Investigation of Nuclear Energy Levels in Lead

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The total neutron cross section of lead was measured from 20 kev to 750 kev with an energy spread of 10 kev. Maxima were observed at 350, 525, and 720 kev, each maximum being preceded by a minimum. In the region surrounding these anomalies, measurements were carried out with a resolution of about 5 kev. An attempt was made to interpret the maxima as due to resonances corresponding to isolated levels in the compound nucleus Pb^{209}. No energy levels were resolved when similar measurements were carried out for bismuth.

INTRODUCTION

A PREVIOUS investigation[1] indicated that the total cross section of lead for fast neutrons did not vary smoothly with energy when measured with neutrons of about 70-kev energy spread. For an element as heavy as lead this observation was unexpected, and it appeared desirable to obtain more detailed information about this anomaly. In the present study the experiment was repeated with better energy resolution.

There is experimental evidence that the density of nuclear energy levels is smaller in lead than in other heavy elements. Lead does not show resonances for slow neutrons,[2] and furthermore it has a very small absorption cross section[3] and a relatively small cross section for inelastic scattering at intermediate energies.[4] The only other heavy element for which similar neutron properties have been observed is bismuth. For this reason bismuth was investigated in the same manner as lead.

EXPERIMENTAL

Total neutron cross sections were measured by simple transmission experiments as described previously.[5] A counter filled with enriched BF_3 and surrounded by paraffin served as neutron detector. As in the earlier work, monoenergetic neutrons of variable energy were produced by the Li(p,n) reaction. The spread in energy of these neutrons depends on three factors; the spread in energy of the incident protons, the thickness of the Li target, and the angle subtended by the detector at the target. The maximum energy spread introduced by this last effect can be calculated from the conservation laws, although the details of the effective energy distribution depend on the variation of the sensitivity of the detector over the detector surface, which was not known. In the geometry used, the maximum energy spread because of angle amounts to ± 1.5 kev at 120 kev and increases to ± 3 kev at 1 Mev for measurements in the forward direction with respect to the incident protons.

Previously, the whole proton beam emerging from the electrostatic generator had been used to bombard the Li target. The energy of these protons was measured and regulated by passing the diatomic hydrogen beam through a small electrostatic analyzer and using a signal from the exit slit of the analyzer to adjust the generator voltage. This method had the disadvantage that the energy spread of the protons could only be estimated and that, for a given voltage on the analyzer, variations in energy occurred which were presumably produced by changes in the geometry of the analyzer because of temperature changes caused by the beam.

In order to obtain higher resolution and more reproducible energy settings, the large electrostatic analyzer described by Warren, Powell, and Herb[6] was used in the present experiments. By appropriate settings of the slit system of this analyzer, a portion of the proton beam of well-defined energy spread could be selected, and the energy of the protons could be accurately determined. For controlling the energy of the generator, the following procedure was used. A signal produced by the magnetically analyzed proton beam was taken off the entrance slit of the analyzer. This signal served to adjust and stabilize the voltage of the generator. The magnetic field was varied until the proton beam passed through the electrostatic analyzer, the generator voltage following the changes of the magnetic field automatically. This method requires short time stability of the magnetic field, but the energy of the proton beam emerging from the electrostatic analyzer is determined solely by the voltage across the analyzer.

For measuring the thickness of the Li target, the method described by Taschek and Hemmendinger[7] was used. The rise of the forward yield of neutrons near threshold is observed as a function of proton energy. The width of the rise depends on the target thickness and the proton energy spread. For the purpose of estimating the neutron energy spread, only the resulting

[1] Bockelman, Peterson, Adair, and Barschall, Phys. Rev. **76**, 277 (1949).
[2] Havens, Rabi, and Rainwater, Phys. Rev. **72**, 634 (1947).
[3] Hughes, Spatz, and Goldstein, Phys. Rev. **75**, 1781 (1949). See also reference 2.
[4] Barschall, Battat, Bright, Graves, Jorgensen, and Manley, Phys. Rev. **72**, 881 (1947).
[5] Adair, Barschall, Bockelman, and Sala, Phys. Rev. **75**, 1124 (1949).
[6] Warren, Powell, and Herb, Rev. Sci. Inst. **18**, 559 (1947).
[7] R. F. Taschek and A. Hemmendinger, Phys. Rev. **74**, 373 (1948).

effect of both these factors needs to be known. By reducing the slit widths of the analyzer and thereby reducing the energy spread of the protons to less than the stopping power of the target, it was possible, however, to measure the energy spread introduced by the target thickness alone.

