AC

GSI-95-02
PREPRINT
JANUAR 1995

NEUTRON MOMENTUM DISTRIBUTIONS FROM 'CORE BREAK-UP' REACTIONS OF HALO NUCLEI

T. NILSSON, Th. BLAICH, M.J.G. BORGE, L.V. CHULKOV, Th.W. ELZE, H. EMLING, H. GEISSEL, K. GRIMM, D. GUILLEMAUD-MUELLER, P.G. HANSEN, R. HOLZMANN, P. HORNSHOJ, F. HUMBERT, H. IRNICH, L. JOHANNSEN, B. JONSON, M. KEIM, J.G. KELLER, H. KLINGLER, J.V. KRATZ, R. KULESSA, D. LAMBRECHT, Y. LEIFELS, M. LEWITOWICZ, A. MAGEL, M.F. MOHAR, A.C. MUELLER, G. MÜNZENBERG, R. NEUGART, F. NICKEL, G. NYMAN, A. RICHTER, K. RIISAGER, M.-G. SAINT-LAURENT, C. SCHEIDENBERGER, G. SCHRIEDER, W. SCHWAB, B.M. SHERRILL, H. SIMON, O. SORLIN, K. STELZER, J. STROTH, O. TENGBLAD, E. WAJDA, K. WILHELMSEN ROLANDER, M. ZINSER, E. ZUDE

(Submitted to Europhys. Lett.)

Gesellschaft für Schwerionenforschung mbH
Postfach 11 05 52 D-64220 Darmstadt Germany

Neutron momentum distributions from "core break-up" reactions of halo nuclei

T. Nilsson[1], Th. Blaich[2], M.J.G. Borge[3], L.V. Chulkov[4], Th.W. Elze[5], H. Emling[6], H. Geissel[6], K. Grimm[5], D. Guillemaud-Mueller[7], P.G. Hansen[8], R. Holzmann[6], P. Hornshøj[8], F. Humbert[6], H. Irnich[5], L. Johannsen[8], B. Jonson[1], M. Keim[10], J.G. Keller[11], H. Klingler[5], J.V. Kratz[2], R. Kulessa[12], D. Lambrecht[2], Y. Leifels[11], M. Lewitowicz[13], A. Magel[6], M.F. Mohar[6], A.C. Mueller[7], G. Münzenberg[6], R. Neugart[10], F. Nickel[6], G. Nyman[1], A. Richter[9], K. Riisager[8], M.-G. Saint-Laurent[13], C. Scheidenberger[6], G. Schrieder[9], W. Schwab[6], B.M.Sherrill[14], H. Simon[9], O. Sorlin[7], K. Stelzer[5], J. Stroth[6], O. Tengblad[15], E. Wajda[12], K. Wilhelmsen Rolander[1], M. Zinser[6] and E. Zude[6]

December 14, 1994

1. Fysiska Institutionen, Chalmers Tekniska Högskola, S-412 96 Göteborg
2. Institut für Kernchemie, Johannes-Gutenberg-Universität, D-55099 Mainz
3. Insto. Estructura de la Materia, CSIC, E-28006 Madrid
4. Russian Scientific Center "Kurchatov Institute", Inst. Gen. and Nucl. Phys., Moscow 123182
5. Institut für Kernphysik, Johann-Wolfgang-Goethe-Universität, D-60486 Frankfurt
6. Gesellschaft für Schwerionenforschung (GSI), D-64291 Darmstadt
7. Institut de Physique Nucléaire, BP 1, F-91406 Orsay Cedex
8. Institut for Fysik og Astronomi, Aarhus Universitet, DK-8000 Aarhus C
9. Institut für Kernphysik, Technische Hochschule, D-64289 Darmstadt
10. Institut für Physik, Universität Mainz, D-55099 Mainz
11. Institut für Experimentalphysik, Ruhr-Universität Bochum, D-44780 Bochum
12. Instytut Fizyki, Uniwersytet Jagelloński, PL-30-059 Kraków
13. GANIL, BP 5027, F-14021 Caen Cedex
14. Michigan State University, East Lansing, MI 48824-1321, USA
15. PPE Division, CERN, CH-1211 Genève 23

Abstract

Neutron angular distributions from violent break-up reactions of ^{11}Li and ^{11}Be have been measured at 28 MeV/u and 280 MeV/u and at 41 MeV/u and 460 MeV/u, respectively. The derived neutron momentum distributions show a narrow component in transverse momentum that is within uncertainties independent of beam energy and target charge. This component is suggested to be simply related to the momentum distribution of the loosely bound halo neutron(s) in the projectiles.

