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Neutron-induced deuteron production from light nuclei at 800 MeV*

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The deuteron sepctra from (n,d) reactions at 800 MeV near 0° are characterized by a high energy quasielastic scattering peak, and at lower momentum, a quasifree scattering peak. The ratio of the quasifree to quasielastic cross sections is approximately 10:1. Both cross sections exhibit an $A^{1/3}$ mass dependence over the range of target nuclei studied. Comparisons are made with corresponding proton-induced quasielastic and quasifree deuteron production.

[NUCLEAR REACTIONS $n+X\to d$. $E_{\rm lab}=800$ MeV. Measured deuteron quasielastic and quasifree cross sections near 0°.]

The interaction of high-energy protons with nuclei leads to a copious production of high-energy deuterons at angles near 0°, both with and without pion production.[1] The deuteron spectra near 0° are characterized by a high-energy peak centered at approximately the momentum expected for free $pd\to dp$ elastic scattering, and a second much more intense peak at about the momentum expected for two-body $pN\to d\pi$ pion production processes.[2] These two peaks are respectively attributed to quasielastic (QE) and quasifree (QF) scattering in the target nuclei. The present work is concerned with neutron-induced deuteron production.

Most experimental measurements with protons have used a deuterium target, and most theoretical analyses have been limited to elastic pd scattering. The failure of the one-nucleon-exchange mechanism to fit the backward peak observed in the pd elastic scattering cross section led Kerman and Kisslinger[3] to propose the existence of N^* $(1688, J=\frac{5}{2}^+)$ components in the deuteron wave function. Gurvitz and Rinat,[4] on the other hand, postulate a deuteron form factor that provides a much larger probability for high momentum transfers than given by presently accepted deuteron form factors. Another approach has been taken by Craigie and Wilkin[5] and Barry,[6] who have employed the one-pion-exchange model through the use of the triangle diagram to describe back angle pd elastic scattering in terms of the $pp\to d\pi^+$ differential cross section.

Quasielastic deuteron production from complex nuclei has been discussed recently by Remler and Sathe,[7] who calculate the dependence of the cross section on atomic number and on energy. In this model the incident nucleon travels through part of the nucleus suffering multiple small angle collisions. It then produces a fast n-p pair with roughly equal forward momenta from some small region situated along its path. This pair travels through the remainder of the nucleus, experiencing multiple small angle collisions. Finally, the n-p pair emerges from the nucleus to remain unbound or to coalesce into a deuteron. The model utilizes only one free parameter, an effective "nucleon pair volume" V_c, which is obtained by matching theory to the present experimentally measured cross section for neutrons on Cu at 0.8 GeV. Remler points out that the study of QE deuteron production can (a) give an estimate of which nuclear regions are probed by such processes, and (b) estimate the importance of off-shell collisions during intranuclear cascades, since the emerging quasielastic deuterons serve as a signature of such internal events. In addition, QE and QF deuteron production should provide information on short range correlations in nuclei.

We report here on measurements of deuterons produced by the LAMPF 800-MeV neutron beam from interactions with targets of ^{6}Li, ^{7}Li, ^{9}Be, ^{12}C, ^{27}Al, and natural Cu at laboratory angles of 0°, 16°, and 24°. The neutron beam, produced via the 0° $d(p,n)2p$ reaction,[8] has a sharp 800-MeV peak and a broad low-intensity component