In the present work, experiments with two different neutron energy spreads were carried out. They will be referred to as being performed with 5-kev and 10-kev resolution, respectively. For the measurements with 5-kev resolution, the slits of the electrostatic analyzer were set to give a proton energy spread of 0.1 percent, while for 10-kev resolution a proton energy spread of 0.2 percent was used. With these slit settings, maximum proton beam currents of 1 and 2.5 microamperes, respectively, were obtained on the target.

A typical measurement of the variation of forward neutron yield with proton energy near threshold is shown in Fig. 1. The difference in proton energy between the threshold for neutron production and the first peak in the yield curve is 4 kev, which may be taken as a measure of the neutron energy spread introduced by the proton beam and the target, since the neutron and proton energy spreads are approximately the same. The actual energy spread may be slightly larger than 4 kev because the sensitivity of the counter used for the detection of the neutrons increased with decreasing neutron energy. Measurements taken with this target will be referred to as having an energy resolution of 5 kev. It was found that, after a day's bombardment, the yield curve rose to the maximum in the same energy interval, but the yield fell off more slowly beyond the maximum. This effect may be caused by non-uniformity of target thickness produced by the beam. Rise curves were taken about twice a day. Whenever a flattening of the maximum was observed, the beam was shifted to another portion of the target.

In principle, it is possible to improve the energy resolution considerably over that used in the present experiments, the only limitation being the Doppler spread which amounts to about ± 200 ev. In practice, the neutron intensity decreases so rapidly as the resolution is improved that measurements with less than 5 kev neutron energy spread appeared to be too time-consuming at present. Furthermore, background difficulties would have decreased the accuracy of the results if the detector were moved farther from the target in order to reduce the neutron energy variation with angle.

MEASUREMENTS ON LEAD

Figure 2 shows the total cross section of lead as a function of neutron energy, taken with a neutron energy spread of about 10 kev. The points represent averages of several runs; their vertical height is a measure of the statistical uncertainty. Sample thicknesses were chosen to give a transmission of about 60 percent at all energies. Corrections for background and scattering into the detector were applied to the cross section. The latter correction amounts to 3 percent assuming isotropic scattering of the neutrons by lead.

In Fig. 2 maxima appear at neutron energies of 350 kev, 525 kev, and 720 kev. The first two maxima are preceded by strong minima; a weak minimum is indicated in front of the third peak. Below 200 kev the cross section shows a rapid rise with decreasing neutron energy, possibly caused by the presence of some unresolved peaks at lower energy.

Using a resolution of 5 kev the three observed peaks were investigated in more detail. The results are shown in Figs. 3–5. In all cases the maxima become higher and the minima lower as the neutron energy spread is decreased.

As mentioned before, the correction for scattering into the detector was applied under the assumption of elastic and isotropic scattering. This assumption is undoubtedly not valid and will introduce some error into the measurements. The cross section for inelastic scattering of neutrons in the energy range under investigation by lead is presumably small.[4] An attempt was made to study this effect by placing some boron carbide in front of the detector at the energy of the minimum at 500 kev. No change of the measured transmission was observed. The effect of anisotropic scattering, however, may be appreciable. Anisotropic scattering will be caused by diffraction scattering and by resonance scattering of neutrons of more than zero units of angular momentum. According to calculations by Professor S. Fluegge, diffraction scattering will increase the correction for scattering into the detector

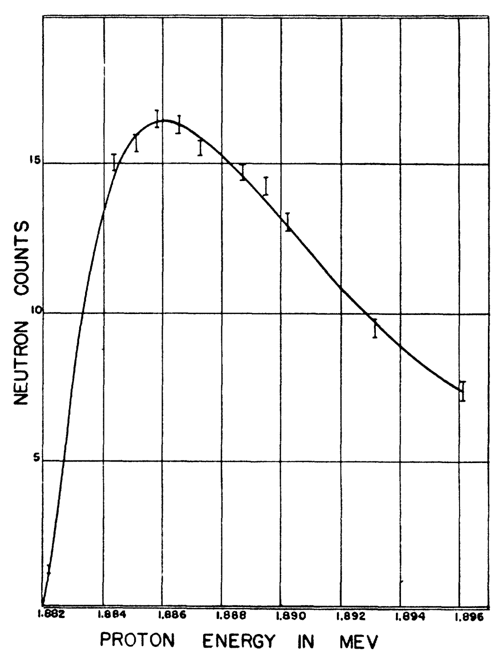

FIG. 1. Forward neutron yield near threshold of Li(p,n) reaction. The energy interval between the threshold for neutron production and the peak is a measure of the neutron energy spread caused by target thickness and energy spread of the incident protons.

by a factor of 3.5 at 500 kev. This means that the cross section should be raised by 7 percent.

Another uncertainty is caused by the hardening of the neutrons in the case of measurements near a sharp peak.