1 Introduction

The last years have witnessed a rapid increase of our knowledge on nuclear halo states, see e.g. the overviews provided in [1,2]. A question only partially answered so far is which experimental probe will provide the most reliable information on the momentum distribution of the halo wavefunction. Previous work (see e.g. ref. [3]) has concentrated on measurements of neutron or charged fragment distributions — both parallel and transverse to the beam direction — from the "halo-removal" channel, i.e. the one-neutron removal channel for ^{11}Be and the two-neutron removal channel for ^{6}He, ^{11}Li, ^{14}Be and similar nuclei. We present here experimental data on neutron transverse momentum distributions from other channels and suggest how these might be interpreted to give information on the structure of the halo ground state.

The experiments were carried out at GANIL and GSI and the experimental procedures have been described in detail elsewhere [4,5,6,7]. Beams of ^{11}Li at 28 MeV/u at GANIL and at a ten times higher energy of 280 MeV/u at GSI and similarly of ^{11}Be at 41 MeV/u and 460 MeV/u were directed on both light and heavy targets. The emerging neutrons were measured in coincidence with the charged fragments used to identify the reaction channel. The neutron detectors are described in refs. [4,5,8].

The data to be discussed stem from collisions in which the core of the halo nucleus, i.e. ^{9}Li in the case of ^{11}Li and ^{10}Be in the case of ^{11}Be, was destroyed during the interaction. We shall refer to these as "core break-up" channels. One particular combination, including all observed channels in which the core interacts (i.e. channels except the halo-removal one), has been presented in [6] and is there denoted the "restricted inclusive" channel.

2 Motivation

Before turning to the experimental data we shall review briefly the present status of the interpretation of momentum distributions from the halo-removal channels. Originally, these distributions were hoped to reflect quite directly the momentum distributions of the halo neutron(s) in the ground state. This hope was partly based on previous experiences from experiments at high energy where the longitudinal core momentum distribution in certain cases seemed to give direct information [9]. However, most experiments at low energies that have been analyzed in detail have shown that the reaction mechanism also plays an important role. This is seen quite clearly in our measured [5] neutron distributions from ^{11}Be, which for light targets show a clear diffraction pattern and for heavier targets a drop at zero angle arising from Coulomb excitation to a final p-state. Although not immediately evident from the data [4], the reaction mechanisms play a similar role for the neutron distributions from ^{11}Li as well [10,11]. Here an important part is also played by the neutron-core and neutron-neutron interactions. Note, that the distributions typically change with beam energy as this can change the relative importance of the different reaction mechanisms.

Both transverse [12] and longitudinal [7,13,14] core momentum distributions have been measured; so far mainly results for ^{11}Li have been published. The transverse distributions have been shown to be affected by reaction mechanisms and final state interactions [15,16], see also [17,18] where neutron and core distributions are considered simultaneously. Finally, one can also extract distributions from the experiments with complete kinematics [19] and an analysis of these [20] leads to quite similar conclusions. The neutron and transverse core momentum distributions derived are clearly different in the various reactions and the width of the longitudinal core momentum distributions seems to vary (although only weakly) with target [7,14]. From the limited theoretical investigations performed so far only the longitudinal core momentum distributions on light targets at high beam energy can be identified as a candidate for an undistorted picture of the ground state [9].

An obvious goal is to find the channels where the measured momentum distribution is as close as possible to the true one. With this in mind we consider here the neutron distributions from collisions in which the core reacts — the core break-up channels. The core-target collision will be violent and will take place on a short time scale so that the sudden approximation may be used for describing the fate of the halo neutrons. We want to test the hypothesis that the neutrons in this case are very little affected by the collision due to their weak coupling to the core and thus emerge with a momentum distribution close to the one of the halo neutron. There are certainly distortions — the part of the wavefunction of the halo neutrons that overlaps with the core will be altered, see e.g. section 3.4 in [6] or the discussion in [9] — but for small momenta (large distances from the core) one might reasonably expect such distortions to be moderate. Hopefully final state interactions may be small due to the velocity difference between the halo neutrons and the core products. The core-target collision will itself give rise to a neutron component, but this is expected to be significantly broader in momentum than the halo component. If the core and the halo decouple, i.e. if the inert-core approximation for the halo nucleus is valid, the core component can in principle be measured in a separate experiment using the core nucleus as projectile.

