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Gamma Rays Excited by the Inelastic Scattering of Neutrons in Lead, Bismuth, Iron, Nickel, and Chromium*

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Using neutrons of the *d*-D reaction at an energy of 3.9 Mev, gamma rays have been excited by the inelastic scattering process in Pb, Bi, Fe, Ni, and Cr. The energies of the gamma rays were measured by scintillation spectrometry.

INTRODUCTION

WHEN neutrons are scattered from nuclei, the inelastic process gives rise to excitation of the target nuclei with the resultant emission of gamma radiation and inelastically scattered neutrons of reduced energy. Measurement of the energies of the inelastically scattered neutron groups locates in energy the nuclear excitation levels. From the level structure, if the knowledge thereof is detailed enough, the gamma-ray spectrum can be predicted. However, very few neutron spectra have been accurately measured, and very little is known of a precise nature concerning the properties of the neutron-excited levels. To determine in a reasonable time the nature of the gamma rays, as well as to study the inelastic cross sections, it has been found more feasible to make direct measurements of the emitted gamma rays, rather than the scattered neutrons.

It has been a general practice to use as sources of primary neutrons the *d*-D or the *d*-T reactions, supplying neutron energies of ~3 Mev and ~14 Mev, respectively. Using Geiger counters and a coincidence technique, the energies of gamma rays excited by fast neutron scattering have been measured by the Oxford group.[1,2] These measurements were confined to the use of *d*-D neutrons of energy 2.5 Mev. A similar technique has been employed at neutron energies of 14 Mev at Los Alamos.[3] Scintillation counting methods have also been applied recently to the problem of the gamma-ray detection.[4–8]

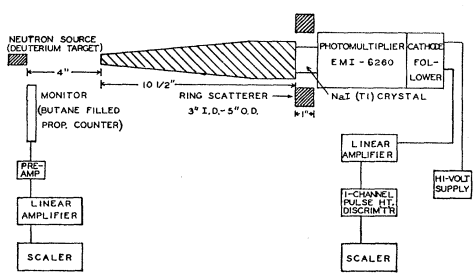

FIG. 1. Geometry and instrumentation for the detection of gamma rays excited by inelastic scattering of neutrons.

EXPERIMENTAL PROCEDURE

Neutrons of energy 3.9 Mev were generated in the smaller Bartol Van de Graaff statitron by passing 1.1-Mev deuterons through a 300-kev thick nickel foil into a chamber containing gaseous deterium. The bombarding beam of magnetically resolved atomic deuterium varied in intensity from 10 to 25 microamperes, half of the beam being lost in striking the supporting grid behind the nickel foil.

The geometry of the scattering measurements is shown in Fig. 1. Neutrons originating in the deuterium target are scattered in the "ring" scatterer surrounding the crystal of NaI-Tl; those scattered inelastically produce gamma rays that are detected in the crystal. The direct beam of neutrons is attenuated by the intervening lead cone. A background counting rate is present which arises from neutrons which are scattered into the crystal by the immediate environment and by the ring scatterer itself. Neutrons which are captured in the crystals of sodium iodide give rise to emissions of gamma rays immediately upon capture, and subsequently to the radiations of the radioactive $I^{128}(T_{\frac{1}{2}}=25$ min) produced. The radiations of I^{128} are characterized by a hard beta-ray spectrum of maximum energy 2.0 Mev. Since an appreciable fraction of the background with scatterer present was indeed found to arise from neutrons deflected into the crystal by the scatterer, the backgrounds with and without the scatterer were evidently different. Consequently, in order to measure the effective background with scatterer present, a ring of graphite was placed around the crystal. Since the first excited level of C^{12} lies at 4.5 Mev, neutrons of 3.9-Mev energy undergo elastic scattering exclusively, and so produce no gamma rays. From a comparison of the product $n\sigma$ for graphite with the same quantity calculated for the elements employed as scatterers, and from a consideration[9] of the angular distribution of fast

* Assisted by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.
[1] Beghian, Grace, Preston, and Halban, Phys. Rev. 77, 286 (1950).
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[3] M. E. Battat, Phys. Rev. 91, 441 (1953).
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[5] L. C. Thompson, Phys. Rev. 89, 905 (1953).
[6] R. B. Day, Phys. Rev. 89, 908 (1953).
[7] Garrett, Hereford, and Sloope, Phys. Rev. 91, 441 (1953).
[8] Scherrer, Smith, Allison, and Faust, Phys. Rev. 91, 768 (1953).
[9] Huber, Baldinger, and Budde, Helv. Phys. Acta 25, 444 (1953); A. E. Remund and R. Ricamo, Helv. Phys. Acta 25, 447 (1953).

neutrons scattered elastically from graphite, it was concluded that graphite should scatter at least as many neutrons into the crystal as do the other scattering elements.

