Nonresonant Neutron Capture in ^{207}Pb?*

B. J. Allen
Australian Atomic Energy Commission, Sutherland, Australia,
and Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

and

R. L. Macklin
Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830
(Received 16 October 1970)

The neutron-capture cross section of the 41-keV resonance in ^{207}Pb has been measured with improved resolution. Resonance asymmetry is not observed within the accuracy of the measurement and consequently there is no evidence for a significant nonresonant capture cross section.

In the interaction of an incident neutron with a target nucleus the excited compound state can exist for a finite time in any of a large number of possible configurations. The study of the γ-ray decay of the compound system can lead to a description of its excited states, and eventually to an understanding of the neutron-capture mechanism. In recent years evidence has been presented which indicates the significance of single-particle transitions and three quasiparticle doorway states (so called direct and semidirect capture) as well as the long-lived statistical interaction in which all nucleons contribute to the excited-state wave function.

The compound nucleus ^{208}Pb represents an ideal case for the investigation of the neutron-capture mechanism in a doubly closed-shell nucleus. In particular it fills the prescription for direct capture as formulated by Lane and Lynn.[1] The ground state of ^{207}Pb is considered to be mainly a $(p_{1/2})^{-1}$ configuration based on the double closed shell of ^{208}Pb. Conversely, the ground state of ^{208}Pb can be considered to be a nearly pure configuration of a single $p_{1/2}$ neutron in the field of the ^{207}Pb ground state. Consequently, after s-wave neutron capture in ^{207}Pb, an $E1$ transition to the ground state of ^{208}Pb is expected and is observed in thermal capture[2] and at the 41-keV ($l=0$) resonance.[3] The ground-state transition is also expected to be strongly favored as it is the only $E1$ transition possible up to an excitation energy of 5.3 MeV. An order-of-magnitude calculation of the direct-capture cross section was made by Lane and Lynn at thermal energy, but the estimate obtained [$\sigma_D(\text{th}) = 54$ mb] was much less than the measured cross section [$\sigma(\text{th}) = 709$ mb].[4]

The first attempt to measure the direct-capture cross section directly was reported by Broomhall and Bird.[5] Measurements were made with a pulsed Van de Graaff accelerator using a biased NaI detector to observe the 41-keV resonance shape. The observation of asymmetry in this resonance would indicate the presence of resonance-direct interference as formulated by Lovas[6] and permit an estimate of σ_D at 41 keV to be obtained. The analysis of the time-of-flight data was complicated by the presence of a nearby p-wave resonance at 37 keV and inadequate time-of-flight resolution. Nevertheless an asymmetry was reported, and the direct-capture cross section determined to be $\sigma_D(41\text{ keV}) = 0.2$ mb and $\sigma_D(\text{th}) = 250$ mb (assuming a $1/v$ dependence).

A later measurement[7] by Bowman, Baglan, and Bird at the Livermore linac employed the inverse reaction $^{208}\text{Pb}(\gamma, n)$. This is an equivalent reaction as $\Gamma_\gamma \approx \Gamma_{\gamma_0}$ for the 41-keV resonance, and is related by the reciprocity relation

$$\sigma(n,\gamma) = \sigma(\gamma,n)(k_\gamma{}^2 g_n / k_n{}^2 g_\gamma),$$

where k and g are the wave numbers and statistical spin factors for the γ-ray and neutron channels.

The result is shown in the inset of Fig. 1, and the strong asymmetry observed was again interpreted in terms of resonance interference with a nonresonant background capture cross section. The direct-capture cross section was found to be $0.8 < \sigma_D < 1.2$ mb/sr, i.e., $\sigma_D(41\text{ keV}) \approx 12.5$ mb. This result is more than 200 times the Lane and Lynn estimate when extrapolated to 41 keV. It was therefore necessary to include an additional nonresonant term to explain the gross disagreement. An upper limit to the semidirect capture at 41 keV was obtained by fitting the giant dipole resonance of ^{208}Pb into the formalism of Longo and Saporetti.[8] Thus the capture cross section was expressed in terms of direct and semidirect

