Resonance Scattering in Indium*

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Resonance scattering from the 1.458-ev level of indium has been studied by a bright-line technique. resonance-scattering cross section of 1600 barns corresponds to a scattering level width of 0.0052 ev and a Γ_n/Γ of 4.5 percent.

INTRODUCTION

PREVIOUS work on nuclear resonance levels produced by low energy neutrons has followed the methods of absorption spectroscopy, the sample under study being interposed between a source emitting neutrons of all energies and the detector.[1] Secondary characteristic sources have occasionally been used involving the scattering of neutrons from samples in a polychromatic or monochromatic beam.[2] The present work uses a characteristic neutron source such that nuclear resonances appear as bright lines against a low intensity background. The bright lines are characteristic of resonance scattering superimposed on a potential scattering background. The method is appropriate, therefore, to the measurement of nuclear-scattering cross sections, both resonance and potential, rather than the total cross section obtained by dark line techniques.

The 1.4-ev resonance of In^{116} was selected for study because of its convenient energy, the high isotopic abundance of In^{115}, its high cross section, and the ease and simplicity of activation studies. Excellent data exist on the total cross section as a function of energy.[3]

EXPERIMENTAL

A scattering pipe (Fig. 1) was inserted into the Brookhaven reactor, together with a 35-hole collimator of such aperature that neutrons originating within the reactor or scattered within the region of appreciable neutron density could not emerge through the collimator. The inner end of the collimator was kept within the reactor shield in a region of low neutron flux to minimize slit scattering. The region observed through the collimator was a neutron trap erected within the opposite shield. The visible surface consisted of a thin steel can filled with boron carbide set well back in the reactor shield. No neutron contribution could be observed from this source.

Air within the tube constitutes an excellent scattering source. The tube and collimator were therefore evacuated. Pressures were ordinarily reduced to less than 0.1-mm Hg before work was attempted. A five-mil (0.12-mm) aluminum window was used to withstand atmospheric pressure. Thick sheet cadmium was used to filter out thermal neutrons scattered by the collimator and sample.

The scattering sample consisted of a thin film containing indium supported on a movable graphite ring and placed at the center of the pipe in the region of maximum neutron flux. Studies were carried out at a distance of 20 feet or greater from the sample. Since pure indium would have melted at the temperature at which the sample was exposed, high melting alloys with tin and lead were used.

Self-activation studies were first carried out using a stack of cadmium covered indium foils, irradiated in the beam emerging from the collimator. These were then counted with conventional thin-window beta-ray counters.

Further studies were conducted using a Cauchois-type sodium chloride curved crystal spectrometer.[4] A sodium chloride crystal with a radius of curvature of approximately forty feet constructively reflected the diverging rays from the collimator through a long boron trifluoride counter. All regions of the crystal used were found to contribute to the diffracted intensity.

OBSERVATIONS

Self-activation studies were first made to evaluate the resonance contribution to the beam emerging from the scattering pipe. The scatterer used consisted of 0.0072 g/cm² of indium alloyed with 0.015 g/cm² of tin. Figure 2 shows the intensity of activation as a function of position in the foil stack. The upper curve shows the absorption curve for indium using a cadmium filter. The slope at zero absorber indicates an absorption

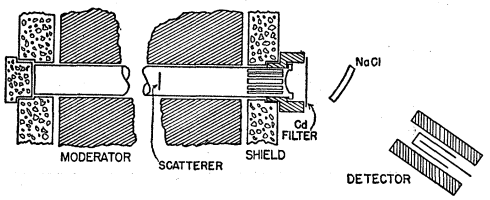

FIG. 1. Schematic arrangement of apparatus.

* Experimental work performed at Brookhaven National Laboratory, a U. S. Atomic Energy Commission laboratory.

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[4] Y. Cauchois, J. phys. **3**, 320 (1932).

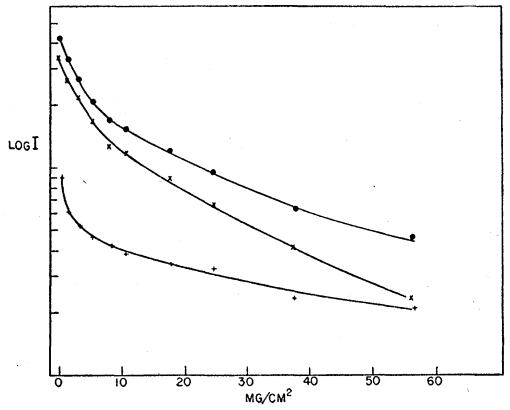

FIG. 2. Self-absorption in indium from 0.0072 g/cm² indium, 0.015 g/cm² tin. Upper curve absorption in indium; lower curve absorption through 0.56 g/cm² rhodium filter; intermediate curve, difference.

cross section of 37 000 barns. This value of the absorption cross section and the intensity of the highly absorbed component are strong indications the incident beam corresponds to an emission spectrum.

