It is to be noted that as the above pressure the mean free path is 4.2 cm, long enough to allow atoms to escape without back-scattering.

Absolute sputtering ratios are measured by simply bombarding the target for a measured time with a constant beam current. The weight loss of the target in micrograms gives the number of metallic atoms sputtered; thus the absolute sputtering ratio is

$$n = \text{No. of atoms sputtered/No. of ions incident.}$$

At 3480 volts: Positive ion current = 54 μa; weight loss, Ag target in $\mu g = 1458$ μg; time of bombardment = 3000 sec; $n = 7.9$ atoms/ions.

The result of a series of measurements at various ion energies are indicated in Fig. 2, as well as results of similar measurements by

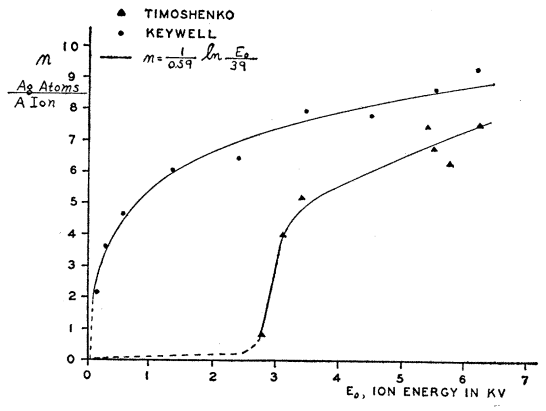

FIG. 2. Sputtering ratio *vs* incident ion energy for Ag—A.

Gregory Timoshenko.[2] The reason for the observed differences is not known.

A striking point of interest in the above data is the small number of atoms sputtered per incident ion compared to the number which is energetically possible. Neglecting heat conduction, a 4000-volt ion incident on silver has sufficient energy to sputter 975 atoms (4.1 ev/atom), yet the actual number sputtered is 8. This number, however, is just the order of the number of collisions required to "cool" a 4000-volt argon atom to an energy of approximately 40 ev, where we consider the silver lattice as a moderator and the argon atom to lose energy by a diffusion-collision process.[3] Neutron diffusion theory can be applied to this process.

According to standard theory, the initial energy of a neutron E_0 will be reduced to E_n after n collisions in a moderator of atomic weight M, where these are related by

$$E_n = E_0 e^{-n\xi}, \quad \xi = 1 - \frac{(M-1)^2}{2M} \ln\frac{M+1}{M-1}. \tag{1}$$

Similarly, if we consider an ion, at. wt A, to be cooled by collisions in the same moderator, it will make a relatively small number of collisions n and reach a characteristic energy below which it can cause no further disturbance in the metallic lattice. For argon ions incident on silver,

$$\xi = 1 - \frac{(M-A)^2}{2MA} \ln\frac{M+A}{M-A} = 0.59, \quad E_n = E_0 e^{-n\xi}. \tag{2}$$

The data observed can be fitted quite closely by least squares from 150–6200 v, as indicated in Fig. 2, by a relation of this form, where $E_n = 39$ v. The sputtering ratio formula for Ag is

$$n = (1/0.59) \ln(E_0/39) \text{ Ag atoms/A ion.}$$

Thus, in agreement with the observed inefficiency of ions in releasing secondary sputtered particles, the following theory of sputtering in the high vacuum is proposed: An energetic ion, upon striking the crystalline lattice, will be "cooled" by a diffusion-collision mechanism similar to neutron cooling. In the process it will make a small number of collisions with the atoms of the material being sputtered, these collisions being violent enough to cause the metal atoms to be dislodged from the lattice and be removed as sputtered material. After the incident ion has made sufficient collisions to cool it to some characteristic energy (the empirical value E_n), the sputtering process will stop. By use of formulas (1) and (2), the sputtering ratio formula is

$$n = (1/\xi) \ln(E_0/E_n).$$

There is a satisfactory agreement between theory and observation for Ag metal bombarded by A ions. The same analytic relation has been indicated for sputtering of Al, Pb, and Cu when these metals are used as cathode materials in the P.I.G. discharge run with argon gas. Further studies will be attempted with additional metals and gases.

I wish to thank Dr. John Backus for use of the 13-in. pole-face magnet and for many helpful suggestions.

* Assisted by the program of the ONR.

[1] A. Guthrie and R. K. Wakerling, *Characteristics of Electrical Discharges in the Magnetic Fields* (McGraw-Hill Book Company, Inc., New York, 1949), first edition, Chap. 11, p. 345; J. Backus, Manhattan District Declassified contribution No. 1327 (1947).
[2] Gregory Timoshenko, J. Appl. Phys. **12**, 69 (1940).
[3] E. Fermi, *Nuclear Physics*, notes compiled by Orear, Rosenfeld, and Schluter (University of Chicago Press, Chicago, 1950), p. 181.

