being present as deformation energy. This model predicts reasonably well the two features of the neutron variation shown on the previous slide, as well as both the absolute magnitude and variation with fragment mass of the total kineti energy. The saw tooth ν curve follows from the extra stiffness towards deformation possessed by near magic nuclei and the symmetric η variation follows, provided that this stiffness is inversely proportional to the specific heat.

The question then arises, is there some qualitative feature that would distinguish between these two pictures. I believe that there is. Let us consider the extra neutrons coming from one of the fragments when an additional Mev of excitation energy is put into the system of both fragments, in other words $\frac{d\nu}{dE_{x\ total}}$. According to the hot spheres in contact model, this derivative is closely related to the separation of adjacent lines on the plot of Slide three. Thus it is expected to be generally increasing from light to heavy masses, but rather constant over the light mass peak and extremely large at mass 132. The actual experimental values for $\frac{d\nu}{dE_{x\ total}}$ are shown by the crosses in Slide 4. They are completely at variance with the picture I have just presented varying by a very large factor over the light peak and being abnormally low at mass 132. On the other hand they lend support to the second picture in which the stiffness of the fragments is large when they are near closed shells. Thus, just as in the stretching of a weak spring coupled to a strong one, the stiff fragment will pick up very little of the extra energy and the floppy one, most of it. The data then seem to support the picture of cold fragments at scission, at least one of which is highly distorted. The dashed lines on the figure show the behavior of $d\nu/dE_x$ if the additional excitation energy is distributed equally between the fragments, the solid line if it all goes onto the one fragment. In the region of mass 96 the light fragments takes almost all of the additional energy, and in general appears to get more than its fair share, again in contrast to the hot sphere picture which would give most of the additional energy to the heavy fragment.

In closing I would like to stress that I have discussed only one example of the results and that all the experimental points were deduced directly from moments of the observed distribution. This is true even in the last slide where the $\langle dv/dE \rangle$ points are essentially given by the mixed moment or covariance $C(v,E) = \langle vE \rangle - \langle v \rangle \langle E \rangle$. It turns out that the covariance is directly related to the slope of the linear least squares fit to the average value of v as a function of E through the equation $C(v,E) = \sigma^2(E) \langle \frac{dv}{dE} \rangle$.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N2
25°
N1
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SOURCE
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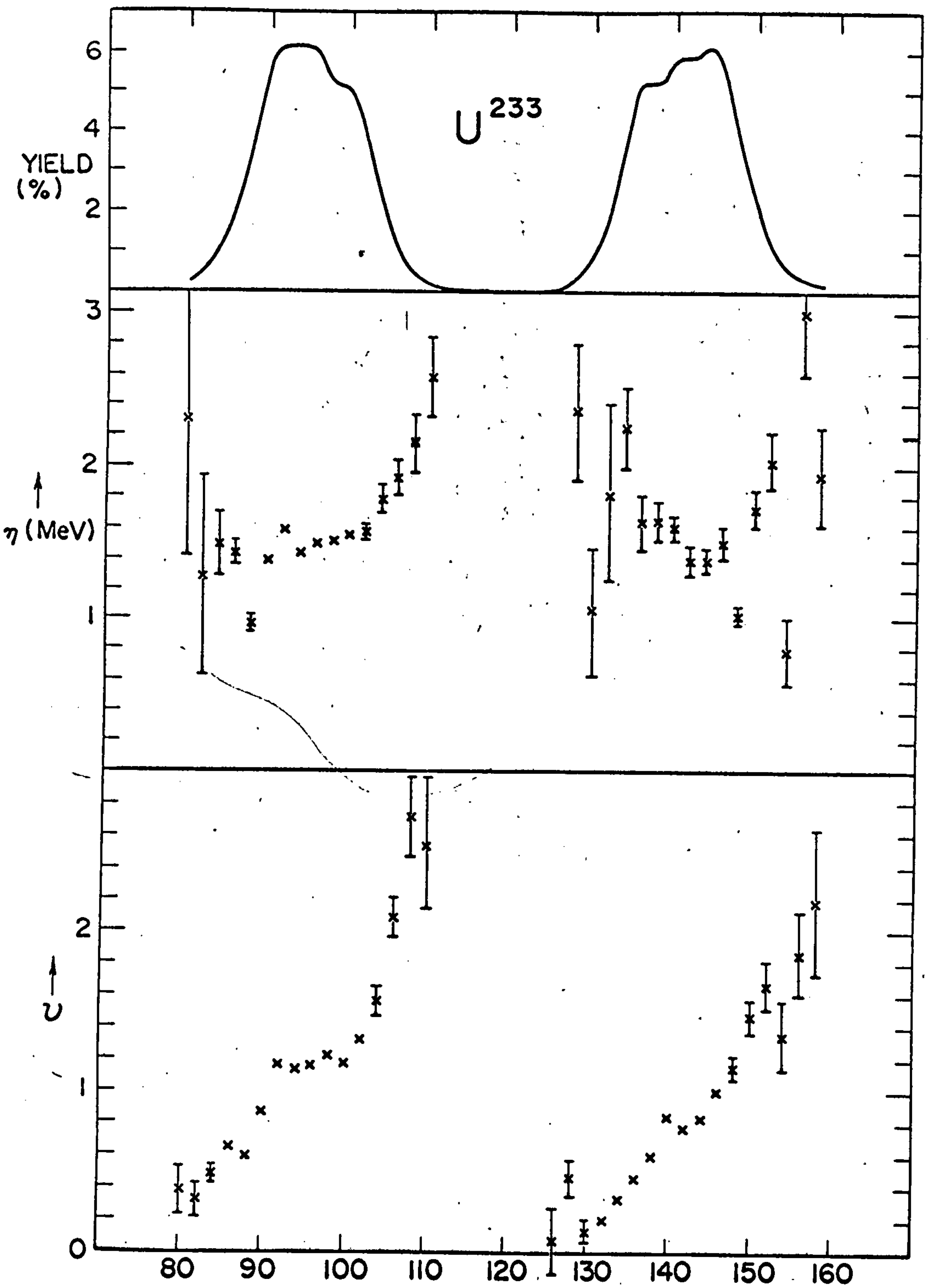