The rhodium resonance at 1.260 ev ($\sigma_a=4600$ b) can serve as an effective filter to remove a large fraction of the indium resonance radiation. The lower curve shows the effect of cadmium plus 0.56 g/cm² of rhodium. The intermediate curve shows the difference or the rhodium absorbable component.

These curves may be decomposed into a sum of four exponential terms representing the absorption of each of the four components in both rhodium and indium:

$$I=12e^{-125N_{\mathrm{Rh}}}e^{-130N_{\mathrm{In}}}+55e^{-270N_{\mathrm{Rh}}}e^{-1900N_{\mathrm{In}}}$$
$$+190e^{-690N_{\mathrm{Rh}}}e^{-12\,000N_{\mathrm{In}}}+400e^{-640N_{\mathrm{Rh}}}e^{-150\,000N_{\mathrm{In}}},$$

where N_{Rh} and N_{In} are the numbers of atoms per cm². Since the cross section of rhodium at 1.46 ev is 700 barns, it is evident that the last two terms are associated with resonance scattering of the 1.458-ev level in indium. The first term, because of the low cross sections, is certainly associated with a small thermal component penetrating the cadmium filter. The second term may not be identified with a single energy component, but is certainly above the thermal region. It is evident therefore that 40 percent of the neutrons from the scattering pipe above the thermal region are associated with the 1.458-ev resonance.

Initial observations using the Cauchois spectrometer were made with the first-order reflection from a sodium chloride crystal [Fig. 3(a)]. The intensity at the maximum is nearly three times the intensity of the energy-independent background (composed of potential scattering, neutrons from other experiments and circuit background).

The peak is seen to be asymmetric when plotted as a function of diffraction angle. For a line of small intrinsic width compared to the slit width, the curve would be symmetrical; whereas for a well-resolved resonance having the form of a Breit-Wigner absorption resonance, asymmetry would be evident in the opposite sense. The asymmetry observed is therefore strong evidence of a scattering resonance showing interference between the potential and resonance terms. It is evident from the resolution triangle that the resonance is not completely resolved.

Figure 3(b) shows the fractional transmission obtained by interposing an indium foil between the bright line source and the counter. In comparing the original data, there is no observable displacement between the bright line scattering maximum and the absorption maximum. The possible displacement can certainly not exceed 0.01 ev.

Further studies were carried out in the second order to double the resolution. The ratio of intensities of the first to second order was 3.6 compared to a theoretical 4. Figure 4 shows the bright line fully resolved. Trans-

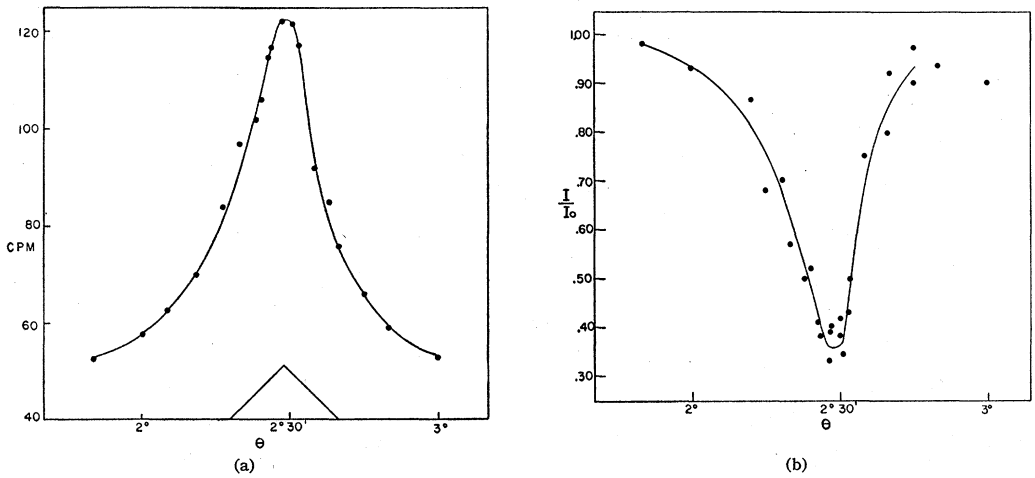

FIG. 3. (a) Bright line from 1.458-ev indium resonance. First-order spectrum from 0.0072 g/cm² indium, 0.015 g/cm² tin. (b) Transmission of 0.018 g/cm² indium using first-order bright line as source.

mission measurements made at the exact resonance indicate a total cross section of 25 000 barns. The precise form of the background contribution is not easy to deduce, and the data are therefore difficult to interpret quantitatively.