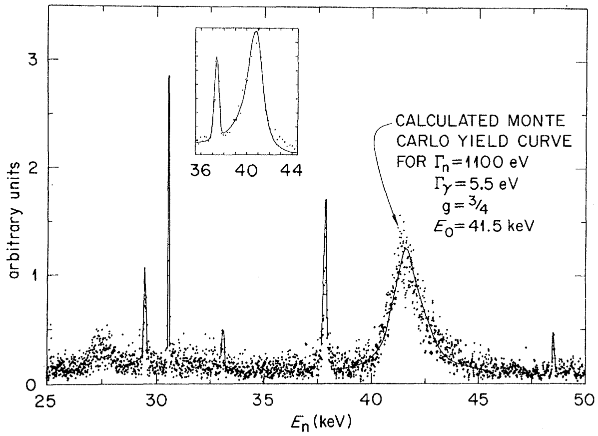

FIG. 1. The neutron-capture yield in a 0.0282-atom/b sample of ^{207}Pb is shown in the energy range 25-50 keV. Energy per channel is 10 eV. The multiple-scattering correction accounts for the high-energy asymmetry of the 41.5-keV resonance and interference effects are not observed. The Livermore result (Ref. 7) is shown in the inset. The broad bump near 27 keV is attributed to capture of sample-scattered neutrons in the fluorocarbon scintillator. No background has been subtracted.

effects, a Breit-Wigner resonance term, and an interference term. However the unlikely assumption that the giant dipole resonance decays exclusively by neutron emission to the ground state of ^{207}Pb was required. The nonresonant cross section at the 41-keV resonance was calculated to be approximately 3.4 mb/sr, i.e., σ_{NR}(41 keV) = 43 mb, and could therefore account for the observed asymmetry.

While the experimental result was confirmed by Haake and McNeill[9] in a second (γ, n) experiment at Toronto, Lane[10] claimed that interference between the direct- and semidirect-capture cross sections would result in a reduced nonresonant cross section. Shakin and Weiss[11] attempted to bridge the widening gap between experiment and theory by accounting for a lower limit of 2.5 mb for the background cross section after a new fit to the Livermore data. These authors calculated the contribution of the tails of the highest subthreshold resonance and of the giant resonance to the nonresonant-capture cross section at 41 keV. The thermal-capture cross section was used to set a limit on the bound-level contribution. These authors found that direct (optical) processes were small compared with the effects of interference from these resonance tails.

Because of the considerable importance of this problem to our understanding of the neutron-capture mechanism, the capture cross section has been remeasured using the Oak Ridge linear electron accelerator (ORELA). The resolution of this experiment is approximately forty times sharper than the early Van de Graaff measurement and seven times the Livermore experiment.

The capture-cross-section facility has been described elsewhere[12] and only a brief summary is given here. Two total-energy detectors at 40 m were used to observe capture γ rays in 142.7 g of separated ^{207}Pb (95%). Timing resolution was approximately 6 nsec, the major contribution being from the linac pulse itself. The ^{207}Pb cross section was measured from 3 keV up to 200 keV using the iodine-capture cross section as a secondary standard, and will be reported in detail at a later date.

The capture cross section in the region of the 41-keV s-wave resonance is shown in Fig. 1. The gross asymmetry observed at Livermore is absent in this result. Asymmetry is observed, however, but at the high-energy side of the resonance, and is accounted for by a multiple-scattering correction obtained from a Monte Carlo code[13] as shown in Fig. 1. Resonance parameters used in the calculation are those of Macklin, Pasma, and Gibbons.[14]

There is no need to invoke any nonresonant capture cross section as asymmetry is not observed within the accuracy of the measurement. Alternatively, an upper limit of about $\sigma_D = 2$ mb at 41 keV can be set for the nonresonant cross section. Greatly improved statistics and a thinner sample are required to reduce this upper limit. It is unfortunate that the interference asymmetry as indicated by Lovas[6] is in the same direction as the multiple-scattering correction.

How then to explain the anomalous (γ, n) results? In both (γ, n) measurements a natural Pb sample was used. At the 41-keV resonance the transmission of emerging neutrons in the ^{208}Pb(γ, n) reaction is reduced substantially on resonance elastic scattering in the 22.6% ^{207}Pb in the natural sample. Thus multiple scattering can occur and many resonance neutrons would lose energy before emerging from the sample. Multiple scattering would have the opposite effect to that in neutron capture and may well account for the observed asymmetry on the low-energy side of the resonance. This effect is not apparent in the 37.5-keV resonance as the recoil energy loss of the emitted neutron is an order of magnitude greater than the resonance width.

The authors are grateful to A. M. Lane and

G. A. Bartholomew for private communications with regard to this problem.

*Research sponsored by the U. S. Atomic Energy Commission under contract with the Union Carbide Corp.