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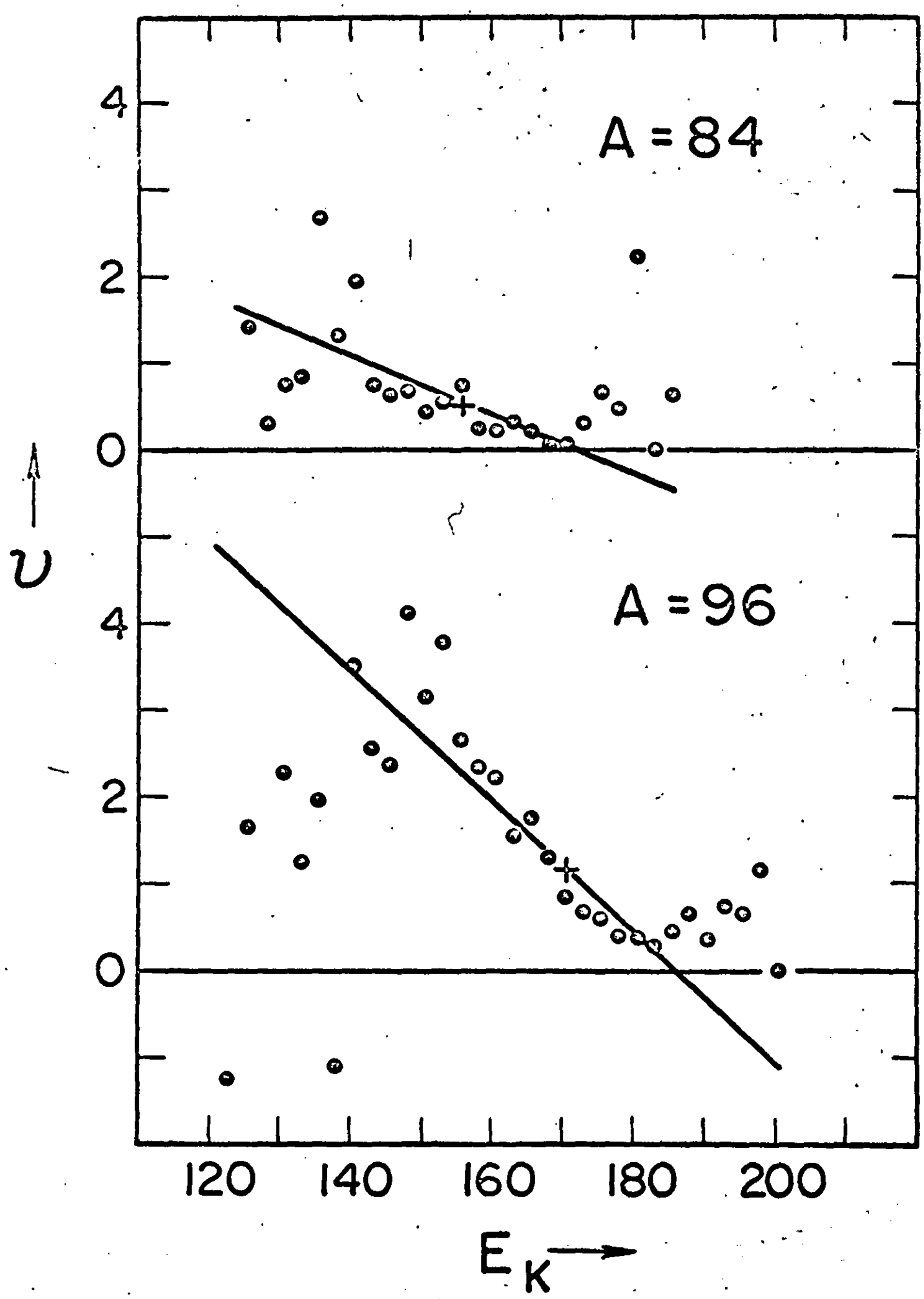