Slow Neutron Resonances in In^{113} and In^{115}†

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THE resonance absorption of slow neutrons by indium was reported in 1936 by Amaldi and Fermi.[1] In recent years the indium cross section has been measured by groups at several laboratories[2–4] and resonances have been reported at 1.44, 3.8, and 9.0 ev. The very strong resonance at 1.44 ev has been assigned to In^{115} on the basis of activation experiments.[2,5] Definite isotopic assignment of the other two resonances could not be made, but they were commonly attributed to In^{113} to account for the cadmium ratio obtained by measuring the activation of In^{114} However, if such isotopic assignment were correct, it would appear that indium has fewer resonances than would be expected from simple

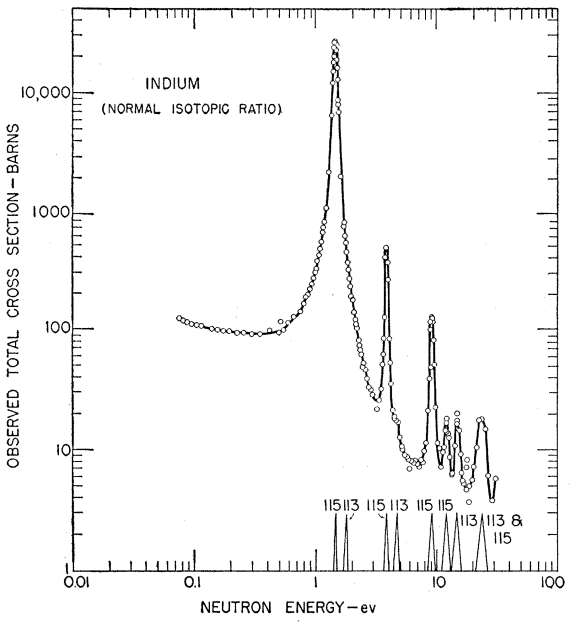

FIG. 1. Total cross section for normal indium.

considerations. If one assumes that the spacing between resonances is of the same order of magnitude as the energy of the first resonance, then In^{115} would be expected to have a spacing between resonances of a few electron volts.

We have recently remeasured the indium cross section to investigate the apparent discrepancy in the density of resonances. The measurements were made with the Brookhaven crystal spectrometer,[6] which uses a beryllium crystal for the monochromator. Beryllium gives relatively good intensity and resolution up to about 50 ev. The total cross section for normal indium obtained with this instrument is shown in Fig. 1.

It is possible to use small samples with the spectrometer; hence enriched isotopes[7] of indium could be used to identify the resonances. The transmission curves for normal and enriched samples are shown in Fig. 2. It should be noted that all three of the reso-

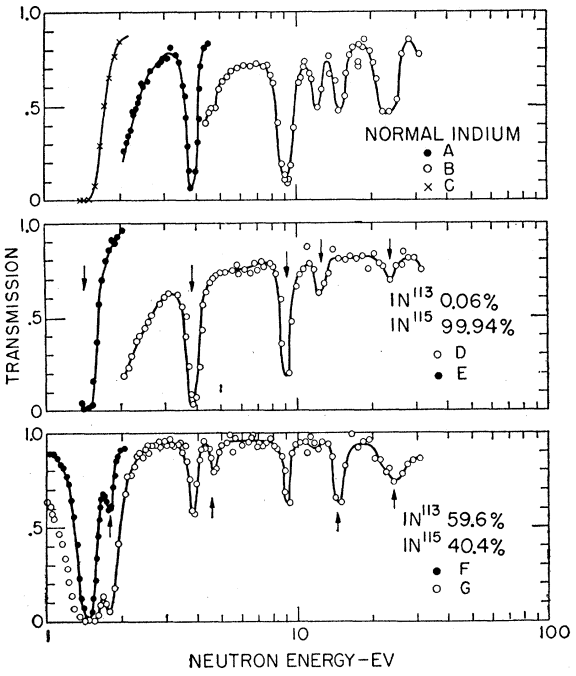

FIG. 2. Transmission for normal indium and two enriched samples. The dip at 25 ev in In^{113} is too broad to be a single resonance. Sample thicknesses are as follows: $A=1.873$, $B=8.003$, $C=0.189$, $D=2.20$, $E=0.14$, $F=0.14$, $G=0.61$ g/cm².

nances previously reported belong to In^{115}. Several additional resonances have been observed in both isotopes. The results are summarized in Table I along with the corresponding resolution width for each resonance.