THE MEASUREMENTS

The energy spectrum of the gamma rays excited by 3.9-Mev neutrons on lead is shown in Fig. 2. In Fig. 2(a) are given the pulse height distributions obtained from the NaI crystal, first with the carbon scatterer present to determine the background, and then with

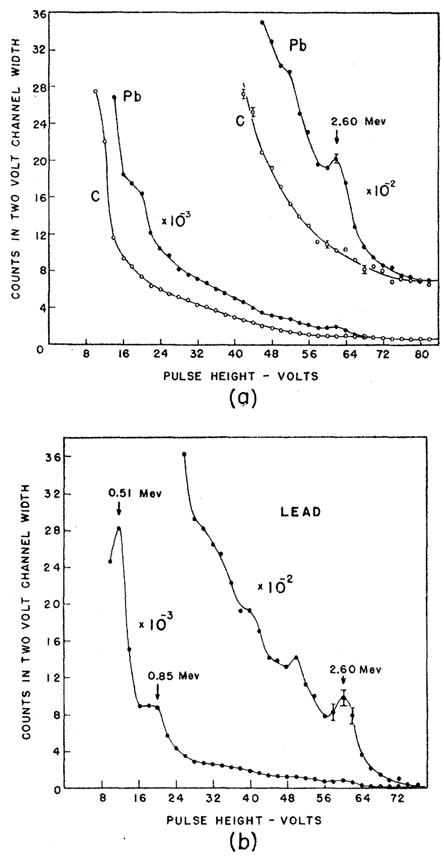

FIG. 2. The energy distribution of pulse heights in the crystal of NaI-Tl with carbon and lead scatterers are shown in Fig. 2(a). Taking the carbon curve as background, the supposed actual contribution of the lead scatterer is shown in Fig. 2(b).

the lead scatterer to determine the gamma rays from the inelastic scattering. The difference curve is given in Fig. 2(b). Although the quantities subtracted are of the same order of magnitude, the experiment was repeated several times, and the results are reproducible in their essential details. Photoelectric peaks corresponding to gamma rays of energies 0.85 and 2.60 Mev are clearly in evidence. Also to be expected are two peaks at 2.1 and 1.6 Mev, caused by pair production in the NaI crystal with the escape of either one or both annihilation quanta from the crystal. These peaks may

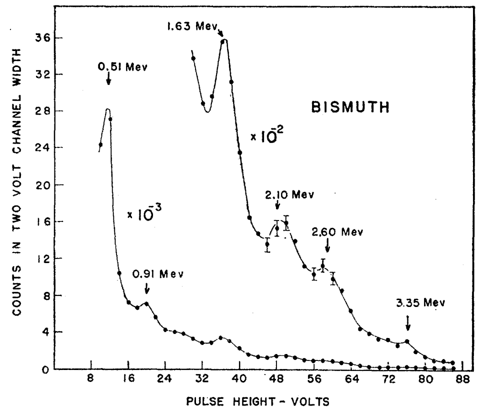

FIG. 3. Pulse-height distribution generated in the crystal of NaI-Tl by the gamma rays resulting from the inelastic scattering of 3.9-Mev neutrons in bismuth.

be superimposed upon a continuum possibly caused in part by low-intensity gamma rays of energy lower than 2.6 Mev. The relatively intense photo peak at 0.51 Mev arises from pair production by the 2.60-Mev gamma ray, and subsequent annihilation occurring within the scatterer itself.

Corroboration of this interpretation of the pulse-height spectrum is obtained by observing the spectrum of the 2.76-Mev gamma ray of Na^{24}. This source, when placed either inside or outside the lead ring, gives a pulse-height distribution which is quite similar in shape to the high-energy region of the spectrum obtained from the lead gamma rays.

An examination of the curves of Fig. 2(a) shows that in the region beyond 2.6 Mev the curves for carbon and lead coincide. Below 2.6 Mev are found the additional contribution of pulses due to the gamma rays from lead. This point is regarded as confirmation of the belief that measurements with the carbon scatterer present yield the true background.

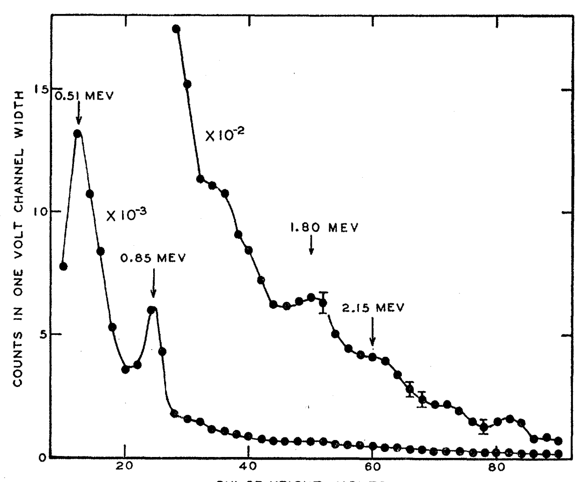

FIG. 4. Gamma-ray spectrum excited by the scattering of 3.9-Mev neutrons in iron.