3 Results

We now turn to the data to see if these expectations are borne out. The first figure presents the neutron angular distributions from the sum of all observed core break-up channels, recorded at GANIL, for ^{11}Li. The angular acceptance in the experiment was not sufficient to allow a clear separation of the experimental spectrum into a "halo" and a "core" component. It was, however, possible to do a rough subtraction of the core component as a short run with a ^{9}Li beam was made. Figure 1 also shows the resulting angular distribution after subtraction for the Be target. With a conservative estimate of the systematic uncertainties involved in the subtraction procedure and fitting the distribution with a single Lorentzian (parametrized by a width parameter Γ) we obtain a full width half maximum (FWHM) for the halo component that converts to a value $\Gamma = 42 \pm 4$ MeV/c. The parametrisation for the Lorentzian is

$$W(p_r)dA = \frac{\Gamma}{4\pi} \frac{dA}{(p_r^2 + \Gamma^2/4)^{3/2}} \ . \qquad (1)$$

where p_r is the (two-dimensional) radial momentum component and dA = $p_r \mathrm{d}p_r \mathrm{d}\phi$. (See [21] for details of the conversion of FWHM to Γ.)

No similar subtraction of the core distribution was feasible for the case of ^{11}Be. Apart from the total neutron distribution taken in anti-coincidence with the core, also distributions obtained with Be and Ti targets with a more restrictive gate, namely demanding a Li or He fragment was obtained here. The data are presented in Figs. 10 and 11 in ref. [6]. The distributions with different gates have the same shape at small angles and thus seem to originate from the same physical process. This is not too surprising if the above hypothesis is correct as the halo neutrons should continue unperturbed no matter what happens to the core[1].

One should note that there is a distinct difference between the distributions obtained at small angles in the halo-removal channel and the core break-up channels. The former shows a clear influence of the reaction mechanism [5,6], while the shape of the latter distribution is universal. The Γ parameters from fits with a single Lorentzian are given in Table 1. The value given for the distribution in coincidence with a Li fragment is the sum over the channels ^{6}Li, ^{7}Li, ^{8}Li and ^{9}Li. As can be seen from the GSI data the latter is noticeably influenced by final state interactions, decreasing the width to 36 MeV/c [22]. The same mechanism is present at the GANIL energy and explains the smaller width measured in the ^{4}Li - channel.

Figures 2 and 3 present neutron angular distributions obtained at GSI for ^{11}Li and for ^{11}Be, respectively. All distributions given are without subtraction of core components. Note that the coverage in transverse momentum is too small for a disentanglement of the core and halo components. The ^{11}Li data were extracted by demanding a charged fragment within the acceptance of the set-up, excluding ^{9}Li. This gave a lower cut-off in A/Z of 2.3 for the ions and therefore excluded channels, like ^{6}Li and ^{4}He, where several neutrons from the core could distort the distribution. The result is thus likely to be less perturbed than the one from the GANIL-data, making core component subtraction less important. The acceptance correction is complex for many of the core break-up channels (the set-up was optimized for the halo-removal channel) which makes the uncertainty of the absolute cross sections large. The shapes of the curves are, however, only determined by counting statistics. The extracted distributions for a C and a Pb target were fitted with single Lorentzians, giving values for Γ of (43 ± 3) MeV/c and (36 ± 4) MeV/c respectively. This is in agreement with the value obtained at 28 MeV/u and shows no significant difference between a light and a heavy target.

The data on ^{11}Be are even more encouraging. Within uncertainties the distributions here are independent of target and reaction channel and furthermore in agreement with the ones obtained at GANIL. The Γ values are again listed in table 1. They agree well with the value of 58.7 MeV/c predicted from the simple model of the ^{11}Be ground state in terms

---

[1] To emphasize this point we consider here core break-up processes in general instead of just the restricted inclusive channel. The count rate will of course decrease for a more restrictive gate, but such distributions are in some cases easier to extract in a clean way experimentally.

of a zero range Yukawa wavefunction [1]. The distributions for the ^{4}He channel could also be extracted. They are slightly wider, 70–80 MeV/c, but we tentatively attribute this to the contribution from the core neutrons which in this channel is significantly larger as seen, e.g., from the average hit multiplicity in the neutron detectors. Direct measurements with a ^{10}Be beam should yield this component and could thereby clarify the situation.