A normal transmission curve is shown in Fig. 5 after filling the scattering pipe with nitrogen. The resonance now shows its normal symmetrical form.

The indium-tin scatterer was replaced by a sample consisting of 0.0094 g/cm² indium 0.021 g/cm² lead, greatly reducing the potential scattering from the alloy. Figure 6 shows data obtained from the new scatterer using a special counting circuit. The asymmetry of the peak is again evident.

A graphite scatterer was used to calibrate the instrument using the identical geometry and counting arrangement. The maximum of Fig. 6 corresponds to a cross section of 350 barns.

ANALYSIS

While the scattering foils are thin by normal standards, important corrections are required near the resonance. Correction was therefore made for attenuation within the scatterer. A spherically-symmetric neutron distribution was assumed together with the observed total cross sections near the resonance found by Sailor.[3] The intensity from the scatterer is

$$I=\int_0^h e^{-\mu x}\int_0^{\frac{1}{2}\pi} e^{-\mu x\sec\theta}\sin\theta d\theta dx + \int_0^h e^{-\mu x}\int_{\frac{1}{2}\pi}^{\pi} e^{-\mu(h-x)\sec\theta}\sin\theta d\theta dx,$$

where h is the thickness of the scatterer and μ its absorption coefficient. The ratio of intensity to that for zero absorption is

$$\frac{I}{I_0}=\frac{1}{h+1}\left[\frac{1}{\mu}\int_0^{\frac{1}{2}\mu}\frac{1-e^{-\mu h(1+\sec\theta)}}{1+\sec\theta}\sin\theta d\theta + \frac{e^{-\mu h}}{\mu}\int_{\frac{1}{2}\pi}^{\pi}\frac{1-e^{-\mu h(\sec\theta-1)}}{\sec\theta-1}\sin\theta d\theta\right].$$

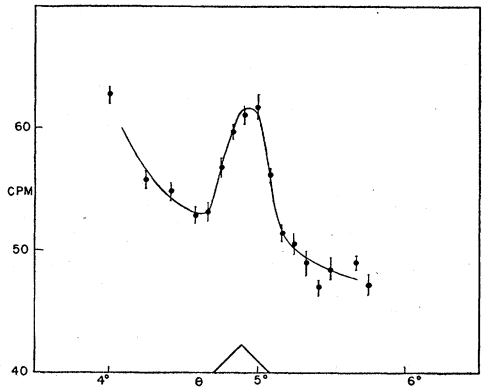

FIG. 4. Bright line in second order from 0.0072 g/cm² indium, 0.015 g/cm² tin.

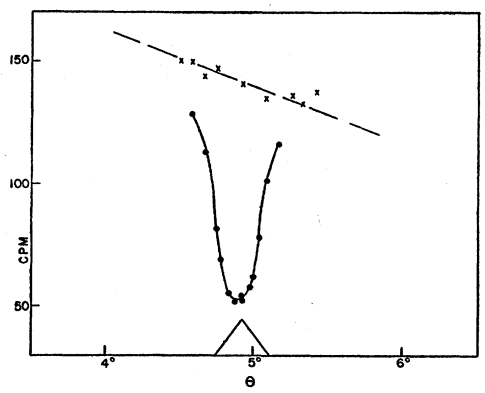

FIG. 5. Dark line in second order using continuous source (crosses) from scattering by nitrogen.

This function was graphically integrated and found to have a value of 0.196 for a cross section of 27 000 barns. It therefore constitutes a major correction to the data. The calculated resonance scattering cross section then becomes 1600 barns.

A theoretical resonance scattering curve has been calculated using the treatment of Wigner[5] with the following assumptions: (a) only s neutrons contribute; (b) spins for $In^{115}=9/2$, $In^{116}=4$; (c) $\Gamma=0.114$ ev; (d) $\sigma_t=27\,000$ barns at resonance; (e) $E_0=1.458$ ev; (f) $\sigma_p=2.2$ barns; (g) $\sigma_{sc}=1600$ barns at resonance. The theoretical curve has been corrected for thick scatterer and is fitted to the data in Fig. 6 using a constant background of 29 cpm. (A slight calculated line reversal has been smoothed out because of insufficient resolving power.)