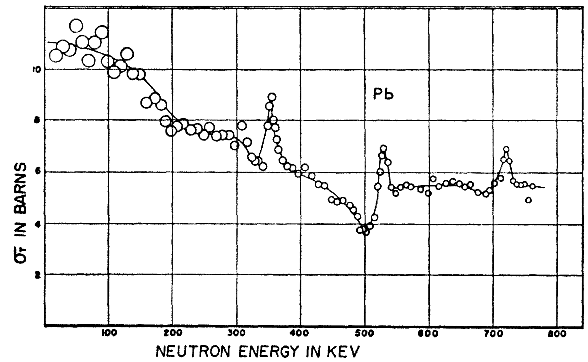

FIG. 2. Total cross section of lead as a function of neutron energy measured with a resolution of 10 kev.

MEASUREMENTS ON BISMUTH

Measurements of the total cross section of bismuth have previously been carried out with a resolution of 20 kev.[8] In view of the results found for lead, the measurements on bismuth were repeated with better resolution and better statistical accuracy. The results obtained with a neutron energy spread of 10 kev are shown in Fig. 6. No evidence for maxima was obtained, indicating that in the energy range up to 500 kev there are no levels wider than 3 kev.

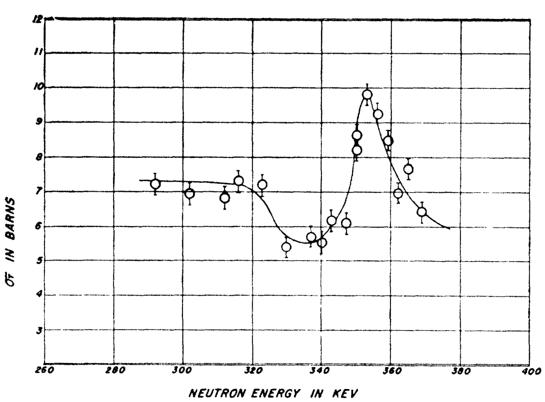

FIG. 3. Total cross section of lead in the neighborhood of the 350-kev resonance investigated with a resolution of about 5 kev.

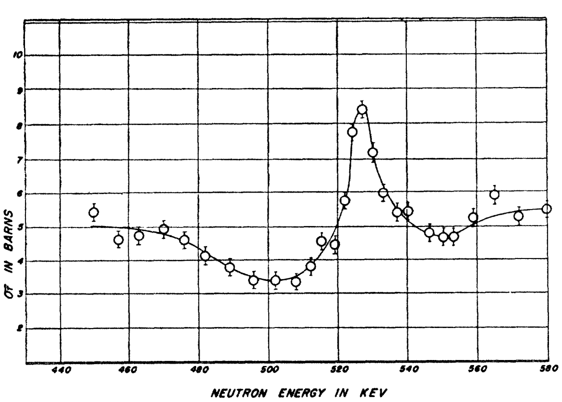

FIG. 4. Total cross section of lead in the neighborhood of the 525-kev resonance investigated with a resolution of about 5 kev.

DISCUSSION

Common lead consists of four isotopes which have approximately the following abundances: Pb^{204} 1 percent, Pb^{206} 24 percent, Pb^{207} 23 percent, and Pb^{208} 52 percent. In the present experiments, only the three more abundant isotopes could produce measurable effects. Relatively wide separations of nuclear energy levels are most likely to be found in observations of the interaction of neutrons with Pb^{208}. According to Wapstra,[9] the binding energy of an additional neutron to Pb^{208} is only 3.7 Mev compared to about twice this number for the other lead isotopes and for most other heavy nuclei. A low binding energy for Pb^{208} may be expected on the basis of the idea of the existence of closed shells in nuclei,[10] since 82 protons and 126 neutrons are believed to form closed shells. According to most theories, the level density in heavy nuclei will increase rapidly with increasing excitation energy. Consequently, the low excitation energy of the compound nucleus Pb^{209} should result in a relatively wide spacing of levels.

Assuming that the observed maxima are due to isolated resonances in the compound nucleus Pb^{209}, it is possible to make statements regarding the angular momenta involved. For the 350-kev resonance the measured difference in cross section between the maximum and the minimum is somewhat greater than 4 barns. A difference of this magnitude would be expected if the compound nucleus has an angular momentum of

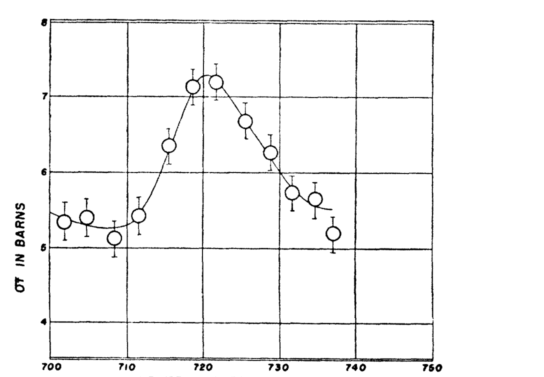

FIG. 5. Total cross section of lead in the neighborhood of the 720-kev resonance investigated with a resolution of about 5 kev.