It appears that the spacing between resonances is about 6 ev in each of the isotopes. The strength of the resonances in any one isotope varies considerably. For example, in In^{115} the resonances at 1.458 and 3.86 ev have relative strengths $(\sigma_0\Gamma^2)_{1.46}/(\sigma_0\Gamma^2)_{3.86}$ ≈ 45. If we assume that Γ_γ is the same order of magnitude for both resonances, then after correcting for the ratio of λ_0^2 one obtains the approximate result $(g\Gamma_n)_{1.458}/(g\Gamma_n)_{3.86}\approx 17$. If it is assumed that only s neutrons are effective in producing the 3.86-ev resonance, it is impossible to explain such a large difference in the magnitude of $g\Gamma_n$ for the two resonances on the basis of current resonance theory.

A more detailed analysis of the resonances is being prepared and will be submitted for publication in the near future.

TABLE I. Neutron resonances in indium isotopes. The term ΔE is the full width at half-maximum of the resolution triangle of the instrument.

E_0 (ev)	Isotope	ΔE (ev)
1.458 ±0.003	115	0.041
1.80 ±0.03	113	0.056
3.86 ±0.02	115	0.176
4.69 ±0.03	113	0.235
9.16 ±0.05	115	0.643
12.1 ±0.1	115	0.98
14.8 ±0.2	113	1.33
22–26 (two or more)	113	~2.8
23.5 ±1.0	115	2.6

† Research carried out under the auspices of the AEC.
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[1] E. Amaldi and E. Fermi, Phys. Rev. **50**, 899 (1936).
[2] C. P. Baker and R. F. Bacher, Phys. Rev. **59**, 332 (1941); Bacher, Baker, and McDaniel, Phys. Rev. **69**, 443 (1945); B. B. McDaniel, Phys. Rev. **70**, 832 (1946).
[3] W. W. Havens, Jr., and J. Rainwater, Phys. Rev. **70**, 154 (1946); Havens, Wu, Rainwater, and Meaker, Phys. Rev. **71**, 165 (1947).
[4] Borst, Ulrich, Osborne, and Hasbrouck, Phys. Rev. **70**, 557 (1946).
[5] J. L. Lawson and J. M. Cork, Phys. Rev. **52**, 531 (1937).
[6] A full description of this instrument will be submitted for publication in the near future.
[7] The enriched isotopes were obtained on loan from the Isotope Research and Production Division of the AEC.

Isomers in Tellurium 133†

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OBSERVED discrepancies in the fission yields of the members of mass-chain 133 suggested the existence of an isomer of Te^{133}.[1] On theoretical grounds, Goldhaber[2] predicted that the 66-min Te^{133} is the upper member of an isomeric pair and that the ground state for Te^{133} probably has a short half-life. This phenomenon may be responsible for the apparent discrepancy in the cumulative fission yields.

In irradiated UO_3 tellurium fission products were first removed and tellurium then isolated from the decay of 4.4-min Sb^{133}. The last tellurium samples show a perceptible growth of a short-lived daughter in the 63-min decay curve. The half-life of the daughter is found to be about 2 min.

In studies of the chemical states of tellurium formed in fission, Williams[3] showed that if the parent isomer is held in acid solution in the valence state +6, most of the daughter will be formed in the lower valence state +4. A fast daughter separation by selective reduction with H_2S was made from the 63-min Te prepared in the +6 state. The daughter fraction decayed with a prominent component of half-life about 2 min. The parent showed a half-life of 63 min.[4]

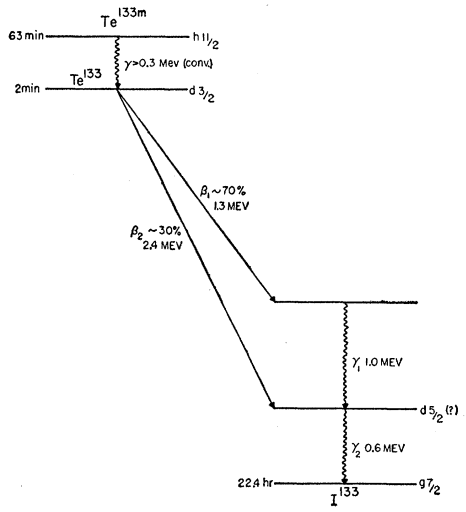

FIG. 1. Tentative decay scheme $Te^{133m}\rightarrow Te^{133}\rightarrow I^{133}$.