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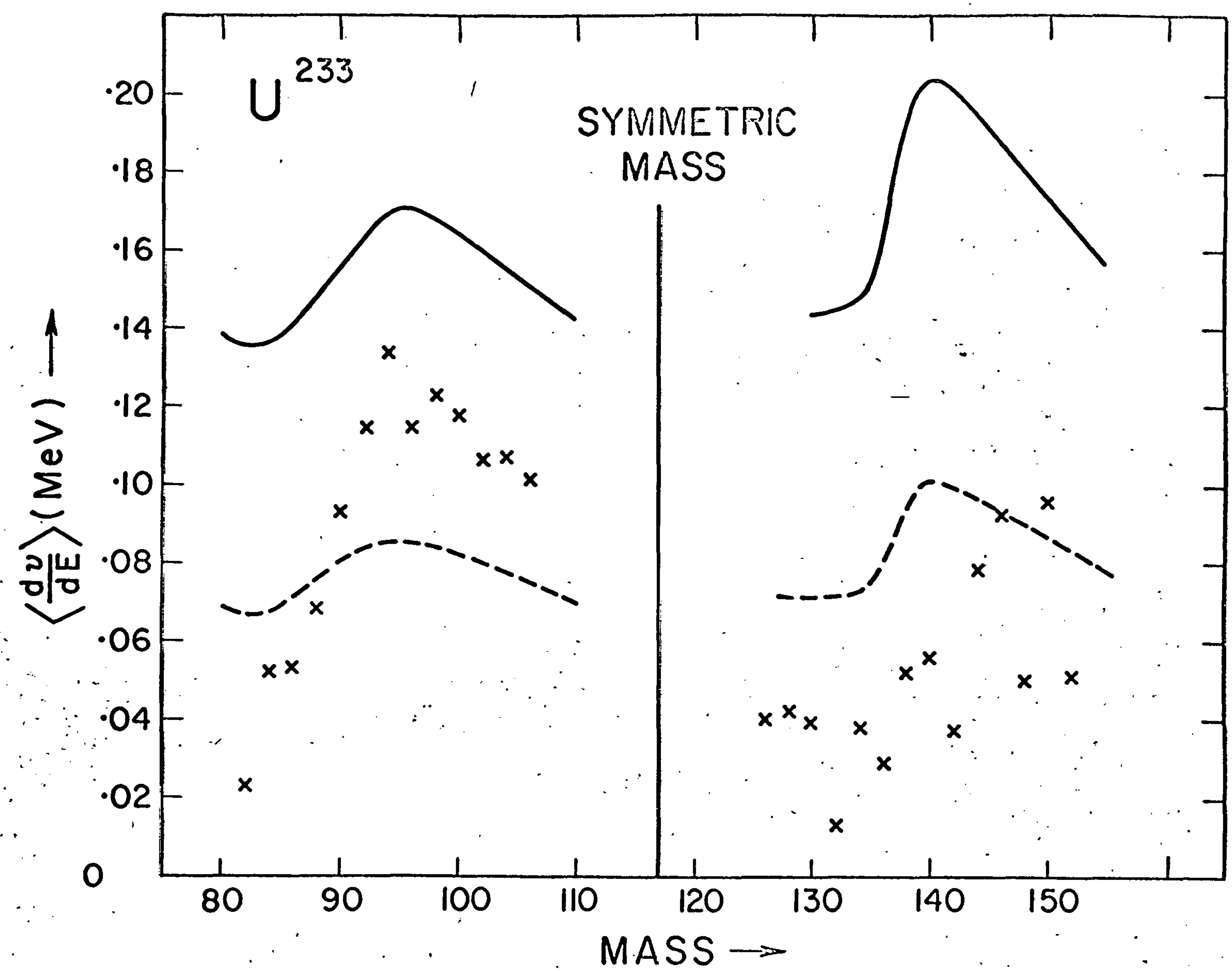

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