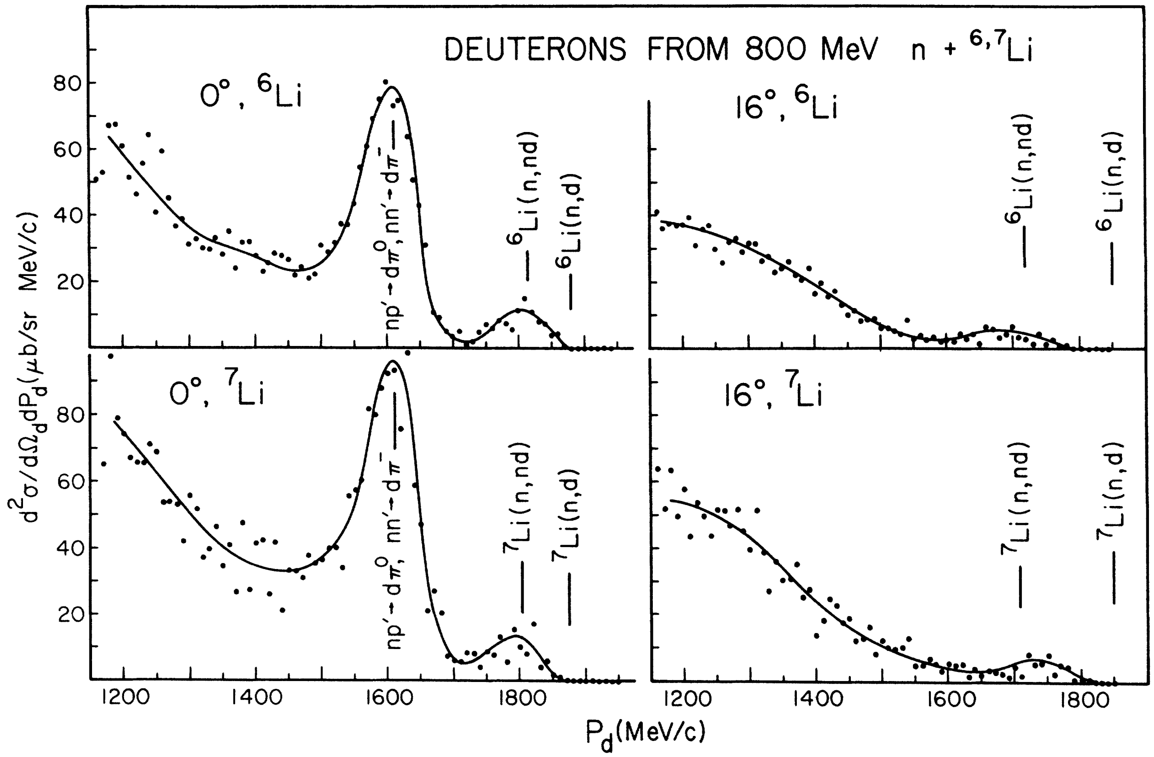

FIG. 1. Deuteron spectra from the reactions $n+{}^7$Li and $n+{}^6$Li at 0° and 16° and 800 MeV.

at lower momenta. Charged particles were momentum analyzed using a single-arm magnetic spectrometer.[9] Particle identification was achieved by means of a rest mass calculation, $m_0=p/\beta\gamma$, the velocity of the charged particle being obtained by means of a time-of-flight measurement. Figure 1 shows deuteron momentum spectra at 0° and 16° from ^{6}Li and ^{7}Li. At 0° the spectra are characterized by a weak peak centered at about 1800 MeV/c, attributed to QE scattering, and a much more intense peak centered at about 1600 MeV/c, at the momentum expected for the QF $np'\to d\pi^0$ and $nn'\to d\pi^-$ processes. The 0° QE and QF widths [full width at half maximum (FWHM)] are approximately 100 MeV/c for all targets. At 16° and 24° there is no evidence for the QF processes, as expected from kinematic considerations. A weak, broad QE peak is still observed at 16° and 24° followed by a rising low-momentum "tail." No evidence is seen at any of the angles for the direct (n,d) pickup process. This is consistent with the ^{12}C(p,d) cross sections reported by Thirion[10] at 700 MeV, which are of the order of microbarns, beneath the sensitivity of the present measurement.

Figure 2 shows the 0° integrated cross sections for both the QE and QF processes versus the mass number A of the target. The QF and QE cross sections exhibit a reasonably smooth $A^{1/3}$ dependence over the whole mass range. The $A^{1/3}$ straight line is drawn through the cross section for Cu. For neutrons on deuterium, the measured 0° QF cross section is about equal to the sum of the corresponding free nucleon cross sections, or about 6 mb/sr.[11] The free $nd\to dn$ elastic cross section at 0° is 0.29 mb/sr.[11] The QF and QE cross section data are shown in Table I.

The QF scattering data for ^{6}Li, ^{7}Li, and ^{9}Be appear anomalously high, which perhaps can be explained by an experimental difficulty which makes the 0° QF data for ^{6}Li and ^{7}Li less reliable than those for the other targets. A veto counter was positioned immediately upstream of the target to ensure that charged particles in the neutron beam would not trigger the spectrometer. Unfortunately, in the QF reaction $nn'\to d\pi^-$ with the deuteron at 0°, the associated π^- is emitted directly backward near 180°, the precise angle being determined by the momentum of the struck neutron. Thus, a sufficiently large veto counter would completely reject $nn'\to d\pi^-$ events but would not affect $np'\to d\pi^0$ events. Measurements and calculations of the effect with a deuterium target and the same geometry as had been used in the ^{6}Li and ^{7}Li work indicated that about 50% of the QF $nn'\to d\pi^-$ events were rejected. Since $\sigma_{nn\to d\pi^-}$