[1]A. M. Lane and J. E. Lynn, Nucl. Phys. 17, 586 (1960).
[2]E. T. Jurney and H. T. Motz, ANL Report No. ANL-6797, 1963 (unpublished), p. 236.
[3]J. A. Biggerstaff, J. R. Bird, J. H. Gibbons, and W. J. Good, Phys. Rev. 154, 1136 (1967).
[4]L. V. Groshev *et al.*, Nucl. Data, Sect. A 5, 404 (1969).
[5]G. J. Broomhall and J. R. Bird, Nucl Phys. 121, 329 (1968).
[6]I. Lovas, Zh. Eksp. Teor. Fiz. 41, 1178 (1961) [Sov. Phys. JETP 14, 840 (1962)].
[7]C. D. Bowman, R. J. Baglan, and B. L. Berman, Phys. Rev. Lett. 23, 796 (1969).
[8]G. Longo and F. Saporetti, Nuovo Cimento 56B, 264 (1968).
[9]L. C. Haacke and K. G. McNeill, Bull. Amer. Phys. Soc. 15, 482 (1970).
[10]A. M. Lane, private communication.
[11]C. M. Shakin and M. S. Weiss, Phys. Rev. C (to be published).
[12]R. L. Macklin and B. J. Allen, to be published.
[13]J. G. Sullivan, G. G. Warner, R. C. Block, and R. W. Hockenbury, Rensselaer Polytechnic Institute Report No. RPI-328-171, 1969 (unpublished), p. 53.
[14]R. L. Macklin, P. J. Pasma, and J. H. Gibbons, Phys. Rev. 136, B695 (1964).

Sensitivity of the (^{3}He,t) Reaction to Final-State Configurations*

J. E. Holden, H. T. Fortune, D. P. Balamuth, and R. W. Zurmühle
University of Pennsylvania, Philadelphia, Pennsylvania 19104
(Received 18 September 1970)

The reactions ^{27}Al(^{3}He,t)^{27}Si and ^{23}Na(^{3}He,t)^{23}Mg have been studied at a bombarding energy of 18 MeV. Within each nucleus angular distributions leading to states of the same spin and parity have been found to show a pronounced dependence on the configuration of the final state, contrary to previous suggestions. Such a dependence is consistent with the results of microscopic distorted-wave Born-approximation calculations.

It has recently been suggested[1] that, for transitions in which there is no parity change, the (^{3}He,t) reaction on odd-mass targets proceeds via the lowest value of orbital angular-momentum transfer permitted by the condition that the intrinsic-spin transfer be zero. Transitions between states of the same angular momentum would thus be characterized by $L=0$; those between states whose angular momenta differ by one or two units by $L=2$. This implies that angular distributions from (^{3}He,t) reactions are generally not sensitive to the detailed configurations of the nuclear states involved. A test of this suggestion consists of studying transitions to states (in a given nucleus) having the same spin and parity but different configurations.

It should be noted that in Ref. 1 all the transitions in which the final-state spin is equal to the target spin are transitions between isobaric analog states (analog transitions). Since the analog state has nearly the same space-spin wave function as the target state, almost any model of the (^{3}He,t) process would predict zero orbital angular-momentum transfer for analog transitions. It is not obvious, then, that this selectivity holds for nonanalog transitions.

Targets in the 2s-1d shell were selected for investigation of configuration dependence. The (^{3}He,t) reaction on ^{23}Na and ^{27}Al was studied using an 18-MeV ^{3}He beam from the University of Pennsylvania's Model EN tandem Van de Graaff accelerator. Tritons were detected in a system of solid-state detector telescopes, using digital particle identification. The energy resolution was 40 keV in both experiments. Angular distributions were measured for many low-lying states.

Angular distributions for the reaction ^{27}Al(^{3}He,t)^{27}Si leading to the two $J^\Pi=\frac{5}{2}^+$ states at 0 and 2.65 MeV in ^{27}Si and for the reaction ^{23}Na(^{3}He,t)^{23}Mg leading to the two $J^\Pi=\frac{3}{2}^+$ states at 0 and 2.90 MeV in ^{23}Mg are displayed in Fig. 1. In both cases the angular distribution for the excited-state transition is quite different from that of the corresponding analog transition, despite the fact that the final-state angular momentum and parity are equal to those of the target. Specifically, the sharp $L=0$ structure is seen to be missing.

The breakdown of the simple prescription of Ref. 1 can be further illustrated by comparing two nonanalog transitions. The (^{3}He,t) angular