4 Conclusions

The width parameters collected in table 1 seem to confirm the hypothesis from section 2: They are much narrower than the ones expected from the systematics of fragmentation [23] and are in order of magnitude as narrow as the ones obtained in the halo-removal channel. As final averages over all data obtained (except in the Li-coincident ones from GANIL where final state interactions interfere) — with error bars dominated by the systematic errors — we get Γ values of 60±5 MeV/c for ^{11}Be and 41±4 MeV/c for ^{11}Li. The former is consistent with the estimate from a simple Yukawa type one-neutron halo wavefunction [6], the latter might therefore correspond to the ^{11}Li halo neutron wavefunction.

To sum up, the neutron distributions from ^{11}Be in core break-up collisions are at small angles essentially independent of beam energy and target charge and agree with the one expected for the original halo ground state wavefunction. This indicates that the momentum distribution of the halo neutron is very little perturbed in a violent core-target collision. The data on ^{11}Li can be interpreted consistently in a similar way.

5 Acknowledgements

This work was supported by the German Federal Minister for Research and Technology (BMFT) under Contracts 06 DA 641 I, 06 BO 103 and 06 MZ 465 and by GSI via Hochschulzusammenarbeitsvereinbarungen under Contracts DA RICK, BO FRE, F ELE, MZKrak and partly supported by the Polish Committee of Scientific Research under Contract PB1158/P3/92/02.

References

[1] P.G. Hansen, Nucl. Phys. **A553** (1993) 89c; B. Jonson, Nucl. Phys. **A574** (1994) 151c; K. Riisager, Rev. Mod. Phys. **66** (1994) 1105

[2] M.V. Zhukov et al., Phys. Reports **231** (1993) 151

[3] Proc. Third Int. Conf. Radioactive Nuclear Beams, East Lansing, May 1993, ed. D.J. Morrissey, (Editions Frontières, 1993)

[4] R. Anne et al., Phys. Lett. **B250** (1990) 19; K. Riisager et al. Nucl. Phys. **A540** (1992) 365

[5] R. Anne et al., Phys. Lett. **B304** (1993) 55

[6] R. Anne et al., Nucl. Phys. **A575** (1994) 125

[7] F. Humbert et al., submitted to Phys. Lett.

[8] Th. Blaich et al., the LAND Collaboration, Nucl. Instr. Meth. **A314** (1992) 136

[9] J. Hüfner and M.C. Nemes, Phys. Rev. **C23** (1981) 2538

[10] H. Esbensen, Phys. Rev. **C44** (1991) 440; H. Esbensen and G.F. Bertsch, Nucl. Phys. **A542** (1992) 310

[11] F. Barranco, E. Vigezzi and R.A. Broglia, Phys. Lett. **B319** (1993) 387

[12] T. Kobayashi et al., Phys. Rev. Lett. **60** (1988) 2599; I. Tanihata et al., Phys. Lett. **287B** (1992) 307

[13] N.A. Orr et al., Phys. Rev. Lett. **69** (1992) 2050

[14] N.A. Orr et al., Phys. Rev. to be published

[15] C.A. Bertulani and K.W. McVoy, Phys. Rev. **C46** (1992) 2638

[16] M.V. Zhukov et al., J. Phys. **G20** (1994) 201

[17] D.V. Fedorov, M.V. Zhukov, J.M. Bang and J.S. Vaagen, NORDITA preprint 92/36 N

[18] A.A. Korsheninnikov and T. Kobayashi, Nucl. Phys. **A567** (1994) 97

[19] K. Ieki et al., Phys. Rev. Lett. **70** (1993) 730; D. Sackett et al., Phys. Rev. **C48** (1993) 118

[20] H. Esbensen, G.F. Bertsch and K. Ieki, Phys. Rev. **C48** (1993) 326

[21] K. Riisager, p. 281 in [3]

[22] The S034, LAND and FRS Collaborations, "Study of the unstable nucleus ^{10}Li in stripping reactions of the radioactive projectiles ^{11}Be and ^{11}Li" to be published.

[23] A.S. Goldhaber, Phys. Lett. **53B** (1974) 306.

Table 1: The width parameter of the radial neutron momentum distributions.

