be reproduced without difficulty. For a high intensity neutron standard it would seem best to *surround* the γ-ray source with Be. However, such a procedure would be impracticable, since the Ra sources available to different investigators are not of uniform shape. Therefore, if one wishes to construct a reproducible standard, one has to choose an arrangement in which the dimensions of the Ra source—as long as they remain within reasonable limits—are not of paramount importance.

With this in mind, we have devised the following "reproducible neutron standard." The Ra source used consisted of 100-mg Ra, enclosed in a glass tube and surrounded by a Monel tube of 1-mm wall thickness, 4.85-mm external diameter and 2-cm length. With this source a solid cylindrical Be block 1.5″ in diameter and 1.5″ high was irradiated. The center of the source was placed 4 cm above, and its axis parallel to, the upper face of the Be cylinder.

To determine the number of neutrons emitted by this photo-neutron source, its intensity *relative* to a "laboratory neutron standard" was measured with an arrangement similar to that of Frisch, v. Halban, and Koch.[2] The *absolute* neutron intensity of the "laboratory neutron standard" was determined by O'Neal and Scharff-Goldhaber by a new method (described in the preceding letter), by which they found that it emits $N=(8.6\pm0.8)\times10^4$ neutrons per sec. In our relative measurement we obtained for the intensity of the "reproducible neutron standard" $(0.072\pm0.002)N$. In this result we have already allowed for the number of neutrons emitted by the Ra source itself (about $0.01N$). The "reproducible neutron standard" therefore emits 62 ± 7 neutrons per millicurie Ra per sec.

Other investigators who might like to use this "reproducible neutron standard" may find it more advantageous to put the Ra source closer to the Be cylinder, when its intensity is comparatively small, or further away when its shape is comparatively bulky. The following table, showing the variation of the neutron intensity with the distance *d* between the center of the source and the upper face of the Be cylinder might therefore prove useful.

d in cm	2	3	4	5	6
Relative neutron intensity	2.35	1.52	1.00	0.716	0.567

We have also determined the neutron intensity of a Ra-α-Be source in terms of the "laboratory neutron standard," and have obtained a value of 6.8×10^3 neutrons per millicurie Ra per sec.

[*] This letter was received for publication on the date indicated but was voluntarily withheld from publication until the end of the war.

[1] See E. J. Murphy, W. C. Bright, M. D. Whitaker, S. A. Korff, and E. T. Clarke, J. Frank. Inst. 231, 357 (1941).

[2] O. R. Frisch, H. v. Halban, and J. Koch, Proc. Danish Acad. 15, 10 (1938).

Resonance Scattering of Fast Neutrons

David C. Grahame
Amherst College, Amherst, Massachusetts

March 3, 1942*

THERE are a number of experimental facts pertaining to the scattering of fast neutrons by atomic nuclei that do not appear to be explainable in an altogether satisfactory manner on the basis of current nuclear theory. It is the purpose of this communication to point out some of these facts and to suggest a possible modification of the theory which appears capable of explaining them.

The facts to which we refer are as follows. (1) Fast neutrons are back-scattered to a measurable extent by such substances as lead and iron without losing the major part of their energy,[1,2] as required by theory.[3] The amount of such back-scattering varies from element to element in a manner suggestive of a resonance phenomenon. (2) Fast neutrons (2.5 Mev) passing through lead emerge with energies intermediate between what one would expect for neutrons inelastically scattered and what one would expect for neutrons elastically scattered or unscattered.[4] (3) Cross sections for inelastic scattering with large energy loss of 2.5 Mev neutrons do not vary monotonically with atomic weight or atomic number.[5] For light elements this might be attributed to resonance of the usual kind, but for heavy elements the spacing of resonance levels is expected to be much too close to permit the observation of resonance phenomena with neutrons whose energies vary by many Kev in even the most favorable cases.[6,7] (Even when the incident neutrons have a very great spread of energies, cross sections for inelastic scattering with large energy loss differ markedly for such near-neighbors as mercury and bismuth.[2]) (4) Inelastic scattering cross sections of most of those nuclei which have been studied show a marked dependence upon neutron energy.[8] The width of the levels observed demands a level spacing greater than that expected from theoretical considerations. (5) Total interaction cross sections for 2.5-Mev neutrons also vary markedly from element to element and otherwise exhibit typical resonance behavior.[9] Since most of the investigations dealing with this problem have been concerned chiefly with the lighter elements, it is not yet certain that resonance phenomena are to be found among the heavy elements, where the disagreement with theory would be the most pronounced. Present indications are that such phenomena are to be found even in elements as heavy as lead, however.

It was suggested by Grahame and Seaborg[2] that a form of neutron scattering might occur in which there is an incomplete amalgamation of the incident neutron with the nucleus which could give rise to scattering of a type involving only small energy loss. Dunlap and Little[4] have pointed out that their results require some such explanation, and the hypothesis which follows is an extension of that idea.

Let us consider that a fast neutron striking a nucleus interacts at first with only a few particles close to the surface. Let it be assumed that the compound nucleus so formed, which we shall call a locally excited or "hot-spot" nucleus, shares its energy with the remainder of the nucleus sufficiently slowly that one may consider the locally excited nucleus as a separate entity with its own set of energy levels. Because of the small number of particles interacting, these levels will be widely spaced by comparison with the levels of a similarly excited compound nucleus of the usual kind. (In this respect the locally excited nucleus will resemble a highly excited light nucleus.) Since the lifetime of the locally excited nucleus will be expected to be small, the resonance levels will be wide, in agreement with experiment. The locally excited nucleus may either re-emit a neutron or share its energy to form the usual type of compound nucleus. In the former case, the re-emitted neutron will generally have the greater part of the energy of the original neutron, since that energy has not been shared with any large number of particles. This we believe to be the mechanism for the process of inelastic scattering with small energy loss. Such scattering will be expected to be nearly isotropic.

If the locally excited nucleus distributes its energy to form the ordinary type of compound nucleus, inelastic scattering with large energy loss or other types of nuclear transformation may ensue in the usual manner. But these phenomena will be dependent upon the resonance levels of the locally excited nucleus which was first formed as well as upon the resonance levels of the compound nucleus, because both sets of energy levels affect the outcome of the initial encounter. For this reason resonance phenomena may be expected in all types of fast neutron interaction, with the possible exception of elastic scattering.

---

* This letter was received for publication on the date indicated but was voluntarily withheld from publication until the end of the war.

[1] H. H. Barschall and R. Ladenburg, Phys. Rev. **61**, 129 (1942).

[2] D. C. Grahame and G. T. Seaborg, Phys. Rev. **53**, 799 (1938).

[3] V. Weisskopf and D. H. Ewing, Phys. Rev. **57**, 472 (1939).

[4] H. F. Dunlap and R. N. Little, Phys. Rev. **60**, 693 (1941).

[5] H. Aoki, Proc. Phys. Math. Soc. Japan **19**, 369 (1937).

[6] H. A. Bethe, Rev. Mod. Phys. **9**, 71 (1937). See Table XXI.

[7] H. Margenau, Phys. Rev. **59**, 627 (1941).

[8] I. Nonaka, Phys. Rev. **59**, 681 (1941).

[9] S. Kikuchi and H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 75 (1939); Phys. Rev. **55**, 108 (1939); H. Aoki, Phys. Rev. **55**, 795 (1939); W. H. Zinn, S. Seely, and V. W. Cohen, Phys. Rev. **56**, 260 (1939); M. R. MacPhail, Phys. Rev. **57**, 669 (1940).