While the fit at small angle is not good, probably due to improper evaluation of the background, the principal discrepancy between the data and theory is on the low energy side of the resonance. The experimental curve

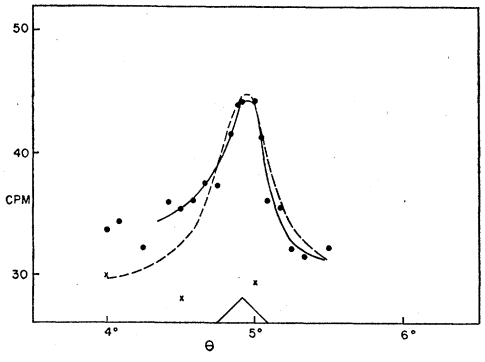

FIG. 6. Bright line in second order from 0.0094 g/cm² indium, 0.021 g/cm² lead. Broken curve is from Breit-Wigner theory of resonance scattering. Crosses give background.

[5] E. P. Wigner, Phys. Rev. **70**, 26 (1946).

appears to be too steep to be fit by the theory. A potential-scattering cross section larger than presently reported might improve this fit.

The derived width of the energy level for scattering was found to be 0.0052 ev, giving a ratio of Γ_n/Γ of 4.5 percent.

The author wishes to express his appreciation for the opportunity to work with the Brookhaven reactor. He wishes particularly to thank V. L. Sailor, H. L. Foote, R. Gminder, and H. Landon for the use of equipment and their continuing assistance through the course of the work.

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The Decay of Rh^{104m} (4.3 Min) and Rh^{104} (44 Sec)

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The radiations of neutron-activated rhodium are studied with 180° constant field conversion electron spectrometers and a gamma-ray scintillation spectrometer. Internal conversion electrons are observed to be associated with the 4.3-minute activity. These are interpreted as arising from two isomeric transitions of 51.1±0.2 and 77.2±0.2 kev in rhodium. By coincidence studies these two transitions are shown to be in cascade. The character of the radiations, as determined from the K/L ratios and lifetime considerations, appears to be $M1$ and $E3$, respectively. Additional gamma-rays of energy 550±10 kev and ~1.2 Mev (weak) are observed with the scintillation spectrometer. The 550-kev transition is associated with both the 44-second and the 4.3-minute periods and is assumed to follow the beta-decay and hence be in Pd^{104}.

INTRODUCTION

As early as 1935, Fermi and associates had observed[1] in rhodium, exposed to slow neutrons, induced radioactivities whose half-lives were 50 seconds and 5 minutes. Subsequent investigators[2] showed that these activities were in rhodium-104 following neutron capture in rhodium-103, and they noted the existence of associated conversion electrons with, however, considerable disagreement as to their energies. From absorption measurements it was concluded that an isomeric transition of about 50 kev in the 4.3-minute activity led to the 44-second beta-emitting level. This in turn was believed to emit a beta-ray of maximum energy about 2.5 Mev followed by a gamma-transition of about 400 kev in the resulting palladium nucleus.

More recent measurements with a scintillation spectrometer have given the metastable transition[3] energy as 52 kev and the transitions[4] in palladium as 560 kev and 1.1 Mev. Other investigators[5] had found for the latter, gamma-rays energies of 41, 180, and 950 kev. One report[6] concluded that most of the electromagnetic radiation observed was due to bremsstrahlung.

TABLE I. Conversion lines associated with the 4.3-minute Rh^{104} decay.

Electron energy (kev)	Relative intensity	Interpretation	Energy sum (kev)	Transition energy (kev)	K/L
27.9	14±3	K(Rh)	51.1	51.1	≳5
47.8	<3	L_1(Rh)	51.2		
54.0	63±9	K(Rh)	77.2	77.2	~0.6
74.1	100±15	L_2(Rh)	77.2		
76.7	8±2	M(Rh)	77.2		

THE PHOTOGRAPHIC SPECTROMETRIC STUDY

In the present investigation the radiations from neutron-activated rhodium are studied with 180° constant-magnetic-field photographic spectrometers and with sodium iodide (thallium-activated) crystal scintillation gamma-spectrometers.

The spectrometers were located close to the Argonne heavy-water-moderated pile so that the irradiated specimens could be transferred quickly from the pile to the spectrometer. The specimens were inserted and removed from the strong neutron flux by means of a pneumatic tube. The photographic spectrometer sources were made of very narrow strips of cellulose tape coated with rhodium oxide and mounted on Lucite frames. The entire frame was irradiated, many successive exposures being required to obtain a satisfactory spectrogram. The injection of the samples into and removal from the cameras was expedited by the use of quick-operating vacuum locks previously described.[7]

The photographic records were made using no-screen emulsion, either on duplitized film or as a single coating on glass plates. The internal conversion electron

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