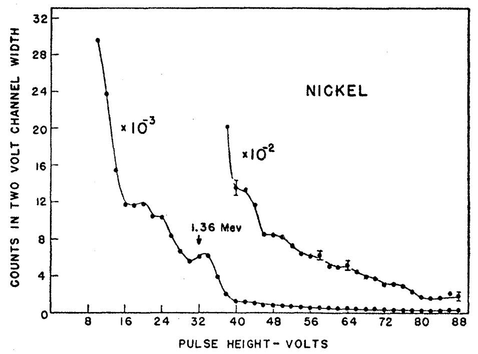

FIG. 5. Gamma-ray spectrum excited by 3.9-Mev neutrons on nickel.

When a scatterer of bismuth was irradiated by 3.9-Mev neutrons, the gamma-ray spectrum of Fig. 3 was obtained. This curve, and those following, have the background observed with the carbon ring already subtracted. The bismuth curve is interpreted to show that gamma rays are emitted at 3.35, 2.60, 1.63, and 0.91 Mev. Again, by comparison with the Na^{24} spectrum, the peak at 2.1 Mev is interpreted as an escape peak of the 2.60-Mev radiation. As in the case of lead, annihilation radiation appears at 0.51 Mev.

The gamma-ray spectrum from neutrons on iron is shown in Fig. 4. The curve can be interpreted as showing the definite presence of the previously reported[5–7] gamma ray at 0.85 Mev as well as gamma rays of quantum energy 1.8 and 2.15 Mev. There is also evidence of gamma rays emitted with quantum energies greater than 2.15 Mev, going up to at least 3.3 Mev. Again, annihilation radiation is seen at 0.51 Mev.

The pulse-height distribution produced by gamma rays from nickel is shown in Fig. 5. There is a clearly identifiable gamma ray at 1.36 Mev, and probably one at 0.9 Mev. In addition there are smaller amounts of radiation at intermediate and higher energies.

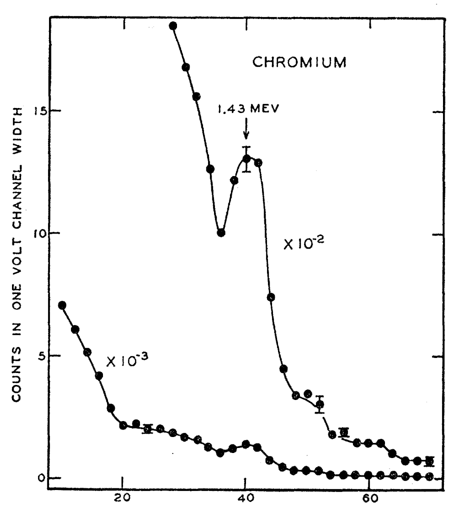

FIG. 6. Gamma-ray spectrum excited by the inelastic scattering of 3.9-Mev neutrons by chromium.

A scatterer of powdered chromium metal was irradiated by neutrons to give the distribution of Fig. 6. A single, broad photoelectric peak is present corresponding to a quantum energy of 1.43 Mev.

The gamma rays listed above are summarized in Table I.

DISCUSSION

An attempt was made to evaluate the relative intensities of the various gamma rays, taking into account the attenuation of the neutrons and gamma rays in each scatterer. Because of the many approximations involved the results will not be given in detail. A general conclusion which evolved was that the inelastic cross sections of the several elements studied do not differ among themselves by more than a factor of two. It is possible that the inelastic cross section for a given element may fluctuate rapidly with the neutron energy. These measurements at 3.9 Mev cannot with certainty be compared with previous data obtained at 4.3 Mev, which indicated appreciably less inelastic scattering in bismuth than in lead.[10] These early measurements[10] were relatively rough, and the estimates of inelastic cross sections could have been in error by a factor of two.

TABLE I. Gamma rays excited by 3.9-Mev neutrons.