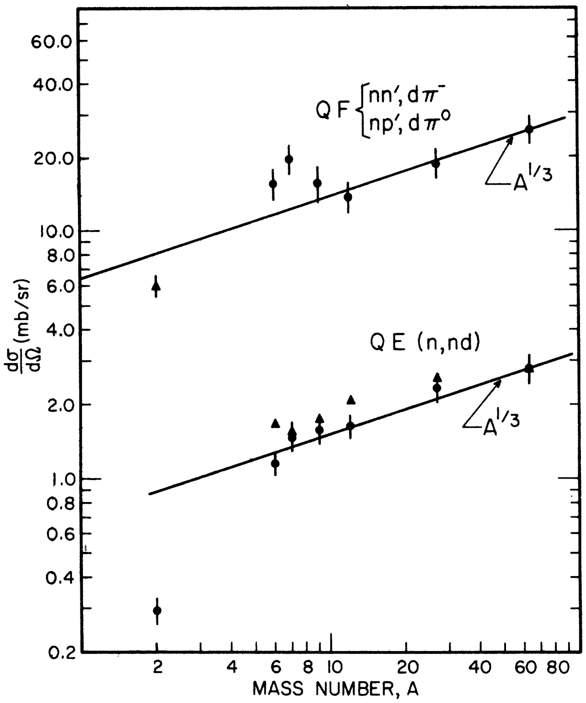

FIG. 2. 0° QE and QF deuteron production differential cross sections vs the mass number A of the target. The triangles indicate theoretical predictions of Ref. 6 normalized to the QE cross section for CU. The cross sections for mass 2 are taken from Ref. 11.

$=2\sigma_{np\rightarrow d\pi^0}$, about 33% of the total QF events were rejected, and this correction was applied to the ^{6}Li and ^{7}Li data. For all other targets, a smaller veto counter was used. For these cases, the calculated correction was 10%.

Our measurements can be compared with similar proton-induced data reported by Dzhelepov at 670 MeV,[2] and with QE measurements by Sutter *et al.*[12] at 1 GeV, and by Boschitz[13] at 582 MeV. Dzhelepov reported the widths (FWHM) of the QF deuteron peak from ^{7}Li and ^{12}C to be about 130 MeV/c at 670 MeV and at a laboratory angle of 6.5°, somewhat broader than the 0° widths of the present work. The cross sections reported in the above proton-induced measurements, when corrected for energy and angular dependences, are in reasonable agreement with our data. The corrections were made by assuming that the QE and QF cross sections vary according to the corresponding free N-d and $pp\rightarrow d\pi^+$ cross sections, respectively. The free nd-dn scattering cross section of 0.29 mb/sr falls well below the QE $A^{1/3}$ curve for an A value of 2. This phenomenon is also apparent in the proton-induced QE data. The average ratio of the integrated QF/QE yields for $A>2$ is 10:1. The cross sections for both ^{6}Li and ^{7}Li are in agreement with the aid of the $A^{1/3}$ dependence to within the experimental errors, but the cross sections for ^{7}Li appear slightly larger than those for ^{6}Li.

The observed A dependence of the QE data agrees well with the theoretical model of Remler.[7] The predictions of the model, normalized to the present QE scattering cross section for Cu, are shown as triangles in Fig. 2. The QE data also indicate that the ratio σ_{QE}/σ_E, where σ_E is the elastic nd differential cross section, tends to remain approximately constant with increasing angle. This also is in qualitative agreement with Remler's model.

Our data, which show that the (n,d) QF and QE cross sections differ in magnitude by approximately a factor of 10 at 0° for all A, would also appear

TABLE I. Integral values of differential cross sections, $\int d^2\sigma/(d\Omega dp)dp$, in mb/sr at 800 MeV. All cross sections have a 15% systematic error. Cross sections for deuterium are taken from Ref. 11. Footnotes (a)–(d) do not apply to deuterium.

Target	Quasifree (QF) 0°(lab) [a]	Quasielastic (QE) 0°(lab) [b]	16°(lab) [c]	24°(lab) [d]
^{2}H	6.0	0.29	0.11	(0.035) [e]
^{6}Li	15.5	1.15	0.29	
^{7}Li	19.6	1.47	0.39	
^{9}Be	15.6	1.56	0.33	0.21
^{12}C	13.4	1.62	0.59	0.31
^{27}Al	18.8	2.30		
Cu	25.6	2.72		

[a] Range is $p=1480$–1680 MeV/c.
[b] Range is $p=1710$–1890 MeV/c.
[c] Range is $p=1650$–1800 MeV/c.
[d] Range is $p=1550$–1730 MeV/c.
[e] Extrapolated value only.

to lend support to the triangle diagram calculation.[5,6] This model, in effect, relates the $nn \to d\pi^-$ and $np \to d\pi^0$ processes to $nd \to dn$ elastic back angle scattering. However, the $A^{1/3}$ dependence can be accounted for by the combined effects of attenuation of incident nucleons inside the nucleus, and of nucleon pairs travelling outward from the point of interaction.[7] That is, the $A^{1/3}$ dependence may not be strongly correlated to the deuteron production mechanism itself, and further investigation of this point would be interesting. It may be noted that, in complex nuclei, either correlated n-p pairs of correlated p-p pairs inside the nucleus can contribute comparably to deuteron production. For example, with the one-pion-exchange model, both $n(np)' \to dn$ and $n(pp)' \to dp$ scattering can occur. The increased probability of finding correlated nucleon pairs in complex nuclei could explain why the cross section for elastic N-d scattering falls well below the $A^{1/3}$ curve for QE scattering from nuclei of higher mass. A similar argument may explain the slightly larger observed QE and QF cross sections for ^{7}Li than for ^{6}Li.

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