Isotope	E_{beam} (MeV/u)	Channel	Target	Γ (MeV/c)
^{11}Li	28	$\neq{}^{9}$Li	Be	42±4
	280	$A/Z > 2.3$	C	43±3
	280	$A/Z > 2.3$	Pb	36±4
^{11}Be	41	$\neq{}^{10}$Be	Be	59±4
	41	$\neq{}^{10}$Be	Ti	61±4
	41	^{4}Li	Be	55±3^{a}
	41	^{4}Li	Ti	50±4^{a}
	460	^{7}Li	C	67±5
	460	^{8}Li	C	56±5

a) Probably influenced by final state interactions (see text). Not included in the average.

Figure Captions

Figure 1 The radial neutron distributions from ^{11}Li reacting on Be, Ni and Au targets (filled squares, triangles and circles, respectively) at 28 MeV/u in anticoincidence with the projectile core (^{9}Li). The open squares give the distribution obtained by subtraction of the total neutron distribution recorded from ^{9}Li reactions in the Be target. The horizontal error bars indicate the angular width of the detectors. The curve shows the distribution according to eq. (1).

Figure 2 The radial neutron distributions from ^{11}Li reacting on a C and a Pb target (filled circles and squares, respectively) at 280 MeV/u in coincidence with a charged fragment. ^{9}Li excluded. The acceptance of the set-up was limited to fragments with $A/Z > 2.3$. The cross-section is given in arbitrary units.The full drawn and hatched curves show the fit to the data according to eq. (1).

Figure 3 As figure 3 but for ^{11}Be reacting on a C at 460 MeV/u. Filled circles denote the distributions in coincidence with ^{7}Li and filled squares the ones in coincidence with ^{8}Li.