Element	Gamma-ray energy (Mev)
Lead	0.85±0.06 2.60±0.06
Bismuth	0.91±0.04 1.63±0.04 2.60±0.06 3.35±0.06
Iron	0.85±0.03 1.80±0.06 2.15±0.08
Nickel	0.90±0.04(?) 1.36±0.04
Chromium	1.43±0.06

Many similarities are found between the gamma rays produced by neutron bombardment and those obtained from radioactive decay. The beta decay of ThC″(Tl^{208}) gives rise to excited states of Pb^{208} which emit well-known 0.86- and 2.61-Mev gamma rays. In like manner the beta decay of Mn^{56} leads to excited states of Fe^{56} which emit gamma rays of 0.85-, 1.8-, and 2.15-Mev energy. Mn^{52} decays by positron emission to excited states of Cr^{52}, with the subsequent appearance of 0.73-, 0.94-, and 1.46-Mev gamma rays. The latter corresponds to the 1.43-Mev gamma ray obtained from the neutron bombardment of chromium. The absence of the 0.73- and 0.94-Mev quanta may be explained by noting that the 1.46-Mev gamma ray arises from a transition

[10] C. E. Mandeville and C. P. Swann, Phys. Rev. 84, 214 (1951).

between the first excited level to the ground state, while the 0.73- and 0.94-Mev quanta come from higher levels. If it is assumed that these higher levels have high spin values, it would not be expected that they would be excited strongly by neutrons of the energy used.

The same argument is applicable in the case of nickel. The radioactive decay of Co^{60} gives two gamma of energy 1.33 and 1.17 Mev, but the neutron bombardment of Ni^{60} produces only one of these, corresponding to the excitation of the first excited state.

It is seen that the pulse-height distributions obtained by neutron scattering in lead, iron, chromium, and nickel are successfully interpreted in terms of gamma rays arising from nuclear energy levels that are known to be excited by other means. This serves as a partial corroboration of the validity of the measurements, and enhances the credence of the results for bismuth, where there is no previous information concerning the energy level structure. The four gamma rays from bismuth give evidence of the presence of a number of excited states which should be observable by other methods of excitation.

ACKNOWLEDGMENT

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Elastic Scattering of Alpha Particles by Neon*

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Differential cross sections for the elastic scattering of alpha particles by neon have been measured at four angles for alpha energies from 2 to 4 Mev. Absolute values of the cross section are good to ± 4 percent. The angles chosen correspond to center-of-mass angles such as to simplify assignments of angular momentum to the scattered resonance wave. Because no nuclear spins are involved, the angular momentum of the scattered wave also fixes the parity and angular momentum of the compound state.

Thirteen resonances were observed. Eleven are attributed to virtual states of Mg^{24} and two are assigned to virtual states of Mg^{26}. The experimental data were analyzed in terms of the Wigner-Eisenbud formalism to determine the additional level parameters: E_r, γ_λ^2 and Δ_λ. The laboratory energies of the $(Ne^{20}+\alpha)$ resonances in Mev, and the total angular momentum and parity assignments of the virtual states are: 2.488(1^-), 2.573 (0^+), 2.652 (2^+), 2.903 (0^+), 3.062 (1^-), 3.184 (2^+), 3.548 (3^-), 3.780 (1^-), 3.801 (2^+), 3.839 (4^+), and 3.923 (2^+). Similarly, the assignments for $(Ne^{22}+\alpha)$ resonances are 3.245 (3^-) and 3.418 (3^-).

The resonances above 3.0-Mev bombarding energy were investigated for competing reactions. No competing reaction with cross sections greater than about one percent of the elastic value were observed.

I. INTRODUCTION

THE elastic scattering of alpha particles by nuclei of zero spin provides a very simple method for classifying the resonant states of the compound nucleus. The method has been discussed in some detail by Cameron[1] and Hill[2] who have studied virtual states of Ne^{20} and O^{16} by alpha scattering on O^{16} and C^{12}. Very briefly stated, the method consists of measuring the elastic scattering cross section as a function of alpha energy at those angles for which the various low-order Legendre polynomials have zeros. The angles at which the resonance scattering vanishes serve to identify clearly the partial waves involved in the resonance scattering. Since no nuclear spins are involved, the angular momentum of the resonance partial wave fixes uniquely the J and parity of the compound nuclear state. The Wigner-Eisenbud dispersion formalism[3,4] may be used to extract the following additional level parameters, E_λ, Δ_λ, ($E_r=E_\lambda+\Delta_\lambda$), and γ_λ^2, where E_λ is the "characteristic" energy of the level, Δ_λ is the level shift, E_r is the resonance energy, and γ_λ^2 is the "reduced" width of the level.

The present experiment has been undertaken to investigate the nuclear energy levels of Mg^{24} by observing resonances in the elastic scattering of alpha particles by Ne^{20}. Earlier work on the scattering of alpha particles by neon[5,6] was done with natural radioactive sources. The energy and angular resolution was too poor to permit observation of resonances below 5-Mev alpha energy. Brubaker studied the reaction from 4 to 7 Mev and observed broad anomalies in the scattering cross-

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‡ National Science Foundation Fellow.

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