[8] Barschall, Bockelman, and Seagondollar, Phys. Rev. **73**, 659 (1948).
[9] A. H. Wapstra, Nature **161**, 529 (1948). L. Rosenfeld, *Nuclear Forces* (Interscience Publishers, New York, 1949), p. 525.
[10] M. G. Mayer, Phys. Rev. **74**, 235 (1948).

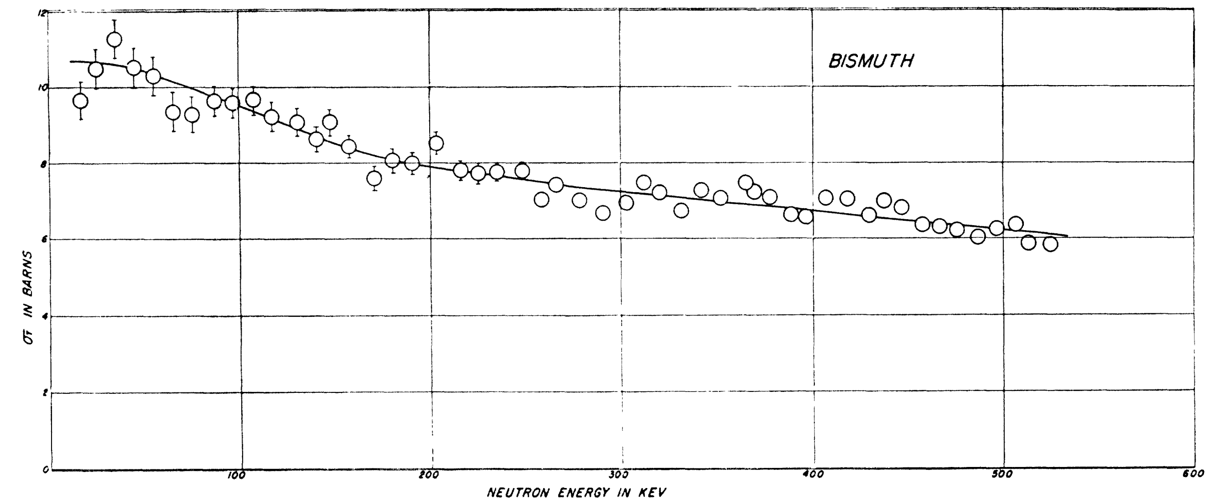

FIG. 6. Total cross section of bismuth as a function of neutron energy measured with a neutron energy spread of 10 kev.

$\frac{1}{2}h$, provided that Pb^{208} has zero spin.[11] Such a compound nucleus may be formed by neutrons of either 0 or 1 unit of angular momentum. Since at this energy about 80 percent of the potential scattering should be s-scattering, the presence of the strong minimum, which is presumably due to destructive interference between resonance and potential scattering, indicates that the resonance is caused by s-neutrons.

At the 525-kev resonance the difference between maximum and minimum is 5 barns. To account for this it is necessary to assume that the compound nucleus has $\frac{3}{2}$ units of angular momentum, and must therefore be formed by either p- or d-neutrons. The magnitude of the minimum again points toward neutrons of small angular momentum. Even if one attributes the resonance to p-neutrons, it seems, however, difficult to understand that the cross section could reach as low a value as it does at 500 kev.

The resonance at 720 kev has an amplitude corresponding to the formation of a compound nucleus of half a unit of angular momentum and should therefore be produced by s- or p-neutrons. For s-neutrons of this energy one should expect a pronounced minimum and a small maximum. Since the observations indicate the opposite behavior, it is believed that the resonance is most likely caused by p-neutrons.

The assignment of the observed maxima to the most abundant lead isotope appears reasonable also from the preceding discussion. If either Pb^{206} or Pb^{207} were the target nuclei involved, it would be necessary to assign the resonances to neutrons of higher angular momenta, which, however, is incompatible with the observed interference effects.

All these arguments presupposed that all the lead isotopes have roughly the same neutron cross section. It is further assumed that the resonances are completely resolved. While all the peaks appear to be wider than the expected neutron energy spread of 5 kev, there is no direct evidence that this was the actual effective resolution. For the first two resonances which appear experimentally sharpest, an increase of the height of the peaks would make it more difficult to fit the measurements to the theoretically predicted behavior.

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[11] H. Kopfermann, Zeits. f. Physik **75**, 363 (1932).