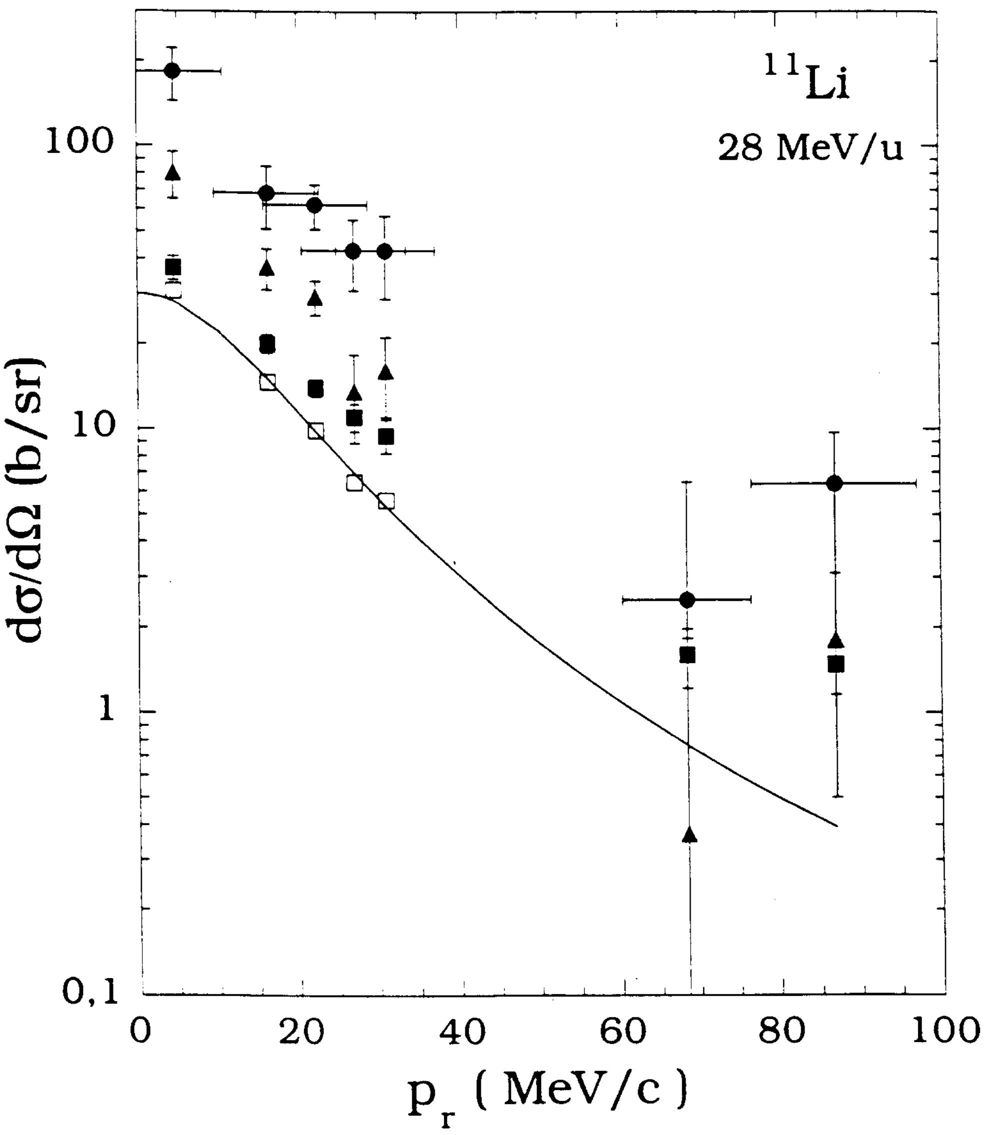
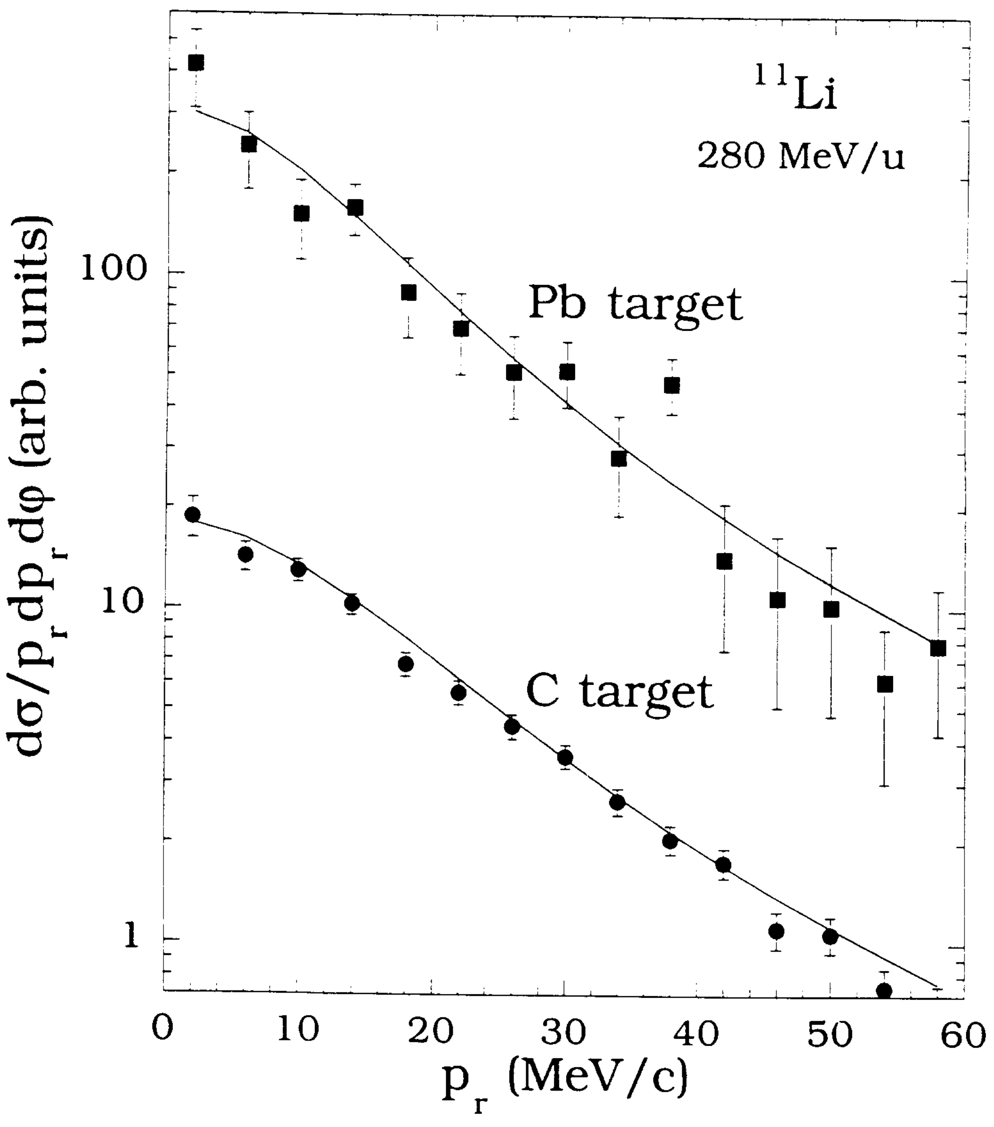
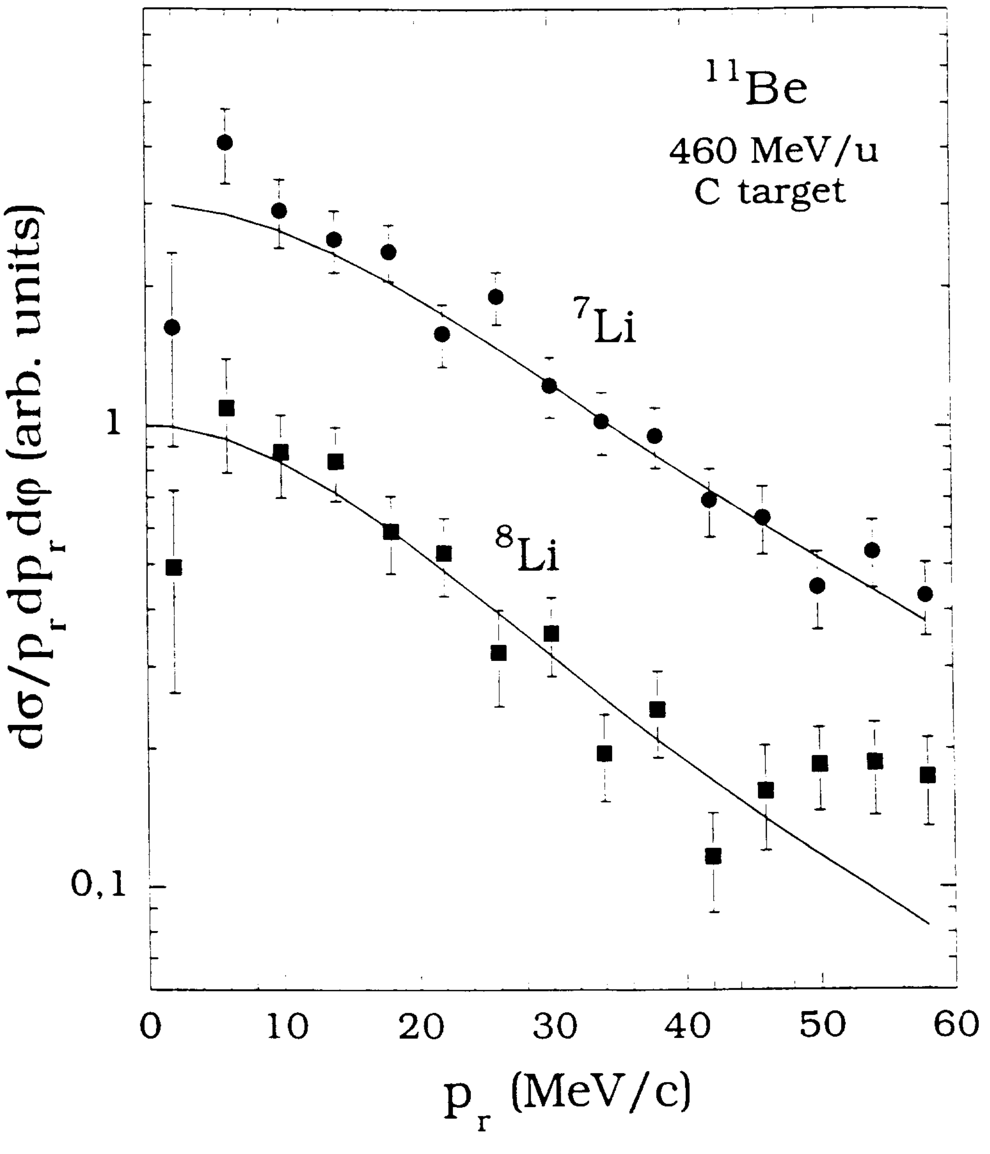


Fig. 1



^{11}Li
280 MeV/u
Pb target
C target
$d\sigma/p_r dp_r d\varphi$ (arb. units)
p_r (MeV/c)
100
10
1
0
10
20
30
40
50
60

Fig. 2



^{11}Be
460 MeV/u
C target
^{7}Li
^{8}Li
$d\sigma/p_r dp_r d\varphi$ (arb. units)
1
0,1
0
10
20
30
40
50
60
p_r (MeV/c)

Fig. 3